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Fluency and reading comprehension in typical readers and dyslexic readers, volume II

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The Simple View of Reading in Children Acquiring a Regular Orthography (Italian): A Network Analysis Approach

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In the present study, we explored the unique contribution of reading accuracy, reading fluency and linguistic comprehension within the frame of Simple View of Reading (SVR). The experimental sample included 118 3rd to 5th grade children learning Italian, a language with a highly regular orthography. We adopted a flexible method of analysis, i.e., the Network Analysis (NA), particularly suited for exploring relations among different domains and where the direct relations between a set of intercorrelated variables is the main interest. Results indicated an independent and unique contribution of syntactic comprehension skills as well as reading fluency and reading accuracy in the comprehension of a written text. The decoding measures were not directly associated with non-verbal reasoning and the latter was not directly associated with reading comprehension but was strongly related to oral syntactic comprehension. Overall, the pattern of findings is broadly consistent with the predictions of SVR and underscores how, in an orthographically regular language, reading fluency and reading accuracy as well as oral comprehension skills directly influence reading comprehension. Data are discussed in a cross-linguistic perspective. Implications for education and rehabilitation are also presented.

Keywords: transparent orthography, reading comprehension, reading accuracy, reading fluency, linguistic comprehension

INTRODUCTION

Reading comprehension is a multifaceted cognitive task that is critical for achieving good results in formal instruction, employment and the activities of daily living. In fact, a wide range of actions rely on individual ability to extract meaning from written texts. In this regard, it is important to frame individual performance within models of reading comprehension that are able to identify individual differences and may help improve both learning curricula and clinical interventions.

One influential model, i.e., the Simple View of Reading (SVR), proposes that processes which determine reading comprehension (R) are captured by two sets of skills: decoding (D) and linguistic comprehension (L) (Gough and Tunmer, 1986; Hoover and Gough, 1990). Decoding is defined as the ability to read isolated single words "*quickly, accurately and silently*" (Gough and Tunmer, 1986; page 7). Linguistic comprehension (L) is defined as the controllare originale:"*process by which, given lexical (*i.e., *word) information, sentence and discourses are interpreted*" (Gough and Tunmer, 1986, page 7). Thus, it refers to higher cognitive processes that go beyond reading and concern the oral language system.

The SVR also predicts that the influence of decoding and linguistic comprehension on reading comprehension will change as a function of schooling and reading proficiency. In the first years of formal instruction, children's decoding skills, not linguistic comprehension, predict reading comprehension. New readers are primarily involved in the effortful task of phonological decoding and word recognition and only invest residual resources in reading comprehension. With reading experience, as children master decoding the relationship between decoding and reading comprehension decreases, and children's differences in linguistic comprehension skills will become the most significant predictors of reading comprehension (Gough and Tunmer, 1986; Hoover and Gough, 1990).

The SVR model has been widely tested in readers of English, a highly opaque orthography, but also in readers of intermediate orthographies (such as French, i.e., Massonnié et al., 2019; European Portuguese, i.e., Cadime et al., 2017; Santos et al., 2020; see also Sparks and Patton, 2016 for Spanish L2 learners and Buil-Legaz et al., 2016 for Spanish-Catalan bilingual children with language deficits) as well as more transparent alphabetic scripts such as Finnish (e.g., Torppa et al., 2016), Greek (e.g., Protopapas et al., 2012, 2013; Kendeou et al., 2013) and Italian (e.g., Roch and Levorato, 2009; Tobia and Bonifacci, 2015). Evidence is also available for readers of some non-alphabetic writing systems, such as Chinese and Arabic (e.g., Joshi et al., 2012; Yeung et al., 2016; Asadi et al., 2017).

It is generally thought that reading decoding and linguistic comprehension explain a large part of the variance in reading comprehension in both orthographic and non-orthographic systems (for reviews see Florit and Cain, 2011; García and Cain, 2014). However, contrasting results have also been reported and some questions still remain. First, different patterns of associations among word decoding, linguistic comprehension and reading comprehension can emerge in different alphabetic orthographies and at different stages of reading because word reading is generally acquired much more easily in transparent orthographies (see for example the meta-analysis by Florit and Cain, 2011). Cross-linguistic studies have shown that orthographic consistency strongly influences the rate and modality of reading acquisition across different languages (for a review, see Ziegler and Goswami, 2005). Studies report longer time needed in opaque orthographies to master reading (e.g., Seymour et al., 2003) and a greater reliance on lexical procedure/larger print-to-sound units than in consistent orthographies (e.g., Ziegler et al., 2001). In the latter case, the fast rate of reading acquisition makes available greater cognitive resources for higher comprehension processes. Thus, readers of transparent orthographies may demonstrate a weaker relationship between decoding and reading comprehension and a stronger one between linguistic and reading comprehension in the early stages of reading acquisition with respect to learners of opaque orthographies (see for example Müller and Brady, 2001; but also see Zamperlin and Carretti, 2010; Tobia and Bonifacci, 2015).

Moreover, the relations between decoding and reading comprehension might depend on the way decoding is measured. In fact, the definition of word recognition as the ability to read single words "*quickly, accurately and silently*" (Gough and Tunmer, 1986; page 7) is somewhat underspecified and has been operationalized in several different ways. Most studies of English readers have measured only the decoding accuracy of either words or non-words. However, there is evidence that reading accuracy and reading rate are correlated but separable constructs (e.g., Bowers and Wolf, 1993; Carver, 1998). Bowers and Wolf (1993) discussed several lines of convergent research that point out precise time mechanisms which, if defective, can hamper efficient connections between phonological and orthographic codes and affect the quality of orthographic codes. Furthermore, accurate decoding may be insufficient to guarantee reading comprehension: if decoding is difficult and not automatized, the attention and cognitive resources necessary to process meaning will be insufficient, resulting in poor comprehension. Automaticity is considered an essential component of fluency[1] (see for example Fuchs et al., 2001).

However, data on English readers are inconclusive with regard to whether decoding fluency adds to the prediction of reading comprehension beyond decoding accuracy: some authors find that it makes a significant contribution (e.g., Silverman et al., 2013), while others do not (e.g., Adolf et al., 2006). Also, for transparent orthographies the results are mixed. It is well-known that fluency[2] intended as reading rate is a particularly sensitive marker of word recognition in transparent orthographies (e.g., Zoccolotti et al., 1999). However, the relative contribution of reading accuracy and fluency to reading comprehension has been rarely analyzed in transparent languages (Florit and Cain, 2011). This issue is particularly relevant for the Italian language, which is the topic of the present study. Italian is a very shallow language that is characterized by high consistency of grapheme-to-phoneme correspondence and a high degree of accuracy in reading both words and non-words by the end of first grade (e.g., Cossu et al., 1995; Orsolini et al., 2006).

Results for Italian are contrasting. In a first study, Florit et al. (2008) observed the strongest correlations between reading comprehension and reading speed in third grade and between reading comprehension and oral comprehension in fifth grade. In a subsequent study, Roch and Levorato (2009) tested the SVR in adolescents with Down's Syndrome (mean age 15 years) and in a small control group of first graders matched for reading comprehension to the participants with Down's

[1]Reading fluency is often measured as a combination of rate and accuracy: the number of correct words read aloud in 1 min (e.g., Shinn et al., 1992; Fuchs et al., 2001).

[2]In these studies fluency is measured in terms of syllables per second (s/s); thus, it captures the dimension of reading rate.

Syndrome. Word reading fluency was the strongest predictor of reading comprehension in the control group, whereas non-word accuracy did not make a unique contribution to reading comprehension over and above listening comprehension. Also Zamperlin and Carretti (2010) and Tobia and Bonifacci (2015) analyzed the development of relations between reading fluency and oral and reading comprehension in children in different grades (from 1st to 8th grade in Zamperlin and Carretti, 2010; from 1st to 5th grade in Tobia and Bonifacci, 2015). In both studies, oral comprehension was a stronger predictor of reading comprehension than reading decoding measures at all grades. In Tobia and Bonifacci (2015) study, reading accuracy played a significant but minor role, and reading fluency was never significant. In Zamperlin and Carretti (2010) study reading fluency was no longer statistically significant in secondary school. Finally, a recent investigation by Florit et al. (2020) on Italian children reported partially inconsistent results. The study was conducted on first-grade children assessed in two different observational moments: at the beginning of the school year (no formal instruction) and after 6 months of schooling. Listening comprehension had a stronger relationship with reading comprehension than both reading decoding parameters; however, also reading fluency, not accuracy, significantly influenced reading comprehension although with a lower magnitude with respect to listening comprehension. In the model, vocabulary measures also played an important role in reading comprehension. In sum, studies of Italian students using the SVR model components present mixed results and the relative contribution of word recognition and linguistic comprehension to reading comprehension remains unclear. Furthermore, some studies reported a greater role of reading rate than accuracy while others failed to detect any role for reading fluency.

The present study aimed to further investigate the relationship between reading decoding (in terms of both fluency and accuracy), reading comprehension and listening comprehension in a sample of third- to fifth-grade Italian children, i.e., who are at a developmental stage in which instrumental decoding rules have been largely acquired. As we were interested in having a large spread of performance in all of these critical measures, we recruited a group of children who attended school regularly and excluded only children with very low non-verbal intelligence. To test the predictions of the SVR model, we relied on the Network Analysis (NA). This is a flexible method for exploring the relationships among various domains, where the main interest is the direct relationship between a set of variables that are intercorrelated with one another.

A network is a model that consists of a set of nodes, which represent entities, and a set of edges that connect the nodes, which represent their relations (e.g., De Nooy, 2011). NA is now used widely in the field of psychology due to its specific characteristics: (a) it is strongly data-driven (i.e., the final model is selected by adopting parameters derived from the data), (b) but can still be used to support theoretical hypotheses, (c) it allows analyzing complex sets of interrelated variables, (d) giving back reliable, parsimonious and replicable results, (e) where the researcher can look simultaneously at multiple variables that are at the same time predicted and predictors (Epskamp et al., 2017). The behavior can be explained as an emerging property of the observed pattern of relations between the variables (Costantini et al., 2015). With NA, the researcher does not need to have an *a priori* model, as in the case of confirmatory factor analysis, thus leaving any possible relationship free to emerge from the data. Additionally, the use of undirected relations allows considering circularity in the studied relations. In this investigation, we used NA to inform about the following questions: (a) the role of reading skills in the reading comprehension of Italian primary school children in the higher grades; (b) the relations between reading fluency, reading accuracy, linguistic comprehension, and reading comprehension, ruling out the contribution of a potentially relevant variable such as non-verbal intelligence. In particular, we examined the role of syntactic comprehension as well as accuracy and speed in reading a meaningful text in explaining text comprehension in a sample of third- to fifth-grade children. We chose an oral syntactic comprehension test because of the generally low variability shown by other tests (such as receptive vocabulary) at the age examined here. Reading skills were explored with the reading aloud of a meaningful passage, in order to have a more functional and ecologically valid measure. The inclusion of non-verbal intelligence as a node in the model allowed studying the unique quote of variance shared by reading decoding, linguistic comprehension and reading comprehension, partialling out the role of non-verbal reasoning.

MATERIALS AND METHODS

Participants

A sample of 118 Italian children (50 females and 68 males), ranging in age from 7.9 to 11.2 years (average age: 9.80 ± 0.80), were recruited from three primary schools in southern Italy. The only exclusion criterion was performance on Raven's Colored Progressive Matrices (Raven, 1965) below the normative values (at least—2 SDs) based on Italian norms (Pruneti, 1996). In particular, 24 3rd grade children (average age: 8.55 ± 0.04), 41 4th grade children (average age: 9.51 ± 0.35) and 53 5th grade children (average age: 10.58 ± 0.30) participated in the study. All children attended school regularly, and none were singled out for socio-economic disadvantage by their teachers. The study was performed in schools in southern Italy, in areas without major migratory flows and devoted to primary and secondary economic sectors. The parents were informed about the research activities and authorized their child's participation by furnishing written informed consent. The study was conducted according to the principles of the Helsinki Declaration and was approved by the school authorities and by the Ethics Committee of Psychological Research of the Department of History, Society and Human Studies—University of Salento (Prot. 101206 -29th July 2020).

Materials

Non-verbal-Intelligence

Raven's Colored Progressive Matrices is a non-verbal test of intelligence and reasoning (Raven, 1965). The test provides a simplified 36-item paper format. Each item contains a pattern problem with one part removed and six pictured inserts, one of which contains the correct pattern. Subjects must select the pattern that completes the target figure. No time limit was given for the task and the standard administration procedure was used. Correct responses were computed (maximum score = 36) and the score was transformed into a z score according to Italian normative data (Pruneti, 1996).

Text Reading Task

Participants' reading level was assessed by administering a standard reading achievement test widely used for Italian children (MT reading test, Cornoldi and Colpo, 2011). The test consists of a series of meaningful texts (short stories taken from children's books) that vary in length and complexity depending on the school grade (from grades 1 to 8) with related grade norms. The length of the text passages used in the present study varied from 168 words in grade 3 to 215 words in grade 5. Each story was printed in black on a white piece of cardboard. None of the texts used for this task were used for the text reading comprehension task (see below). Children read a single text depending on their grade; they were asked to read the text aloud as correctly and fluently as possible within a 4-minute time limit There was no reference to reading comprehension in the instructions. Two parameters were computed: (1) reading fluency obtained by the number of syllables read/seconds; (2) accuracy calculated as the number of errors, adjusted for the length of the text read. Following the manual, accuracy scoring takes into account the functional meaning of errors. Each word with an elision, substitution, insertion or inversion of letters is scored as 1 error, while changes in stress assignment, hesitations, spontaneous self-corrections, errors that do not change the meaning of the text and repetitions of the same errors are given a 1/2 score. Raw individual data were transformed into z scores, according to norms of their reference-grade groups (Cornoldi and Colpo, 2011). Each performance was recorded in order to check errors, also with an offline correction. Test-retest indexes for reading speed, as reported by the manual, ranged between 0.85 and 0.96.

Text Comprehension Task

The task materials consisted of a series of narrative texts (Cornoldi and Colpo, 2011). For 3rd to 5th grade, texts ranged in length from 226 to 306 words and their length increased with school grade (a different text was used for each grade). The children were asked to read the text in silence at their own pace; then, they had to respond to 10 multiple choice questions, choosing one out of four possible alternatives. The comprehension questions concern information that is either explicitly stated or implied by the text. There is no time limit and the children are allowed to return to the text while responding to the questions in order to minimize memory load. The final score is calculated as the total number of correct responses. Raw individual data were transformed into z scores, according to the norms of their reference groups (Cornoldi and Colpo, 2011). Alpha coefficients, as reported by the manual, ranges between 0.61 and 0.83 depending on grade.

Syntactic Comprehension Task

Syntactic comprehension was assessed by administering the Syntactic Comprehension Task (SC-T), which is a test adapted from the TROG by Bishop (1989) and which is part of the Child Neuropsychological Battery (Bisiacchi et al., 2005), a comprehensive battery of tests designed to assess various neuropsychological skills in children aged 5 through 11. The SC-T consists of 18 items: the child listens to a sentence and is asked to identify which, among four pictures (to choose which picture out of four alternatives is the one that represents the meaning of the sentence. The wrong alternative options include distractors related to the correct response. The distractors can be lexical (items 1–8) or syntactic alternatives (items 9–18). No time limit is given. One point is given for each correct response (maximum score = 18). The total accuracy score obtained by each child was transformed into a z score, in line with the normative data (Bisiacchi et al., 2005).

Procedure

The tests were administered in two sessions. The intelligence, text reading and syntactic comprehension tasks were given individually in a quiet room in the children's school. The sequence of tests was randomized across participants. The individual session was ca. 35–45 min long. The MT comprehension test was group-administered and took about 10 min.

Statistical Analysis

Networks are a convenient option for modeling complex patterns of relationships. They allow analyzing several variables and the complexity of their relationships and give back readable outputs and indices. Networks are transdisciplinary and in psychology have been somewhat classical to model personality, psychopathology and attitudes (Cramer et al., 2012; Schmittmann et al., 2013; Costantini et al., 2015, 2017; Dalege et al., 2016; Borsboom, 2017). More recently, networks have been used to characterize neuropsychological performances in adults (Tosi et al., 2020; Ferguson and Alzheimer's Disease Neuroimaging Initiative, 2021) and to understand the relationship among math, reading and spelling skills in children (Zoccolotti et al., 2021).

A network is composed of a set of elements named nodes (i.e., the variables) and their connections named edges (i.e., the relationship). In networks assessing psychological phenomena, the edges are typically estimated with the Gaussian Graphical Model (GGM; Epskamp et al., 2017). Within GGM, an edge expresses a regularized partial correlation.

In this study, a GGM network was estimated using the graphical "*least absolute shrinkage and selection operator*" (LASSO; Tibshirani, 1996) algorithm as a regularization parameter (Friedman et al., 2008). The value of the LASSO is chosen by using the Extended Bayesian Information Criterion, a method for carrying out quantitative model selection, which is tuned by a parameter γ and which we set at.25, as suggested in the literature (Epskamp, 2016). The adoption of the LASSO leads small connections to shrink to zero (McNeish, 2015; Epskamp and Fried, 2018). The scope of the LASSO is to return a conservative network model that reduces overfitting and limits false-positive edges, producing replicable and interpretable results (Costantini et al., 2015).

Thus, how should an edge be interpreted? Two nodes are conditionally dependent when an edge connects them. The connection can be read as a partial correlation, i.e., the association between the two variables, net of the variance explained by the other variables in the network. This means that the association cannot be explained by the fact that another association is part of the network and the relation between the two variables is direct. When two nodes are disconnected, it means that they are conditionally independent, given with respect to the other nodes of the network, i.e., there is no variance shared uniquely by the two variables.

GGM may have a low sensitivity (i.e., not all real edges are detected) but it has a high specificity (i.e., few false positives) because of the regularization parameter (Epskamp et al., 2018). It is important to note that the potentially missing edges are those that are smaller and less consistent. On the contrary, this method basically does not produce false positives; thus, if an edge is estimated, it has to be considered to be true (Epskamp et al., 2018).

GGMs can also be read as a predictive model. The neighbors of each node correspond to its predictors. A node with high strength centrality is also a node that is highly predictable given the others, quantifying the predictability of a node according to the number of its neighbors and the strength of its connections (Barrat et al., 2004).

Notably, the GGM relations are undirected. The consequence of adopting undirected relations is that circular homeostatic effects can be detected and interpreted (e.g., A influences B which influences C which influences A), while using directed methods, like structural equation modeling, circularity cannot be observed. Networks are not better *per se*, but they may provide a different perspective that can obtain converging evidence from different methodological approaches in independent studies. However, they offer the important feature of looking simultaneously at multiple variables that are predicted and predictors at the same time.

The stability of the results was checked using a bootstrapping procedure (1.000 resampling); the bootstrapping leads in calculating the confidence intervals (CI) of each edge. By inspecting CIs, one can identify different types of edges. The edges that do not include 0 are stronger and more likely to be replicated. For these edges, one can expect to find an edge different from 0 in 95% of the samplings; thus, it is likely to be replicated in future studies. The edges estimated as different from 0, but including 0 in the CI, highlight the associations that could pass undetected in different samples (e.g., in a replication). Notably, GGM adopting the eBIC Lasso estimator is known to be particularly reliable in not producing false-positive results; thus, one can interpret these edges as very likely to be true (i.e., as the first type presented). At the same time, one should also have careful consideration in expecting future replications. Finally, edges that have CI crossing the 0 are particularly unreliable because future replications are expected to also find results in the opposite direction. This class of edges should therefore be considered as 0.

JASP software (JASP Team, 2020) was used to run the analyses. JASP (Version 0.14)(Computer software) is a software that grounds the network module on the *bootnet* and *qgraph* (Epskamp et al., 2012) packages of the R statistical software (R Core Team, 2020).

RESULTS

Means, standard deviations and ranges for the variables of interest are reported in **Table 1**. Mean z-transformed data for measures of reading comprehension, reading speed/accuracy, and syntactic comprehension were close to zero, indicating marginal deviations from the same age standardization samples. Notably, a large spread of performance was present for all variables, indicating no clear evidence of a restriction of range or a ceiling effect. Also mean performance for the measure of non-verbal intelligence was close to zero; note that due to the exclusion criteria none of the children performed below 2 SDs on Raven's test.

Inspection of individual data showed that 95% of participants had average or good levels of performance in reading comprehension (only six children underperformed), 97% in reading fluency, 94% in reading accuracy and 99% in syntactic comprehension. Overall, only nine children (7.6%) showed a marked reading delay (two children for both reading parameters, two only for reading fluency, and five children only for accuracy), and only one child underperformed in the syntactic comprehension task. They were not removed from the analyses because none had cognitive impairments.

Figure 1 shows the best network estimation representing the relationships among the variables examined. The exact values of all edges, as well as the simple correlations among all variables, are reported in **Table 2**. The strength centrality index is reported on the diagonal of **Table 2**. **Figure 2** reports the Bootstrap results.

TABLE 1 | Means, standard deviations and range values for Comprehension, Reading fluency, Reading accuracy, Syntactic comprehension, and Non-verbal intelligence.

Variable	Comprehension	Reading speed	Reading accuracy	Syntactic comprehension	Non-verbal intelligence
Mean	−0.24	−0.368	−0.378	0.229	−0.242
Standard deviation	0.758	0.809	1.091	0.845	0.8
Minimum	−2.72	−2.863	−4.702	−2.44	−1.91
Maximum	0.61	1.48	0.9	1.54	1.35

Values indicate z scores with respect to standard norms.

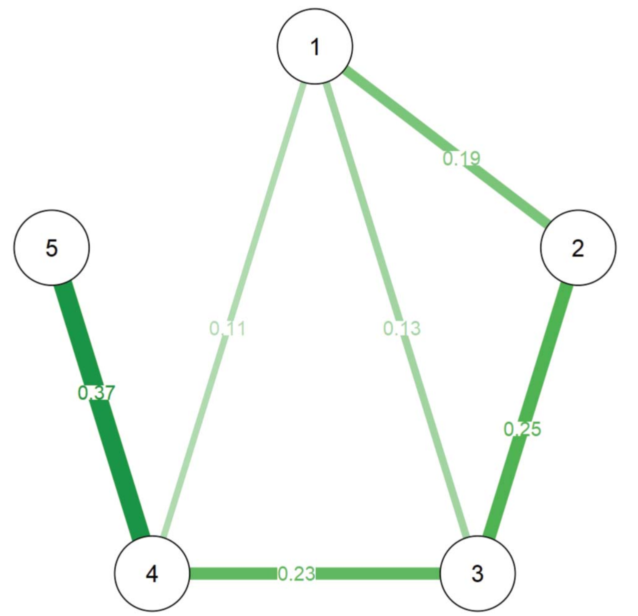

FIGURE 1 | The edges represent regularized partial correlations. Green lines show positive associations. Red lines would have indicated negative ones (none observed). The nodes indicate the variables as it follows: (1) Text Comprehension, (2) Reading fluency, (3) Reading accuracy, (4) Syntactic comprehension, and (5) Non-verbal intelligence.

Inspection of the network (**Figure 1**) suggests a number of main observations:

(1) the comprehension ability on a written text is directly associated with oral syntactic comprehension and text decoding skills;
(2) both reading fluency and reading accuracy are associated with reading comprehension; as network weights are partial correlations, this indicates that both accuracy and fluency have a unique quota of variance shared with reading comprehension;
(3) non-verbal intelligence, as measured with the Raven test, is strongly related to oral syntactic comprehension but not directly with reading comprehension;
(4) reading fluency and reading accuracy are not directly associated with non-verbal intelligence. Inspection of the 95% CI of the edges (obtained with the non-parametric bootstrap analysis; see **Figure 2**) confirms the reliability of the estimated network. Three observations support this claim:
(a) the edge bootstrap mean overlaps with the estimated edge for all the estimated edges different from 0;
(b) only two estimated edges different from 0 include the 0 in the CI; they are the weakest and 0 stands in the cue of the CI; and
(c) the CI of the estimated edges different from 0 never cross the 0 even when they include it.

DISCUSSION

This study explored the unique contribution of reading accuracy, reading fluency and linguistic comprehension to the reading comprehension of Italian 3rd-to 5th graders using a network analysis, which is particularly suited to estimating the relations among different but interrelated variables, at the net of each other. Thus, this approach changes the perspective by producing an interpretable output of the simultaneous estimation of each specific association and, could lead to a more comprehensive view of the phenomenon.

Results clearly confirmed the independent and unique contribution of linguistic comprehension over reading comprehension but also pointed out the relevant contribution of both reading fluency and reading accuracy. This pattern of findings is broadly consistent with the predictions of SVR (Gough and Tunmer, 1986; Hoover and Gough, 1990). The decoding measures were not directly associated with non-verbal reasoning, nor was the latter directly associated with reading comprehension; however, it was strongly related to oral syntactic comprehension. In sum, in Italian children, at a stage in which they have already acquired the rudiments of literacy, reading fluency, in terms of reading rate, is a strong and independent predictor of reading comprehension together with reading accuracy and oral comprehension. Notably the identification of this pattern highlights the specific contribution of the network analysis. Simple correlations (see the upper part of **Table 2**) suggest a less clear pattern where all the variables correlate to some extent with each other, including spurious correlations. The network approach simplifies the picture and removes the non-unique associations, thus unveiling the direct paths.

TABLE 2 | The lower part of the matrix reports the network weights, which correspond to regularized partial correlations (in dark gray). The upper part of the matrix reports simple correlations measured with Pearson's r (in a light gray background). The diagonal reports the strength centrality index, which is the sum of all the weights that a node receives (in white). Strength also measures the predictability of a node given all the others.

Variable	Text comprehension	Reading fluency	Reading accuracy	Syntactic comprehension	Non-verbal intelligence
Text comprehension	0.42	0.29	0.28	0.29	0.14
Reading fluency	0.19	0.44	0.36	0.16	0.02
Reading accuracy	0.13	0.25	0.61	0.30	0.17
Syntactic comprehension	0.11	0.00	0.23	0.70	0.47
Non-verbal intelligence	0.00	0.00	0.00	0.37	0.37

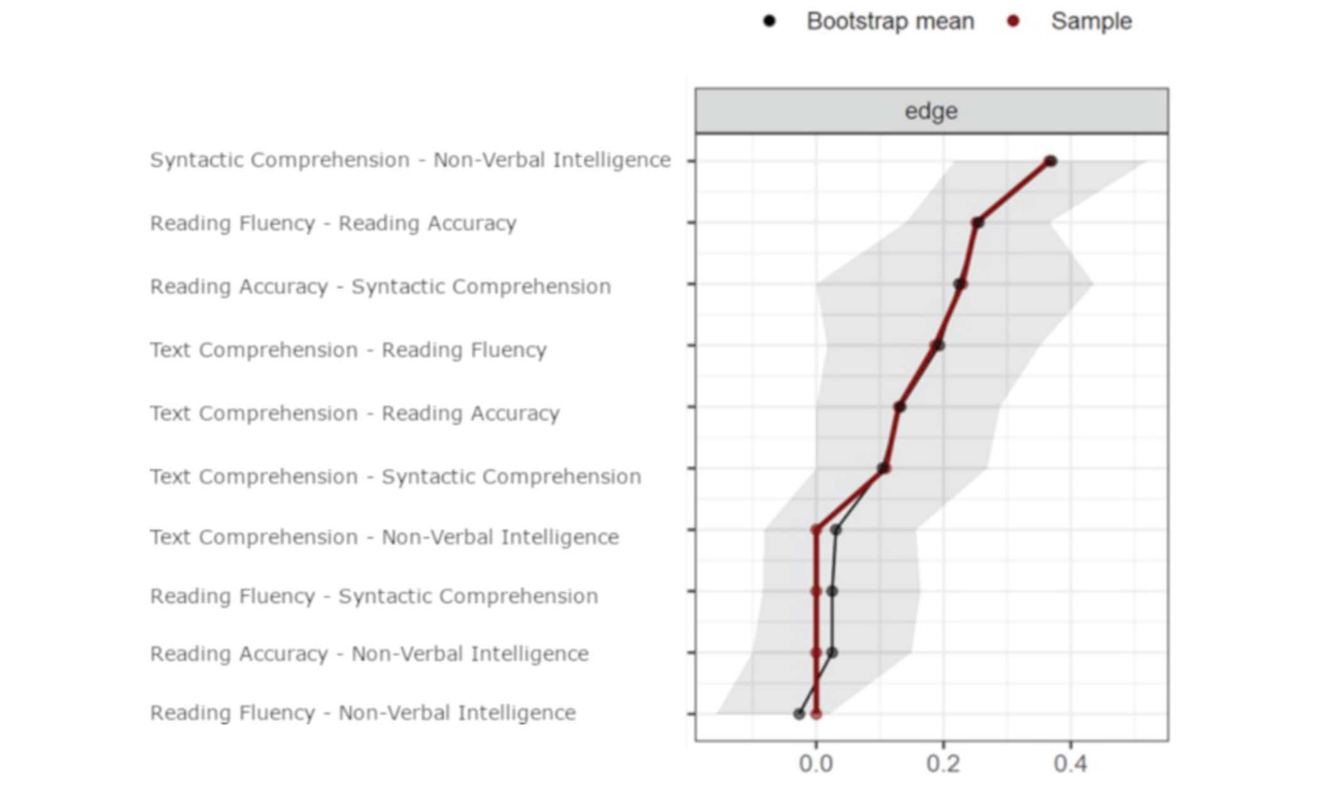

FIGURE 2 | Red dots indicate the edge value of the estimated network. Black dots indicate the average edge value over 1,000 bootstrap resampling. The gray shadow represents the 95% confidence intervals estimated with the bootstrap resampling. Edges are ordered by the estimated strength.

Our data are only partially consistent with those reported in previous studies of Italian children. First, they confirm that oral comprehension is directly associated with the ability to extract meaning from written texts (see Zamperlin and Carretti, 2010 and Tobia and Bonifacci, 2015, for similar results). Word decoding constitutes the necessary point of entry for reading comprehension. However many of the cognitive operations involved in reading comprehension are shared with the oral language system, thus a set of linguistic and cognitive processes is also essential (see Castles et al., 2018). Reading comprehension, in fact, implies the creation of a mental representation of the passage by combining information from the text to background information, such as sense of the words and their syntactic role in sentences, discernment of grammar rules and also knowledge of things and their relationship. Consistently, in our sample individual ability to understand oral sentences was associated with the ability to derive meaning from written texts.

With regard to reading decoding, our results fit with those reported by Florit and collaborators that reading speed/fluency measures significantly contributed to reading comprehension at least in first graders (Florit et al., 2020) and third graders (Florit et al., 2008); they are at variance with those of other studies which failed to detect any predictive role of reading fluency (Tobia and Bonifacci, 2015).

Various methodological differences may have contributed to this pattern of results. First, the studies included different measures of word recognition, reading comprehension and listening comprehension. As to the different reading measures, Tobia and Bonifacci (2015) and Florit et al. (2020) created two separate latent variables, i.e., one for reading accuracy and the other for reading fluency, based on different accuracy and fluency measures (non-word and word accuracy vs fluency in Florit et al.'s study; text reading accuracy vs fluency in Tobia and Bonifacci's study) while Roch and Levorato (2009) included only measures of reading accuracy for non-words and reading speed for words. In the present study, we considered reading speed and accuracy in reading a meaningful text (rather than pseudoword decoding), a more functional and ecologically valid task. It seems reasonable that taking into account different reading accuracy and fluency/speed measures should affect the relative load applied by the main constituents of the model. Also, the use of meaningful texts in the present study might have fostered the involvement of semantic components (with children trying to understand the meaning of the passage while reading) and, in turn, yielded a stronger association of reading accuracy with syntactic comprehension as well with text comprehension (with respect to studies that used pseudoword reading as a measure of decoding).

Moreover, there is also evidence that the type of comprehension test and the way in which comprehension is assessed inpacts the evaluation of the SVR: some measures of reading comprehension are more reliant on decoding skills than others (e.g., Cutting and Scarborough, 2006) or touch different aspects of language comprehension (Cain and Oakhill, 2006). For example, short passages, read aloud with cloze/multiple choice questions are more dependent on decoding skills than longer passages, read silently, and with open questions (see for example Keenan et al., 2008). Therefore, open questions rely more on semantic elaboration and the ability to organize the individual response on the basis of most relevant and secondary elements of the text, cloze/multiple choice questions rely more on memory/recognition processes. In the comprehension task used by Tobia and Bonifacci (2015), children were required to read aloud two passages (reading fluency and accuracy were recorded while reading the comprehension text). Texts were of medium length, without figures, and comprehension was tested with open questions that required both text-based comprehension processes (local comprehension) or inferential reasoning (global comprehension). The reading comprehension task paralleled the listening comprehension task; both required text-based and inferential processes. Also, in Zamperlin and Carretti (2010) study, the linguistic comprehension task was a composite measure that included the same passage used to assess reading comprehension but presented in a listening mode. As posited by the authors themselves, the collinearity between measures of reading and linguistic comprehension may have biased the results. In our study, reading decoding parameters and reading comprehension were evaluated with different text passages. The reading comprehension passages were of medium length and comprehension was assessed with multiple-choice questions, which mainly referred to given information. Finally, linguistic comprehension was assessed with an independent task, with respect to reading comprehension, and shared only the multiple-choice response modality with the latter. In synthesis, there were no risks of collinearity between measures and the reading comprehension task adopted relied more on decoding skills than semantic and discourse skills.

Finally, the difference in the results may also be due to the different statistical analyses used in the various studies. In the present research, we use the NA, which is particularly suited for isolating the specific role of each predictor in the SVR model. In fact, simple correlations may depend on a number of potential sources of co-variation, including similarity in the text materials and format. By contrast, the edges in NA indicate relationships that cannot be accounted for by any of the other measures considered. In this way, they return the specific weight of every single variable in the model. Furthermore, NA evaluates the reliability of the observed relationships, thus allowing an estimate of the replicability of results. Based on these considerations, we propose that the present results provide strong evidence that both accuracy and reading rate contribute to the prediction of reading comprehension in Italian children.

Our data support the SVR model also in learners of transparent orthography, specifying that the word recognition component has to contemplate a measure of reading fluency, intended as rate of reading, together with reading accuracy. Findings are consistent with results obtained both in transparent (e.i., Tilstra et al., 2009; Protopapas et al., 2012), intermediate orthographies (such as French, i.e., Massonnié et al., 2019; European Portuguese, i.e., Cadime et al., 2017; Santos et al., 2020) and opaque orthographies (e.g., Joshi and Aaron, 2000; Kershaw and Schatschneider, 2012; Silverman et al., 2013) that support the necessity to add a fluency component to the SVR. After all, fluent reading is the result of a number of processes, that interact each other, and that need be curried out efficiently and automatically (Breznitz, 2006). In other words, fluency captures the development of rapid rates of processing in the various components of reading from letter recognition and orthographic-to-phonological mapping, to word recognition and even semantic encoding (e.g., Wolf and Katzir-Cohen, 2001). Rate is one dimension of automaticity. A process is automatic if it is rapid, undemanding and does not require conscious control or voluntary attention (LaBerge and Samuels, 1974; Logan, 1988, 1997). When applied to reading, these elements indicate parallel, instead of serial, processing of words, they are non-intentional (i.e., the process occurs regardless of the willingness of the reader) and finally they are so quick and smooth that underlying processes are beyond conscious analysis.

The present findings in a transparent orthography seem relevant in a cross-linguistic perspective. On one hand, children learning a transparent orthography such as Italian rely more on small grain sizes in reading with respect to children learning more opaque orthographies that use a larger grain size (e.g., Marinelli et al., 2014, 2016). This makes reading in transparent orthographies a more serial process, well grasped by the reading rate dimension. On the other hand, the higher accuracy reached by Italian children after only a few years of schooling, as well as the smaller inter-individual variability, could have made the accuracy measure less sensitive to capturing word reading proficiency and in turn less related to reading comprehension with respect to more opaque orthographies. Note that, also in opaque orthographies, to explain some inconsistency among studies, it was proposed that once children become more accurate in their word reading fluency could be a more sensitive indicator of word reading ability and variability in fluency effectively accounts for reading comprehension (Language and Reading Research Consortium, 2015). Nevertheless, we found an independent, strong and unique contribution of both reading fluency and accuracy in explaining reading comprehension. Thus, the hypothesis (e.g., Müller and Brady, 2001) of a weaker relationship between decoding and reading comprehension, and conversely a stronger one between linguistic and reading comprehension among learners of consistent respect to opaque orthographies was not confirmed.

The present study has a number of limitations. We examined children in the final years of primary school, i.e., when the basic assets of reading are acquired and lexical reading is detectable also in a language with a highly transparent orthography such as Italian (Burani et al., 2002). While there is some indication that children are relatively homogeneous in the 8–10 year age range, it would have been interesting to detail the developmental trend over the three classes examined. However, this proved difficult for methodological reasons. First, the sample size for this study would have been reasonable for network analysis if the three classes had been collapsed together. If we had split it into three sub-groups, each one would have been too small to allow for reliable estimates. Second, if we had added age as a node it would have been technically feasible but incorrect as ages are not independent of grade level. Thus, including a continuous variable in the model would actually have hidden an ordinal variable (with three levels), and the GGM is poor in estimating ordinal variables with only a few levels. Finally, we analyzed z-scores in order to correct for differences in age and materials used. Thus, adding an age node or splitting graphs in three would provided a sort of double-dipping in the age variable, which is somehow under control when proper materials and standardizations are used. Thus, even though the general confounds related to age were under control, we have to conclude that it was impossible to detail the developmental trend within the age span considered, which is a limitation of the study. Further work is needed to clarify this point.

Another limitation concerns the possibility of generalizing the present results. We aimed to examine a sample without imposing limits of performance in the critical variables and only used low non-verbal intelligence as an exclusion criterion. Further, we obtained our sample from middle-class areas without critical migratory flows. Results confirmed the presence of great variability across children in all critical variables, including reading accuracy, which is a measure at risk for ceiling effects in a highly transparent orthography such as Italian. However, although we attempted to limit as much as possible potential selection bias (e.g., only children with very low non-verbal intelligence were excluded), our sample does not include a stratification of demographic variables. Thus, it would be incorrect to consider our sample as perfectly representative of the entire Italian primary school population, and generalizing results should be undertaken with caution.

Finally, our results have educational and rehabilitative implications. Thus, even when decoding deficits manifest as inadequate reading fluency they are expected to have an indirect but important influence on reading comprehension. Decoding and comprehension are likely to proceed well when both processes operate "automatically," which also means at a reasonable rate. In this vein, it was found that reading rate contributes to the understanding of reading passages because it has a mediating role between reading strategy awareness/use and reading comprehension (Rahimi and Babaei, 2021). Consequently, in the case of poor comprehenders the assessment of decoding skills might help in choosing the appropriate rehabilitation interventions. Moreover, reading trainings fostering faster and parallel word recognition will have carry-over effects on reading comprehension. In a recent study on English as a foreign language, it was found that a reading training that significantly improving students' reading rate also had a significant role in empowering their ability to process and better grasp the text (Rahimi and Babaei, 2021).

Overall, our data support the SVR model of reading also in learners of a transparent orthography. Furthermore, they indicate that when reading rate is taken as a component of reading fluency it effectively captures the dimension of automaticity and should be taken into account together with reading accuracy and the processes involved in linguistic comprehension in predicting text comprehension outcomes.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of Psychological Research of the Department of History, Society and Human Studies—University of Salento (Prot. 101206—29th July 2020). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

PA, CM, and PZ contributed to the conception and design of the study. LM organized the database. DR organized the database and performed the statistical analysis. PA wrote the first draft of the manuscript. All authors wrote sections of the manuscript, contributed to manuscript revision, read, and approved the submitted version.

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The Role of Emoticons in the Comprehension of Emotional and Non-emotional Messages in Dyslexic Youth – A Preliminary Study

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The study explored how well-dyslexic youth deals with written messages in an environment simulating popular social network communication system. The messaging systems, present more and more in pandemic and post-pandemic online world, are rich in nonverbal aspects of communicating, namely, the emoticons. The pertinent question was whether the presence of emoticons in written messages of emotional and non-emotional content changes the comprehension of the messages. Thirty-two pupils aged 11–15 took part in the study, 16 had a school-approved diagnosis of dyslexia and were included in the experimental group. Sixteen controls had no diagnosed disabilities. Both groups viewed short messages of four types (each including seven communicates): verbal-informative (without emoticons and emotional verbal content), verbal-emotive (without emoticons, with emotional verbal content), emoticon-informative (including emoticon-like small pictures, but without emotional content either verbal or nonverbal), and emoticon-emotive (with standard emoticons and including verbal-emotional content). The participants had to answer short questions after quick presentation of each message that tested their comprehension of the content. RTs and accuracy of the answers were analyzed. Students without dyslexia had shorter response times to the questions regarding all types of messages than the dyslexic participants. The answers of the experimental group to the questions about the emoticon-informative messages were less correct. The study pointed tentatively to the beneficial role of emoticons (especially the nonstandard, i.e., of non-emotional kind) in reading short messages with understanding.

Keywords: reading, verbal communication, nonverbal communication, computer-mediated communication, emojis

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INTRODUCTION

Of all the learning disabilities developmental dyslexia is the most common, with prevalence rate up to 17% of the population (Shaywitz, 1998) and many of the school children undiagnosed (Barbiero et al., 2012). It is also a source of potentially long-term behavioral, emotional, and psychosocial problems, especially in adolescents (Singer, 2005; Ingesson, 2007; Eissa, 2010). Dyslexia is characterized by poor accuracy and/or fluency in reading, which, alongside poor spelling and decoding abilities, directly impact reading comprehension. According to one of the most influential theories on the causes of dyslexia at its roots is deficits in phonemic access, manipulations, and retrieval (Démonet et al., 2004; Eissa, 2010; Moura et al., 2017; Peters et al., 2020). Effectively, children have difficulties in perception or awareness that words are made up of small, distinctive units that have the potential to differentiate word form and its meaning. These units are long-term representations of higher order than their singular modality-based (auditory, visual, and sensory) counterparts (Démonet et al., 2004). Since phonological (phoneme-based) processes closely relate to the act of hearing and speaking, the deficits can be especially pronounced in reading, which entails awareness that a written word's units, i.e., letters represent the speech sounds and that they both relate to phonemes. In fact, the phonological awareness is the best single predictor of successful reading (Brady and Shankweiler, 2013). Those phonological working memory deficits have been shown to adversely affect executive functions, such as inhibitory control and selective attention in school children (Barbosa et al., 2019). Indeed, there is some data that developmental dyslexia could be related to more general problems in higher-order cognitive mechanisms like executive attention and multimodal working memory (Varvara et al., 2014).

Dyslexia creates obvious problems in school, but also in personal and social spheres, where adolescents may feel the most vulnerable. Since many social contacts at the current time consist of writing and reading short communications, and this is especially true for the adolescents taking advantage of social media (Valkenburg and Peter, 2011; Oprea and Stan, 2012), it is worthwhile to investigate how young dyslexic people perform while reading short messages of various kinds and how the factors present in online messaging systems affect the performance. The main goal of the present study then is to evaluate reading comprehension of dyslexic youth faced with messages similar to the ones used in popular social networking communication systems in relation to the content of the communicates. It is novel in its approach of exploring reading comprehension in dyslexic youth on the basis of short online messaging. From theoretical standpoint, it could also point out the significant aspects of digital written text perception in general, with a special focus on its nonverbal elements, which are closest and most "natural" counterparts of nonverbal speech units (i.e., facial expressions, emblems, and gestures).

Indeed, one of the most distinctive characteristics of the online messaging systems [or computer-mediated communication (CMC)] is the presence of nonverbal "aids" or cues to the word-based communicates, i.e., the emoticons. Emotional icons (emoticons) are graphic signs that often supplement verbal messages in CMC (Dresner and Herring, 2010) and they perform nonverbal functions in such communication (Lo, 2008). Essentially, they are paralinguistic cues of expressing emotional meaning (Aldunate and González-Ibáñez, 2017), originally developed and used in CMC for the lack of natural means of expressiveness (i.e., face expressions). They are used to express not only emotions and humor, but also to strengthen the verbal contents of the message while impacting its interpretation (Derks et al., 2008a,b). The latter function seems of importance, because it is a less obvious one and could serve to accentuate or better convey strictly informative (non-emotional) contents of the message (e.g., by presenting graphically the most important, content-wise, element of the message). Such emoticons are called "nonstandard" in the present study. Furthermore, emoticons have been described as conveying specific aspects of the speech acts, like user's intentions (Dresner and Herring, 2010; dos Reis et al., 2018). In broader terms then, emoticons can serve as mediums of illocutionary force. Illocutionary acts are utterances, by which we state, question, command, or promise (Searle, 1969). Because emoticons function in such a wide array of ways, they can have great importance in the proper comprehension of written messages in CMC. In fact, the main rationale behind the present study is their apparent role in enhancing the comprehension of the messages in terms of accuracy of emotions, intentions and attitudes perception (Lo, 2008), clarification of sarcastic or literal meaning (Filik et al., 2016), and user-reported reduction of discourse ambiguity (Kaye et al., 2016). Moreover most young people born after 1980 (from the so-called Millennials generation) are well versed in emoticon use and depend heavily on them in their daily exchanges of written messages (Krohn, 2004).

Fundamentally, emoticons serve as prompts for or reinforcements of both emotional and strictly informative contents of the written communication. Their purpose is to make one's message as understandable as possible, especially in relation to those elements that are of particular significance to the sender (emotional or non-emotional). Since emoticons are nonverbal in nature, they can be of potentially substantial help in written message comprehension for people with poor reading ability. In the case of dyslexia, these graphic signs could provide non-phonemic strengthening elements enabling readers to achieve better comprehension of the message. There is some data regarding the fact that dyslexic people consciously encode word-like stimuli (pseudowords) differently than controls (attenuated late brain responses), whereas there is no such difference while encoding simple graphic symbols (Schulte-Körne et al., 2004). It is worthwhile then to examine the role and potential benefits of emoticons in reading comprehension in dyslexic youths, who are well acquainted with them and who depend on CMC in their daily lives, especially in the present day's pandemic and post-pandemic situation, which forces more social isolation and online-only contacts. In the present exploratory and preliminary study, we are interested if and how standard (emotional) and nonstandard types of emoticons help young students with dyslexia in the understanding of both emotional and non-emotional verbal online messages. We expect overall worse performance (reading times and accuracy) in dyslexic participants as compared with the controls, with some beneficial effects of emoticons on the messages comprehension observed especially in the experimental group.

MATERIALS AND METHODS

Advanced Preparation

In order to gather more information on the students of the age group and their communication preferences, we used two complementary data sources. One was special national research on young people (National Research Institute of Poland NASK report; Bochenek and Lange, 2019) and the other were the current study's conversations and interviews with school children. The short interviews preceded the day of the experiment and they were conducted at the same school as the experimental sessions. This was facilitated by school's counselors, who had access to the dyslexia diagnosis of the pupils. The researchers recruited 34 students who participated in the interview stage in preparation for the study (dyslexic $N = 17$). Of these, 32 took part in the subsequent study. We also contacted 15 age-matched students attending many different schools, who did not take part in the study, *via* e-mails and smart phone messages prior to the interviews. During the conversations, questions regarding preferred social media platforms as well as the main purpose and characteristics of their usage (see below for details) were asked. This was done in order to confirm the more robust data from the NASK report.

The interviews conducted in preparation for the study supported the data from the NASK report in terms of the importance of communication *via* social media for adolescents. According to the report, only 0.2% of primary school respondents declared having no profile on social media sites and 77.8% of respondents stated that they use Facebook as their favorite social media platform. Based on the data, it was decided that an adaptation of Facebook Messenger would be used as a basis for materials to be presented in the study (ecological validity purposes). The conversations with the age group confirmed that adolescents are very familiar with the Messenger. The respondents highlighted the fact that they used the application primarily for social purposes. Regardless of the frequency of active usage of the Messenger to send messages, most of the young people were subjected to its passive influence, i.e., getting messages from other people. The pupils were asked specific questions regarding topics of conversations and also emoticons most commonly used in the Messenger. It was concluded that adolescents communicate by the means of the Messenger application to talk about daily life, school, current events, nearby future, and to arrange meetings and dates. Although the use of emoticons was dependent on personal preferences, the most often used ones were those related to emotional states, enrichment of expression, or replacement of words.

Participants

Thirty-two Polish primary school pupils aged 11 to 15 (mean = 13.28, $SD = 1.05$) took part in the study (females $N = 15$). Sixteen participants (mean age = 12.81, $SD = 1.22$, females $n = 8$) were qualified to the experimental group on the basis of dyslexia diagnosis, and 16 participants (mean age = 13.75, $SD = 0.57$, females $n = 9$) made part of the control group. Dyslexia diagnosis was based on the headmaster's and school counselors' declaration stating that particular children had certificates from a psychological and pedagogical counseling center. Children diagnosed with other specific developmental disorders of scholastic skills were not included in the experimental group. Students in the control group had no diagnosed impairments.

The research was conducted in accordance with the ethical demands, provided and approved by the Commission on the Ethics of Scientific Research at the Jagiellonian University Institute of Applied Psychology. Before the experiment, signed consent forms were also obtained from parents or legal guardians of the participants.

Materials

We devised the messages on the basis of the data sources (NASK report and the preceding interviews) and implemented them in a picture frame that simulated the Messenger's graphical user interface.

The messages were divided into four groups. Every group consisted of seven separate messages (each containing on average four sentences, minimum three, maximum six, made up of content words resembling the youth lexicon as closely as possible, with no difficult or infrequent words present). The first group was called verbal-informative (V-I) and its messages lacked emotional content and any emoticons (sentences and questions on neutral topics regarding school, house chores, and extra-curricular activities); the second group, verbal-emotive (V-E), lacked emoticons but possessed emotional verbal content (sentences and questions on significant, stressful, or exciting topics); the third was called emoticon-informative (E-I) and it included nonstandard emoticons (signs illustrating objects, events, and persons) and the verbal content of its messages was non-emotional; and lastly, the fourth group, emoticon-emotive (E-E), included standard emoticons (expressing various emotional states) and emotional verbal content. Each message within the two emoticon groups contained four emoticons. **Figure 1** illustrates samples of two messages used in the experiment.

In order to test the comprehension of the written messages from each group, 28 sets of questions were prepared. It was decided to posit two types of test questions, both strictly relating to the content of each message: two single-choice questions (with four possible answers) and two yes or no questions (four questions for every message in total). The two types of questions were presented for every message shown. Such design let us examines the understanding of the conveyed content, and not the short-term memorization of a specific word used in a message. The questions referred to crucial content that could be important to the recipient in the case of receiving similar types of messages in real life. Here, we present two examples of the questions:

Were there any beverages on the shopping list? Yes/no.

The sender of the message needs the guitar because: (1) he will play a gig, *(2) he has a guitar class scheduled*, *(3) he will participate in a family get-together*, and *(4) he just wants to play it.*

Additionally, Edinburgh Handedness Inventory (Oldfield, 1971) was administered.

Procedure

The procedure was programmed in the PsychoPy2 software (Peirce et al., 2019). The experiment was conducted in classrooms which were made available by headmasters and school counselors. Firstly, the participants were asked to fill out the consent form and then Edinburgh Handedness Inventory. Next, the procedure

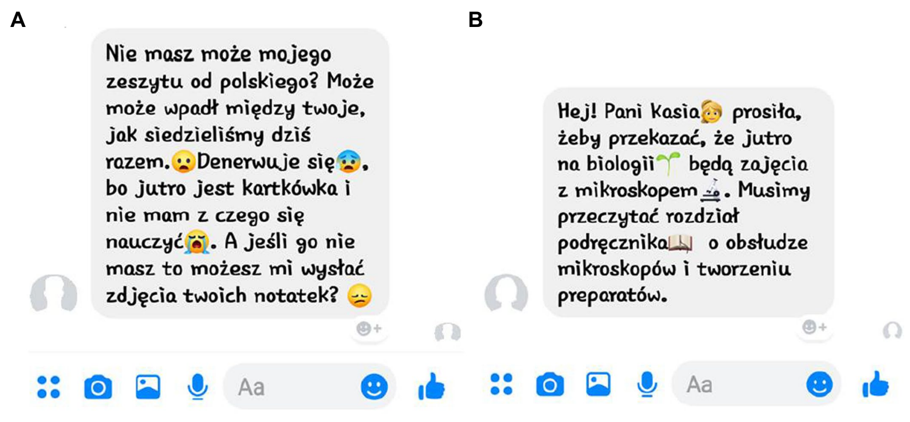


FIGURE 1 | Two sample messages with emoticons used in the experiment. **(A)** Emoticon-emotive (E-E) message, translated from Polish: *Do you have my Polish class notebook? Maybe it ended up in your things, while we were sitting together*. (emoticon) *I am nervous* (emoticon), *because we have a test tomorrow and I cannot prepare without it* (emoticon). *If you do not have it, would you send me pictures of your notes?* (emoticon). **(B)** Emoticon-informative (E-I) message, translated from Polish: *Hey! Mrs. Jones* (emoticon) *asked to tell others that tomorrow in biology class* (emoticon) *we will work with microscopes* (emoticon). *We need to read a chapter from the manual* (emoticon) *on the use of the microscopes and the preparation of the samples*. Message icons and layout © Facebook.

was run on a notebook, starting with instructions that detailed the task ahead and introduced the training session, in which two sample messages (not present in the actual experimental run) with the standardized sets of questions were presented. After the training session, the participants had the opportunity to ask questions if anything was unclear to them. Then, the main experimental session began. Each participant was faced with all the messages in random order from four groups described in the materials section. Each message was presented for 20 s on the computer screen and immediately after each presentation a set of four questions (two multiple-choice questions and two yes or no questions) was presented randomly one at a time. There was no time limit for giving answers. Reaction time and correctness of the answers were registered. The whole procedure took approximately 30 min. At the end, the participants received words of appreciation and were free to leave.

RESULTS

The statistical analyses were conducted in the Statistica 13 and SPSS 26 software packages. Edinburgh Handedness Inventory revealed that most of the participants were right handed (n = 30) and a few left handed (n = 2). The main experimental session analyses were based on one independent variable with four levels (type of message: verbal-informative V-I, verbal-emotive V-E, emoticon-informative E-I, and emoticon-emotive E-E) and two dependent variables (RTs – mean from the single choice and yes/no questions to each type of message and the correctness of answers – mean sum of the points of the four questions).

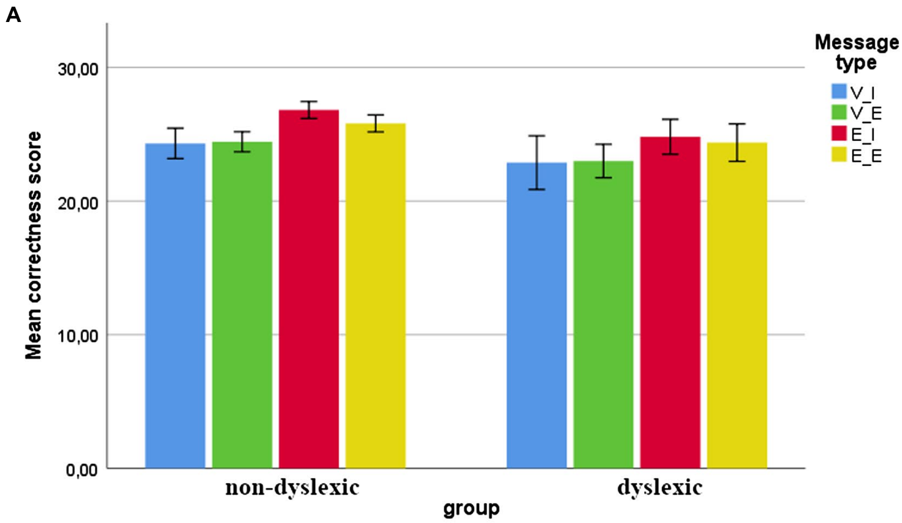
In the first part of the analysis, distributions of the RT and accuracy of the answers were tested. The W Shapiro-Wilk test was conducted for this purpose. A normal distribution was revealed for variables: RTs of the answers to the questions on V-E and V-I messages as well as E-I messages. Other variables turned out not to have normal distribution. Further inspection of the accuracy scores distributions revealed that the data were negatively skewed. Log10 transformation attempt at normalization did not change the skewness of the distribution. Therefore, the differences in the correctness variable were analyzed with the nonparametric test.

Reaction Times of the Answers

Since the present study was exploratory and preliminary in nature, it is worthwhile to emphasize the descriptive statistics first in order to indicate general trends. In the case of the RTs, the quickest answers were given to emoticon-emotive (E-E) messages in both groups (dyslexic group mean 5.72 s, SD = 1.88, min 3.43, max 10.85; non-dyslexic group mean 3.9, SD = 0.61, min 2.94, max 4.84) and the longest to verbal-informative (V-I) messages, again in both groups (dyslexic mean 6.07, SD = 1.84, min 3.9, max 11.16; non-dyslexic mean 4.31, SD = 0.85, min 3.05, max 5.92). **Figure 2** illustrates the descriptives (see **Figure 2B** for the RTs).

In order to compare the groups in terms of the RTs of answers having similar normal distribution, analysis of variance was conducted. The results showed statistically significant differences between the control and experimental groups, $F(3.28) = 4.36$, $p < 0.05$. In order to evaluate the differences of particular variables between the groups, Bonferroni's *post-hoc* test was carried out. All the variables turned out to be significant ($p < 0.05$). The results indicate getting significantly shorter reaction times of answers to all the types of messages examined in the group of participants without dyslexia. **Table 1** presents the differences in RTs between the groups.

Also, the RTs of answers to questions regarding the verbal-emotive (V-E) messages were overall faster than to verbal-informative (V-I) ones (mean RTs 4.96 < 5.19, p = 0.02) for all the participants (irrespective of group). In other words, the answers to verbal-only messages with emotional content were given faster than to those without emotional content.



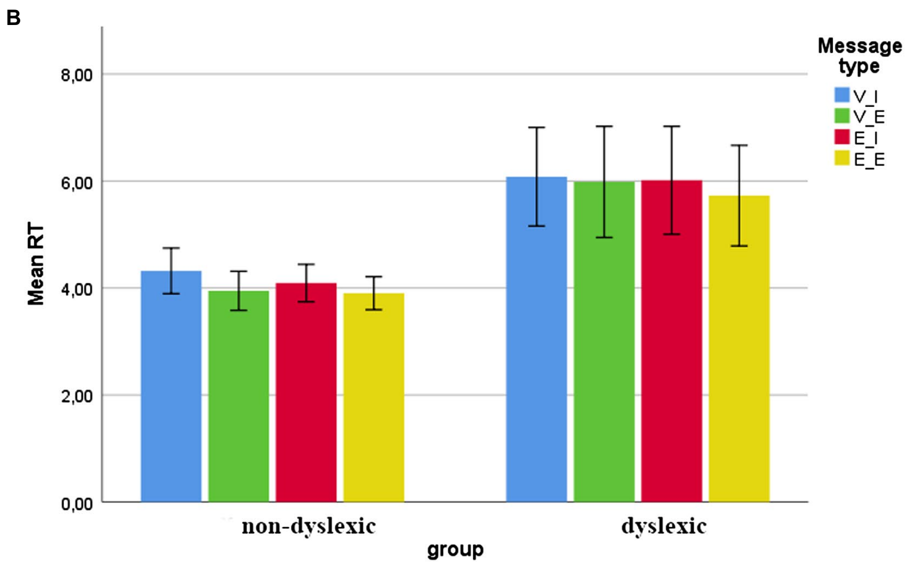


FIGURE 2 | Mean scores for all the message types in two groups with standard error bars. **(A)** Mean correctness score **(B)** mean RT (in seconds). V-I, verbal-informative message; V-E, verbal-emotive; E-I, emoticon-informative; and E-E, emoticon-emotive.

TABLE 1 | Mean RT of answers to three types of messages in two groups with significance levels of Bonferroni's tests.

Message type	Dyslexia group	No dyslexia group
V-I	6.08*	4.32*
V-E	5.98*	3.95*
E-I	6.01*	4.09*

V-I, verbal-informative message; V-E, verbal-emotive; and E-I, emoticon-informative. $^{*}p < 0.01$.

Correctness of the Answers

As in the case of the RTs, we emphasize the descriptives as indicators of general trends. The most accurate answers were given to emoticon-informative (E-I) messages in both groups (dyslexic group mean 24.81, *SD* = 2.61, min 20, max 28; non-dyslexic group mean 26.81, *SD* = 1.27, min 24, max 28) and the least accurate to the verbal-informative (V-I) ones, again in both groups (dyslexic mean 22.88, *SD* = 4.01, min 14, max 27; non-dyslexic mean 24.31, *SD* = 2.27, min 20, max 28). **Figure 2** illustrates the descriptives (see **Figure 2A** for accuracy scores).

The lack of normal distribution of the correctness variable resulted in conducting nonparametric Mann-Whitney *U* test. The results indicate the significance ($U = 64.5$, $p < 0.05$) of the correctness related to one type of message, i.e., having informative content with (nonstandard) emoticons (E-I). Answers of the control group turned out to be more accurate comparing to the ones given by the participants from the experimental group. **Table 2** shows the differences.

TABLE 2 | Mann-Whitney U test statistics (with the continuity correction) of the correctness of answers between groups for the four types of messages used in the study.

Message type	*U*	*Z*	*p*	*Z* (correct)	*P*	*N* important (Dyslexia group)	*N* important (No dyslexia group)
V-I	112.0000	−0.58	0.559	−0.59	0.554	16	16
V-E	64.0000	−1.63	0.101	−1.68	0.092	16	16
E-I	64.5000	−2.37	0.017	−2.42	0.015	16	16
E-E	90.0000	−1.41	0.157	−1.44	0.148	16	16

V-I, verbal-informative message; V-E, verbal-emotive; E-I, emoticon-informative; and E-E, emoticon-emotive.

To look for differences in the accuracy of the answers to different messages within the groups, Wilcoxon rank sum test was conducted. In dyslexic group, the most accurate answers were given to informative messages with nonstandard emoticons (E-I) and those differed significantly with purely verbal-informative messages (V-I), $W = 96.00$, $p = 0.005$, and verbal-emotional messages (V-E), $W = 89.00$, $p = 0.002$. More accurate answers were also given to emotional messages with emoticons (E-E) as compared to emotional ones without any emoticons (V-E), $W = 23.00$, $p = 0.03$. In non-dyslexic group, the higher accuracy of the answers to E-I messages was even more pronounced, with significant differences as compared to V-I messages, $W = 6.00$, $p = 0.006$, V-E messages, $W = 12.00$, $p = 0.003$, and even E-E ones, $W = 19.50$, $p = 0.03$. There were also differences observed between (more accurate) answers to E-E messages and V-I ones, $W = 56.00$, $p = 0.03$, as well as between E-E messages and V-E ones, $W = 9.00$, $p = 0.009$.

DISCUSSION

The aim of the preliminary study was to explore whether the presence of two types of emoticons (traditional and nonstandard) within emotional and non-emotional verbal messages helps with the comprehension of their contents in dyslexic youth. The reading disability is proven to influence adversely young people's growth and wellbeing, both in social and personal domains (Terras et al., 2009; Eissa, 2010; Glazzard, 2010; Dahle et al., 2011) with children's behavior and personality being negatively affected as well, impacting their quality of life (Gagliano et al., 2014; Huang et al., 2020), which in turn may lead to such severe problems as depression and suicidality. This necessitates coping programs based on whole-school support systems (Firth et al., 2013) or special compensation tools, e.g., software with user-driven functionalities aiding reading comprehension and fluency (Rodriguez-Goncalves et al., 2021), especially taking into account the fact that many teachers lack the strategies to evaluate and intervene in dyslexic students (Leite, 2012; Ryder and Norwich, 2019). In an ever isolated pandemic and post-pandemic world that depends more and more heavily on CMC, whether for social, educational, or personal purposes, it is especially important to study what are the possible beneficial factors in reading comprehension for dyslexic young people. That is why we decided to look into the most characteristic, yet constantly expanding and developing aspect of the CMC, i.e., emoticons. Emoticons have evolved from simple graphic signs relating to smiles, frowning, or expressions of sadness (imitations of facial expressions) to illustrations of complex concepts of significance for the sender (objects, persons, events, and situations; Dresner and Herring, 2010). They also became less typographic and more human or reality-based in nature and as such are sometimes called *emojis* (Aldunate and González-Ibáñez, 2017). In the present study, we decided to employ emoticons (emojis) that belonged to two main types: traditional, emotion-based and nonstandard, information (object or person)-based ones.

We compared the comprehension of the written messages with or without emoticons on the basis of reaction times and accuracy (correctness) of the answers given in experimental (dyslexic) and control groups of age and sex matched participants. We expected poorer overall performance of the experimental group, which was confirmed as far as the RTs were concerned. Longer RTs in dyslexic youth could point to the problems in reaching the proper information through the working memory (first questions on the contents of the messages were asked immediately after 20 s of message presentation), which could be due to the impaired comprehension of time-restricted text presentation. Alternatively, the effect could be seen as the result of trouble in the encoding of the (written) questions themselves, either on the basis of their only verbal (phonological) elements or processing of fast and rapidly changing stimuli. The latter aspect could relate to the speed processing hypothesis of deficits in dyslexia (Tallal, 1980). However, the alternative explanation seems a less probable one, since the questions were explicitly designed to be as simple and straightforward as possible tests of content comprehension (single choice and yes/no types of questions, no time limit for an answer). The overall high performance in the accuracy of the answers (see below) would attest to that. The RT effect can be seen as a point in favor for providing more time during educational process for dyslexic youth, including written state examination.

The general trends as indicted by descriptive statistics point to the fastest answers being given in response to emoticon-emotive messages in both groups. This possibly relates to the main effect of quickest RTs to the verbal messages rich in emotional content (see below), but also could be seen as a tentative point in favor of traditional (face-expression based) emoticons as the most common and natural paralinguistic cues in CMC that could help in written message encoding (Aldunate and González-Ibáñez, 2017). Conversely, messages lacking any nonverbal cues and without emotional content (verbal-informative only) seem to be the hardest to process in CMC (having the lowest accuracy scores in both groups as well, see **Figure 2A**).

We also noted a general main effect of emotional content of strictly verbal messages on the RTs, with overall (irrespective of group) shorter RTs to the emotive messages as compared to the informative ones. As such, it is marginally interesting in the context of the present study, but it possibly showcases a well-researched aspect of preferential processing of emotional stimuli, pictorial or verbal alike, evidenced strongly even on brain activity measures (for a review on image-based studies, see Olofsson et al., 2008 and on word-based studies, see Citron, 2012). It could also relate to the specific aspect of better memorization of autobiographical content rich in emotional elements (Christianson and Safer, 1995), since the messages used in the study had social and personal overtones and they related to the episodes of everyday life commonly experienced by young people.

We have observed differences in relation to accuracy of the answers between the experimental and control groups. Significantly more accurate answers were given by non-dyslexic participants to messages with emoticons and of informative content only. The graphic signs in those messages were of nonstandard type, i.e., small pictures of objects or persons that were also expressed verbally. These newer kinds of emoticons (which might as well be called "infoicons") repeat or reinforce content already conveyed. They seem of particular use for quickly grasping the meaning or better encoding of the content to be recognized within the next minute. Non-dyslexic people seem to make the best use of such graphic reinforcement of the verbal message content (also as compared to all the other types of messages within that group). However, on the basis of within-subject analysis, we tentatively observed the benefits of exactly that kind of emoticons for dyslexic people as well. Trends indicated by descriptives (see **Figure 2A**) attest to that as well. The analyses and general trend observations showed that the answers to the informative messages with nonstandard emoticons (E-I ones) were the most accurate ones and they differed significantly with both types of messages (informative and emotional in content) that lacked emoticons. Possibly then, it is the nonstandard emoticons that are of most benefit to the individuals with reading impairment, since they are purely nonverbal (non-phonemic) signs that serve as graphic transcripts of verbal content, and thus help in the message comprehension. As such, they could be implemented into educational programs and online studies as aids in reading comprehension tasks.

Traditional emoticons (conveying basic emotional states, such as happiness, sadness, and surprise) on the other hand could be seen as more complex in nature since they do not duplicate the content, but rather add nuanced interpretation (or intentions) of the sender to it. What is more, although they too are nonverbal functionally, they could be seen as quasi-nonverbal elements (Lo, 2008), as the additional content to the verbal series (verbal cues). Such an interpretation should be approached cautiously, because there was no significant difference in the accuracy of answers between messages with traditional and nonstandard emoticons in the experimental group (it was present however in the controls). Interestingly, there is some evidence that people with dyslexia have visual attention deficits that relate to general visual domain, rather than to strictly verbal one (Lobier et al., 2012).

It is also worth noting that the overall accuracy-based performance of the dyslexic group was high (only one significant difference between the groups). This can point to the fact that the task was very simple indeed, or alternatively that the CMC which was simulated by design in the study's procedure, is a very natural and enabling environment, especially for young people, including those with reading disabilities, even though they require more time to react to the written messages (see RT effects described above).

The overall trend of higher accuracy of the answers to messages rich in both kinds of emoticons as compared to the strictly verbal messages in both groups is also worth mentioning. This general tentative effect seems to confirm special role of emoticons in CMC in enhancing the comprehension of the written text, possibly by strengthening the verbal content of the message (Derks et al., 2008a) or clarifying its ambiguity (Kaye et al., 2016). The most important aspect that the study points to is their potential benefit for dyslexic students as aids in educational process and social interactions alike (obviously, since the claim is based on the results of a simple preliminary study it should be treated very cautiously). In a world that depends on CMC more and more in educational, professional, and personal spheres, the need to understand and pinpoint crucial aspects of written content comprehension for people with reading impairments is a pressing matter. Future research on larger samples should focus on short yet condensed (content-wise) messages and text excerpts in detailing the role of various kinds of emoticons (standard vs. nonstandard) with different degrees of complexity (colors, shapes, and animations) and determining the most beneficial type of paralinguistic cue for written content comprehension (with strict control for communication patterns of young people). The new, nonstandard object-based emoticons reinforcing the verbal content by essentially doubling it, bearing close resemblance to reality (*emoji* class) as present in the most popular social network messaging system (duplicated in the present study) seem the most promising or interesting of the aids.

Lastly, limitations of the study ought to be mentioned. Since the study was explorative and preliminary in nature, the sample size of the participants was small, and no prospective power analysis was done to determine the adequate sample. This obviously limits the interpretation of the data and results obtained. Retrospective power analysis was not implemented, since it adds no new information on the statistical tests outside the value of p and should be avoided (Lenth, 2001). Furthermore, the score distribution of the correctness variable was not normal and this resulted in conducting nonparametric tests. Both of these factors (the non-normal distribution probably stemming in part from the small sample size) renders the analysis problematic and the interpretations of the results and conclusions based on them should be treated cautiously and only as tentative indicators of the possible effects in the population. The other cause of the non-normal distributions of the correctness results worth mentioning is very low difficulty of the task employed and this in turn resulted in a positive bias (toward the high end of scales) of the scores (negatively skewed distribution). The study design itself could be seen as not optimal for full investigation into emoticons and its impact on the comprehension of various kinds of online messages, since for simplicity and ecological validity purposes it lacked, e.g., emotional text message condition with nonstandard (non-emotional) emoticons (such messages seem rare in real CMC). Furthermore, there are some potential confounding factors that could have had an impact on the results, like initial level of text comprehension, long-term experience with CMC, which should be addressed and controlled in future full-scale research.

Overall, the study obtained some tentative and promising results, which pointed to specific factors of importance in reading comprehension of the students with dyslexia (the nonstandard emoticons, longer times of written message processing). As such merits replication on larger samples and further exploration of the abovementioned aspects related to online written content so commonly accessed by young people nowadays.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Commission on the Ethics of Scientific Research of the Institute of Applied Psychology, Jagiellonian University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

EL contributed to the study design, the gathering of the data, the analysis and interpretation of the data, and the drafting of the manuscript. SG contributed to the study design, the analysis and interpretation of the data, and the drafting and critical revision of the manuscript. All authors contributed to the article and approved the submitted version.

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Disrupted Spatial Organization of Cued Exogenous Attention Persists Into Adulthood in Developmental Dyslexia

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Purpose: Abnormal exogenous attention orienting and diffused spatial distribution of attention have been associated with reading impairment in children with developmental dyslexia. However, studies in adults have failed to replicate such relationships. The goal of the present study was to address this issue by assessing exogenous visual attention and its peripheral spatial distribution in adults with developmental dyslexia.

Methods: We measured response times, accuracy and eye movements of 18 dyslexics and 19 typical readers in a cued discrimination paradigm, in which stimuli were presented at different peripheral eccentricities.

Results: Results showed that adults with developmental dyslexia were slower that controls in using their mechanisms of exogenous attention orienting. Moreover, we found that while controls became slower with the increase of eccentricity, dyslexics showed an abnormal inflection at 10° as well as similar response times at the most distant eccentricities. Finally, dyslexics show attentional facilitation deficits above 12° of eccentricity, suggesting an attentional engagement deficit at far periphery.

Conclusion: Taken together, our findings indicate that, in dyslexia, the temporal deficits in orientation of attention and its abnormal peripheral spatial distribution are not restricted to childhood and persist into adulthood. Our results are, therefore, consistent with the hypothesis that the neural network underlying selective spatial attention is disrupted in dyslexia.

Keywords: dyslexia, exogenous attention, visual eccentricity, reaction time, cueing

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INTRODUCTION

Developmental dyslexia (DD) is characterized by a reading impairment, despite normal intelligence and adequate reading instruction. Although phonological processing deficits are well established as core deficits in DD (Snowling, 1981; Ziegler and Goswami, 2005), it has been suggested that attentional impairments may also contribute to the pathophysiology of this condition (Cestnick and Coltheart, 1999; Vidyasagar, 1999, 2019; Hari and Renvall, 2001; Facoetti et al., 2005, 2006; Bosse et al., 2007; Vidyasagar and Pammer, 2010; Pina Rodrigues et al., 2017a). Accordingly, several types of attention deficits have been reported in DD: narrowed visual attentional window and reduced visual attention span (Bosse et al., 2007); stronger effects of crowding (Bouma and Legein, 1977; Spinelli et al., 2002; Pernet et al., 2006; Martelli et al., 2009; Moores et al., 2011; Callens et al., 2013); noise exclusion deficits (Sperling et al., 2005, 2006; Pina Rodrigues et al., 2017a); and, particularly relevant for this study, abnormal spatial distribution of attention (Facoetti and Turatto, 2000; Facoetti and Molteni, 2001) and impaired attention orienting (Brannan and Williams, 1987; Facoetti et al., 2000b, 2003a, 2006; Facoetti and Molteni, 2001; Hari and Renvall, 2001; Kinsey et al., 2004; Valdois et al., 2004; Roach and Hogben, 2008; Vidyasagar and Pammer, 2010; Franceschini et al., 2012; Gabrieli and Norton, 2012). Moreover, it has been shown that prereading visuo-attentional skills can predict reading impairments (Franceschini et al., 2012; Carroll et al., 2016; Valdois et al., 2019) and that attentional training is able to improve reading in dyslexics (Franceschini et al., 2013), suggesting a causal link between attentional deficits and reading impairments.

Fluent reading requires precise and rapid selection of relevant stimuli among distractors (Bouma, 1970; Bouma and Legein, 1977; Reynolds and Besner, 2006), which critically requires efficient orientation of attention (Cestnick and Coltheart, 1999; Vidyasagar, 1999; Facoetti et al., 2006; Perry et al., 2007; Vidyasagar and Pammer, 2010). In particular, the orientation onto each sublexical unit is crucial for graphemic parsing, defined as the process determining the graphemic elements of a word, which, according to computational models of reading, precede spelling-to-sound conversion mechanisms (McCandliss et al., 2003; Whitney and Cornelissen, 2005; Perry et al., 2007). Indeed, before the application of the grapheme-to-phoneme correspondences, graphemes have to be accurately selected through rapid serial attentional orienting. This mechanism allows the selective processing of relevant letter-to-speech sound correspondence while suppressing the irrelevant ones.

Spatial orientation of attention can be voluntary, *via* a mechanism known as endogenous attention, or automatic, stimulus-driven, termed exogenous attention (Fuller et al., 2008). These two systems are also labeled as sustained (endogenous) and transient (exogenous) due to the difference in their processing time-courses. Whereas the effects of endogenous attention require few hundred milliseconds to fully develop and can be maintained with effort, exogenous attention peaks within 100 to 120 ms and diminishes rapidly thereafter (Nakayama and MacKeben, 1989; Cheal and Lyon, 1991).

It is worth pointing out that the attentional orienting system is anatomically based in the parietal dorsal stream, which in turn, has strong input from the magnocellular system (Gori and Facoetti, 2015). Several studies have shown temporal deficits in DD often suggested to be associated with magnocellular dysfunction (Livingstone et al., 1991; Cornelissen et al., 1995; Stein and Walsh, 1997; Iles et al., 2000; Talcott et al., 2002; Laycock et al., 2012; Pina Rodrigues et al., 2017b) and, in an important recent study, it has been demonstrated a causal link between magnocellular deficits and DD (Gori et al., 2016). Hari and Renvall (2001) proposed that parietal attentional dysfunction could underlie such deficits. Specifically, these authors suggested sluggish attentional shifting (SAS) as a causal factor for temporal processing impairment in DD (Hari and Renvall, 2001). Attentional shifting refers to the engagement mechanisms onto a relevant object and subsequent disengagement from the previous object to the next one. In terms of reading processes, this failure can cause impaired speech segmentation and scanning of letter strings, which in turn can result in poor phonemic/graphemic representations and, thus, in reading difficulties (Lallier et al., 2010; Krause, 2015). Another brain structure that has been implicated either in exogenous attention orienting mechanisms as in reading impairments in DD is the cerebellum. Besides the evidence that oculomotor structures in the cerebellum are involved in the generation of exogenous shifts of attention (Baier et al., 2010; Striemer et al., 2015b) and that other cerebellar structures may provide input to the exogenous attention neural network (Striemer et al., 2015a), it has been proposed that cerebellum abnormalities in DD can lead to an impairment in skill automatization with consequent reading difficulties (Nicolson et al., 2001; Nicolson and Fawcett, 2005).

Several studies have shown that automatic exogenous orientation of attention is impaired in dyslexic children (see Facoetti, 2012; Gabrieli and Norton, 2012 for reviews). This subject was particularly explored by Facoetti and colleagues in a series of experiments (Facoetti et al., 2000b, 2003a,b, 2005, 2010; Facoetti and Molteni, 2001; Ruffino et al., 2014). By using cueing paradigms, in which participants are asked to react as quickly as possible to the appearance of target stimuli preceded by spatial cues, and manipulating the stimulus onset asynchrony (SOA) (i.e., interval between cue and target-stimulus) to activate both endogenous and exogenous systems, these authors showed that cueing effects are absent in dyslexics only at the shortest intervals, i.e., when exogenous mechanism are recruited (Facoetti et al., 2000b, 2003a). This impairment was found to be correlated with sublexical reading deficits in children with DD, pointing to a direct link between phonological skills and exogenous attentional mechanisms (Facoetti et al., 2010; Ruffino et al., 2014, 2010). Importantly, Franceschini et al. (2012) found, in a longitudinal study, that prereading exogenous attention orienting, assessed by cueing paradigms, predicts reading acquisition and several reading skills, such as text, word, and pseudoword reading. These authors found that the abnormality in orienting of attention is rather prevalent early in development. In their sample, 60% of future poor reader children were impaired in attention orienting at the prereading stage. Nevertheless, the role of attentional orienting mechanisms in the reading deficits is a subject still under debate. Several studies also using cueing paradigms with variable SOAs suggested preserved exogenous and endogenous attention orienting in adults with DD (Judge et al., 2007, 2013; Moores et al., 2011, 2015), raising the hypothesis that deficits in exogenous orienting of attention observed in DD children do not persist and hindering the claim of a causal link between such deficits and reading impairments.

The literature concerning spatial distribution of visual attention in DD is also contradictory. While some studies found an abnormal spatial distribution in these patients (Geiger and Lettvin, 1987; Geiger et al., 1992, 2008;

Facoetti and Turatto, 2000; Facoetti and Molteni, 2001), others did not (Judge et al., 2007; Moores et al., 2015). Among the studies that favor the atypical spatial distribution hypothesis are the ones from Geiger and Lettvin (1987) and Geiger et al. (1992, 2008), who found that, in the presence of lateral masking, dyslexics recognize letters visually farther in the periphery than typical readers. The authors suggested that dyslexics exhibited a wider visual perceptual mode. Their finding was corroborated by other studies (Perry et al., 1989; Dautrich, 1993; Lorusso et al., 2004) and found to be present across different subtypes of DD (Lorusso et al., 2004). Additionally, Facoetti et al. (2001) and Facoetti and Molteni (2001) studied attention orienting at different visual eccentricities and found that DD children did not show normal eccentricity effects as controls, corroborating a diffuse-distributed attention mode in DD. On the other hand, Judge et al., using the task used by Facoetti and Molteni (2001), showed that, unlike children, DD adults exhibit normal eccentricity effects (Judge et al., 2007). Their work was supported by a study (Moores et al., 2015) in which results show similar effects of eccentricity and cueing in DD and controls also arguing against the notion of a more distributed attention in DD adults than in typical readers.

Taking into account the literature discrepancies and the ongoing debate described above, the main aim of the present study was to investigate exogenous visual attention in DD adults and its peripheral spatial distribution. Particularly, we intended to investigate facilitation and inhibition attentional effects in DD adults and controls. Facilitation effect refers to the fact that when a target is preceded by a spatial cue at the same location, it's detection is faster than at uncued locations due to the shifting of attention to the cued location prior to the presentation of the target. On the other hand, attentional inhibition refers to the ability to suppress and ignore salient yet irrelevant features in the scene (Posner, 1980). To assess exogenous orienting of attention we used a classical cueing paradigm, in which peripheral pre-cues were presented, followed by a short SOA. We then adapted this paradigm to a discrimination task. Discrimination requires more attentional resources than simple detection and, therefore, is expected to be more prone to cueing effects. In order to study attentional effects, and since automatic orienting is supposed to occur regardless of the validity of the cue or even when subjects are not aware of the cue (McCormick, 1997; Rosen et al., 1999), uninformative cues were included in the experiment. Spatial distribution of attention was tested by presenting the target stimuli at parafoveal and perifoveal peripheral eccentricities, ranging from 8° to 14°.

MATERIALS AND METHODS

Participants

Eighteen developmental dyslexics and nineteen age and IQ matched controls were recruited. Individuals with dyslexia had all received a formal diagnosis of dyslexia from a qualified psychologist or an education authority official, and none had been diagnosed with any other developmental disorder (e.g., ADHD) or any neurological or psychiatric disorder. Controls were adults with no history of learning, developmental, cognitive, neurological, or neuropsychiatric disorders. All participants were assessed in terms of reading performance and intelligence level. For the reading assessment, a sub-test from the Psycholinguist Assessments of Language Processing in Aphasia - Portuguese version (PALPA-P; Castro et al., 2007) was used. In this sub-test, participants were asked to read a list of 60 words and pseudowords as quickly as possible. The measures obtained from this sub-test were reading speed (in seconds) and accuracy (number of words correctly read). Intelligence level was measured through the Raven Progressive Matrices Test – Set 1 (RPM; Raven et al., 1976). All participants had normal or corrected to normal vision. Participants' demographics and reading and intelligence scores are summarized in **Table 1**. The study was conducted in accordance with the tenets of the Declaration of Helsinki and was approved by the Ethics Committee of the Faculty of Medicine of the University of Coimbra. Written informed consent was obtained from the participants, after an explanation of the nature of the study.

Apparatus

The experiment was conducted in a dark room. Stimuli were delivered using the Presentation software (Neurobehavioral Systems) on a 38 × 30.2 cm (41.6 × 33.6° visual angle) computer screen with a resolution of 1280 × 1024 pixels and a luminance of 108 cd/m2. The distance between the subjects' eyes and the computer screen was 52 cm. A chin and forehead rest was used to ensure a stable viewing position throughout testing. To ensure that subjects fixated the center of the stimulus display during the experiment, the subject's gaze position was monitored using an eye-tracker SMI iViewX High-speed (SensoMotoric Instruments GmbH, Germany).

Stimuli and Procedure

The stimuli consisted of Gabor patches, comprising a simple sinusoidal grating convolved by a Gaussian envelope (spatial frequency – 2 cpd; envelope SD – 0.25°; contrast – 50% Michelson). Stimuli were presented one at a time at two levels of viewing eccentricity (parafoveal and perifoveal) in the four quadrants of the visual field. In the parafoveal level, stimuli

TABLE 1 | Summary statistics for the two groups of participants.

	Dyslexics (n = 18)			Controls (n = 19)			
	Mean	**Range**	**SD**	**Mean**	**Range**	**SD**	***p*-Value**
Age (years)	27.08	19–44	7.05	25.05	20–36	4.03	0.443
Education (years)	15.56	13–17	1.58	16.21	14–17	1.08	0.149
RPM	10.08	8–12	1.19	11.14	8–12	1.68	0.063
PALPA-P reading speed (s)	71.67	42–105	18.20	42.33	31–52	7.43	< 0.05
PALPA-P accuracy	50.31	42–57	4.48	57.67	56–59	1.21	< 0.01
Gender (m:f)	8:10			9:10			1.00

P-values for t-test comparisons (except for gender, for which the Chi-square test was used) between the two groups are reported (p < 0.05 values are considered significant).

appeared at 8 and 10 degrees of eccentricity, while in the perifoveal level appeared at 12 and 14 degrees (Strasburger et al., 2011). The patches were randomly oriented at 45 or 135 degrees from the vertical and participants were asked to discriminate, as quickly as possible, the orientation of the gratings by pressing the corresponding button of a response box. A fixation cross was presented at the center of the screen and participants were instructed to fixate the cross throughout the whole experiment. Participants' reliability was evaluated by randomly interleaving false positive and false negative catch trials. In the false negative trials stimuli were presented at the center of the screen, in the location where subjects were instructed to fixate. False positive trials consisted in trials where only the pre-cue was presented. In these trials participants were instructed to not respond. Performance reliability was assessed by monitoring fixation loss and computing false positive and negative errors. A percentage of $\geq$33% of false positive and negative errors was defined as exclusion criteria, according to standard procedures (Ribeiro et al., 2012; Mateus et al., 2013). The sizes of the stimuli were scaled with viewing eccentricity using a magnification factor estimate for the temporal visual field, M (Rovamo and Virsu, 1979): $M = M0(1 + 0.29E + 0.000012E3)$, where E represents eccentricity and M0 represents the size of the stimuli at the smallest eccentricity. The smallest eccentricity in our experiment was the fovea where the stimulus size was 0.83°. Therefore, stimulus sizes were 2.76°, 3.24°, 3.74°, and 4.2° for the 8°, 10°, 12°, and 14° of eccentricity, respectively.

Exogenous orienting of attention was assessed using a variant of Posner's task (Posner, 1980) comprising visual targets preceded by spatial cues (valid, invalid, and neutral). In the valid and invalid trials, the cue consisted in a salient black dot (0.23°) presented either at the same eccentricity and visual quadrant of the subsequent stimuli (valid) or at the same eccentricity but at a randomized different visual quadrant of the subsequent stimuli (invalid). In the neutral trials, four identical black dots were presented simultaneous at 14° of eccentricity in the four visual quadrants. Attentional facilitation effects were obtained computing the difference between neutral and valid cue conditions while attentional inhibition effects referred to the difference between invalid and neutral cue conditions. Participants were informed of the possible appearance of black dots in the screen and were instructed to not attend to them.

Each trial began after subjects continuously foveated the fixation cross for 500 ms. After that, the cue was presented for 30 ms, followed by a stimulus onset asynchrony (SOA) of 70 ms, after which the stimulus appeared for 100 ms. The maximum time allowed for response was 1500 ms (see **Figure 1**).

The experiment consisted of 2 runs of 600 trials each (1200 in total), separated by an interval in which the subjects were allowed to rest. Eye-tracker calibration was repeated after the rest period. Stimuli were randomly presented in six conditions (two levels of eccentricity × three types of cue), each having 160 trials. In addition, 120 false positive and 120 false negative trials were presented. Therefore, the experiment consisted on 1200 trials, divided in 960 experimental trials and 240 control trials, with a maximum duration of 1 h for each participant (45 min for the experiment and 15 min for rest and recalibration). Before the experiment began, participants made a practice run (80 trials) to become familiarized with the task. The dependent variable of interest was the response time (RT) since we expected accuracy to be close to ceiling.

Statistical Analysis

All statistical analyses were performed using the IBM SPSS statistical software package, version 20.0 (SPSS, Inc., Chicago, IL, United States). Mean correct RTs were analyzed with a mixed ANOVA, with group as the between factor (dyslexics and controls) and eccentricity (8°, 10°, 12°, and 14°) and cue (valid, invalid, and neutral) as within factors. Results with $p < 0.05$ were considered statistically significant. Outliers, defined as RTs above or below 3 SD from the group's mean, were not detected. None of the participants scored $\geq$33% in false positive and

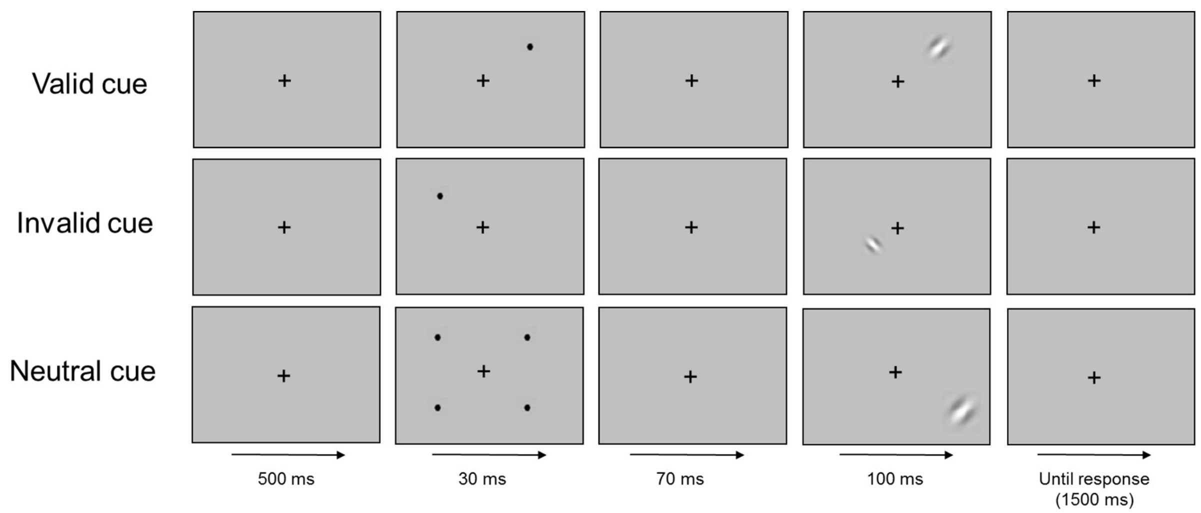

FIGURE 1 | Schematic representation of the time course (left to right) of the procedure.

false negative trials and, therefore, all participants were included in the analysis.

RESULTS

As expected, accuracy was close to ceiling, being above 90% in all conditions in both groups, which ensured that both dyslexics and controls were able to perform the task correctly (**Table 2**). There was no significant main effect of group, as well as no significant effect of cue. Both dyslexics and controls had similar accuracy across the task and the type of cue did not affect participant's accuracy. The main effect of eccentricity was significant [$F(1,35) = 4.24$, $p < 0.05$; $\eta_p^2 = 0.114$]. Participants were more accurate at parafoveal eccentricities than at perifoveal (difference = 0.7%, $p < 0.05$). There were no significant interactions.

Regarding RTs analysis, the main effect of group was significant [$F(1,35) = 6.41$, $p < 0.05$; $\eta_p^2 = 0.155$] showing that dyslexics were globally slower than controls (RTs were 626 ms for DD and 570 ms for controls). The main effect of cue was also significant [$F(2,70) = 13.13$, $p < 0.001$; $\eta_p^2 = 0.273$], and similar in both groups [$F(2,70) = 0.04$, $p = 0.958$]. Participants were faster when a valid cue was presented than when invalid ($p < 0.001$) or neutral ($p < 0.01$) cues were displayed. Eccentricity was also found to have an effect in RTs [$F(3,105) = 19.06$, $p < 0.001$; $\eta_p^2 = 0.353$]. Overall, participants became slower with increases in eccentricity, except between 8° and 10° where the RTs were equivalent. The smallest (but still significant) difference between eccentricities was found for the comparison between 10° and 12° (difference = 8 ms, $p < 0.05$) (see **Figure 2**).

Interestingly, the eccentricity × group interaction was found to be significant [$F(3,105) = 3.12$, $p < 0.05$; $\eta_p^2 = 0.082$], showing that eccentricity had a different effect on the RTs of each group (see **Figure 3**). *Post hoc* analysis for the different pairs of eccentricity revealed a different behavior of dyslexics at 10° of eccentricity [$F(1,35) = 11.38$, $p < 0.01$; $\eta_p^2 = 0.245$ for the comparison between 8° and 10° and $F(1,35) = 6.25$, $p < 0.05$; $\eta_p^2 = 0.152$ for the comparison between 10° and 12°]. While the RTs of controls followed the expected increase with eccentricity, dyslexics showed an inflection at 10° of eccentricity, increasing again at 12°. Additionally, to further investigate the effect of eccentricity in each group, one-way ANOVAs were performed in each group separately, using eccentricity (8°, 10°, 12°, 14°) as within factor. Controls showed a trend for a significant difference between 8° and 10° eccentricity (difference = 9 ms, $p = 0.06$), as well a significant difference between 12° and 14° eccentricity (difference = 14 ms, $p < 0.001$). On the contrary, DD participants only showed a significant difference between 10° and 12° eccentricity (difference = 15 ms, $p < 0.05$). Importantly,

TABLE 2 | Means and standard deviation (in brackets) of the hit rates (percentage) of dyslexics and controls at the four viewing eccentricities (8°, 10°, 12°, and 14°) and for the three cue types (valid, invalid, and neutral).

	Dyslexics			Controls		
	Valid	**Invalid**	**Neutral**	**Valid**	**Invalid**	**Neutral**
8°	92.81 (3.52)	92.42 (6.40)	93.44 (4.97)	94.61 (5.32)	95.13 (5.53)	93.82 (5.84)
10°	93.28 (4.74)	92.81 (4.80)	89.53 (7.27)	93.75 (4.86)	93.62 (5.03)	93.75 (6.24)
12°	90.55 (5.83)	92.19 (4.29)	92.42 (4.67)	95.53 (4.32)	93.42 (5.73)	94.54 (5.91)
14°	91.56 (6.10)	89.67 (5.23)	89.68 (6.17)	94.34 (4.48)	93.75 (4.23)	93.03 (6.32)

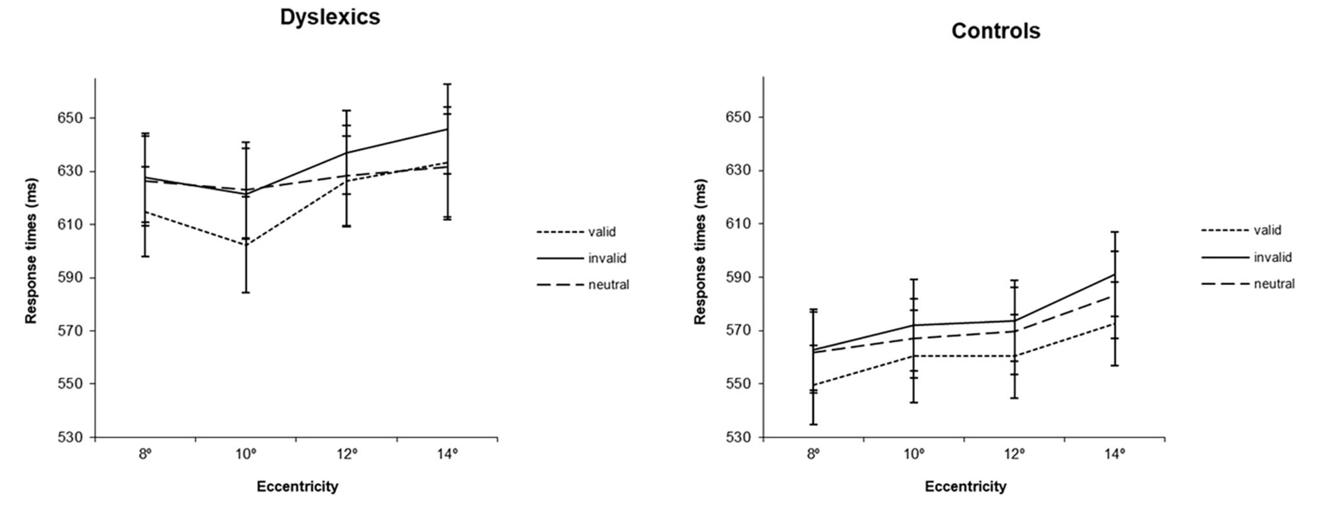

FIGURE 2 | Average response times (ms) for the three types of cues (valid, invalid and neutral) at four eccentricities (8°, 10°, 12°, 14°) for dyslexics and controls. Error bars indicate ±SE.

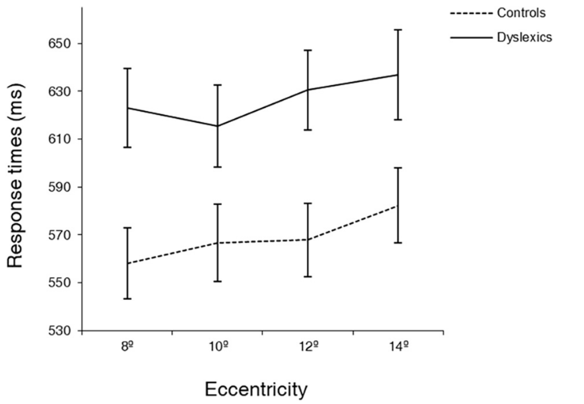

FIGURE 3 | Average response times (ms) at four eccentricities (8, 10, 12, 14°) for dyslexics and controls. Note the different behavior of dyslexics and controls at 10° of eccentricity. Error bars indicate ±SE.

controls were, as expected, faster at 8° of eccentricity than at 14° of eccentricity (difference = 27 ms, $p < 0.001$). In contrast, DD adults showed no significantly different RTs at the most distant eccentricities tested.

The non-linear behavior of DD participants, particularly at 10° of eccentricity, as well as the different distribution of the data in both groups (see **Figure 2**), motivated us to explore the effect of cue at different levels of eccentricities. Based on the different pattern of behavior in dyslexics that we observed at 10° of eccentricity, we therefore defined this eccentricity as a cutoff and collapsed the 4° of eccentricity in two levels, the first comprising 8° and 10° (equal or below the identified 10° cutoff); and the second comprising 12 and 14° (above the cutoff). We then investigated attentional facilitation (difference between neutral and valid conditions) and attentional inhibition (difference between invalid and neutral conditions) effects at near (8°–10°) and far (12°–14°) periphery. For that, we performed a mixed ANOVA, with group as between factor (dyslexics and controls) and eccentricity (8°–10° and 12°–14°) and attentional effect (facilitation and inhibition) as within factors. Notably, we found a significant group × eccentricity × attentional effect interaction [$F(1,35) = 4.24$, $p < 0.05$; $\eta_p^2 = 0.114$]. *Post hoc* analyses showed that both groups have a different facilitation effect depending on the spatial location of the stimuli [$F(1,35) = 4.42$, $p < 0.05$; $\eta_p^2 = 0.118$]. While in controls, the facilitation effect is similar at near and far periphery (mean 8/10 = 9.44, mean 10/12 = 9.94 ms; difference = 0.50 ms, $p > 0.05$), in dyslexics it is absent at the far periphery (mean 8/10 = 15.91, mean 10/12 = −4.04 ms; difference = 19.95 ms, $p < 0.05$) (see **Figure 4**).

DISCUSSION

In the current study, we investigated the exogenous orienting of attention and its spatial distribution across the peripheral visual field in dyslexic and typically reading adults.

We showed that dyslexic adults have temporal deficits in orientation of attention. Although this has already been described in children with DD (Facoetti et al., 2000b, 2003a,b, 2005; Banfi et al., 2017), the current study is, to our knowledge, the first to demonstrate this impairment in adults with DD. Our finding thus indicates that the temporal deficits in orientation of attention in this population are not restricted to childhood and, therefore, persist into adulthood. Our study contrasts with other works (Judge et al., 2007, 2013; Moores et al., 2015), which found similar RTs in adults with DD and controls in tasks requiring rapid orientation of attention. This discrepant result can be accounted in terms of spatial position of the stimuli. In these studies, the eccentricities at which the stimuli were presented ranged from 0.7° (Moores et al., 2015) to 9° (Judge et al., 2007) of visual angle. The eccentricities tested in the current study were substantially larger, with a minimum of 8° and a maximum of 14°. If DD patients suffer from anomalous peripheral spatial distribution of attention, this fact can by itself indicate that this discrepancy is only apparent, and may be due to the herein proposed distinct structure of spatial attention.

Actually, the hypothesis of abnormal spatial distribution of attention in the peripheral visual field of DD adults is supported by the two additional main findings of this study. First, DD adults showed abnormal eccentricity effects, reflecting a wider distribution of attention than controls. Such pattern has been already described in children with DD (Facoetti et al., 2000a). However, previous studies (Judge et al., 2007; Moores et al., 2015) have found similar effects of eccentricity in adults with and without DD. Nonetheless, the eccentricities tested corresponded to foveal, parafoveal, and perifoveal processing, while the present study used more peripheral eccentricities, outside of the macular zone (Strasburger et al., 2011). Our finding, therefore, adds to previous evidence by showing that the abnormal distribution of peripheral visual attention observed is present in adults thereby persisting beyond development.

The second finding that supports an atypical spatial distribution of visual attention in DD adults is that attentional cueing effects in DD are dependent on viewing eccentricity. In accordance with previous studies (Posner, 1980; Posner et al., 1980), normal reading adults showed cue effects at all levels of eccentricity. On the contrary, RTs of dyslexic adults could only benefit from valid cues (i.e., show facilitation effects) when stimuli were presented at less peripheral eccentricities. Thus, DD adults are not capable of efficiently using valid cues to rapidly direct attention to more peripheral eccentricities, suggesting an attentional engagement deficit at far periphery (Posner et al., 1984). This result is in accordance with that of Moores et al. (2015) who found an indication that DD adults need more time to focus attention to far eccentricities. However, it is important to note that Roach and Hogben (2004) found a similar impairment at lower eccentricities. Nonetheless, their task included distractor stimuli in set sizes up to 16 elements, which likely brought an increment of difficulty to DD adults since it is known that crowding affects DD more than controls (Moores et al., 2011).

It is important to note that reading experience can influence perceptual and cognitive functions, also in adult brains (Dehaene et al., 2015). However, given the fairly high reading experience of our dyslexic sample (mean years of education/instruction above 15 years, at least university attendance), it is very unlikely that

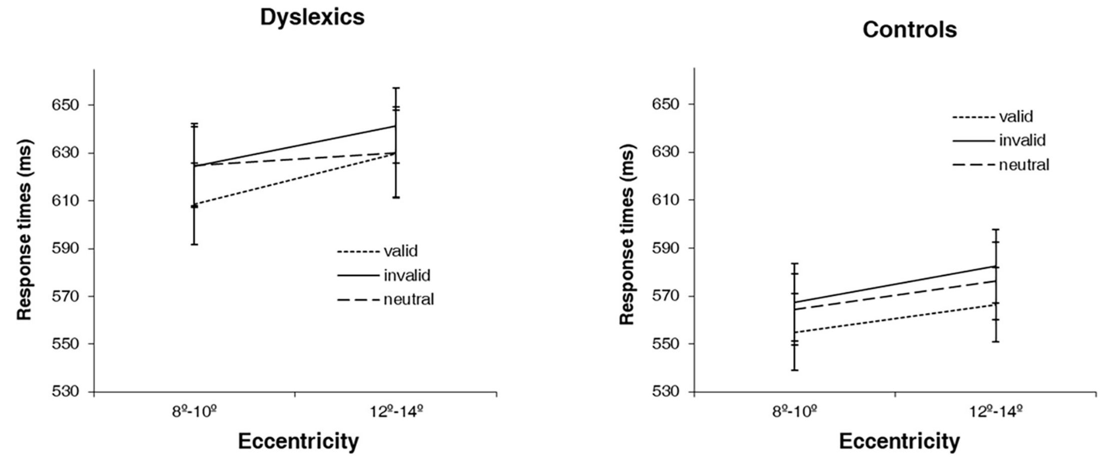

FIGURE 4 | Average response times (ms) for the 3 types of cues (valid, invalid and neutral) at two levels of eccentricity (8°–10° and 12°–14°) for dyslexics and controls. Error bars indicate ±SE.

the present results are merely consequence of reduced reading exposition in dyslexic group.

Along with attention impairments, phonological awareness (e.g., Snowling, 1981) and automatization (Nicolson et al., 2001) deficits are known to be also present in DD individuals. Interestingly, on one hand, since orienting of attention is crucial to the selection and segmentation of stimuli, deficits on this mechanism may precede the difficulties of dyslexics on the perception and manipulation of phonemes. On the other hand, given the automatic nature of the orienting deficits found in this study, such deficits are consistent with the automatization deficits also found in this condition.

Our findings are also consistent with the notion that covert attention mechanisms, as measured by Posner-like paradigms, operate in a distinct manner in central and peripheral vision in health and disease, as also observed in a previous study from our group in Parkinson disease (Sampaio et al., 2011). In that study we found impaired high-level attentional modulation of contrast sensitivity in the visual periphery (up to 15°), where mechanisms of covert attention are at higher demands. A critical role for peripheral vision is justified by the fact that it can be used to make a snapshot of the local context (van Asselen and Castelo-Branco, 2009).

A limitation of the present study refers to the lack of an assessment of attention with a conventional attention test, such as the d2 test (Brickenkamp and Zillmer, 1998). However, although one may expect a relationship between results on conventional attention tests and on the task performed in this study, the specific mechanism of attention targeted in this work (exogenous orienting of attention) is not covered by such tests. The characteristics of this mechanism (involuntary, automatic, rapid, and stimulus-driven) hinders its assessment by conventional attention tests and, from our knowledge, there are no commercial tests developed to evaluate it. Nonetheless, one may expect significant correlations between results on the experimental task and on conventional attention tests, due to the involvement in both cases of processes such as sustained attention and processing and perceptual speed, that are assessed on classical and widely used attention tests.

Finally, we speculate that our results may be interpreted within the framework of the role of right posterior parietal cortex in spatial attention. Particularly, the right temporo-parietal junction (TPJ) is known to be involved in the network responsible for exogenous orienting of attention (Corbetta and Shulman, 2002, 2011). Consistent with the hypothesis of a right posterior parietal dysfunction in dyslexia (e.g., Hari et al., 1999; Facoetti et al., 2001), some studies observed deficient activations in the right TPJ in dyslexics when performing phonological decoding tasks (e.g., Hoeft et al., 2006). Moreover, a very recent study (Lazzaro et al., 2021) has shown significant effects of tDCS on temporo-parietal regions either on reading performance as on visuo-spatial skills of dyslexic children and adolescents. Overall, the findings of the present study endorse this hypothesis by showing that the mechanisms of rapid orienting of spatial attention are impaired in adults with DD.

CONCLUSION

In the present study we found that adults with dyslexia exhibit global temporal deficits in a task requiring orientation of attention. Moreover, we showed that an abnormal peripheral spatial distribution of attention is also not restricted to children with dyslexia and persists into adulthood. Overall, our results suggest an impairment of the neural network underlying selective spatial attention (rooted at right posterior parietal regions) in dyslexia.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the Faculty of Medicine of the University of Coimbra. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AP, MC-B, and MA designed the study. AP collected and analyzed the data. All authors discussed the results. AP wrote the manuscript with input from MC-B and MA.

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Reading Comprehension Predictors in European Portuguese Adults

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Research on the predictors of reading comprehension has been largely focused on school-aged children and mainly in opaque orthographies, hindering the generalization of the results to adult populations and more transparent orthographies. In the present study, we aim to test two versions of the Simple View of Reading (SVR): the original model and an extended version, including reading fluency and vocabulary. Additional mediation models were analyzed to verify if other reading comprehension predictors (rapid automatized naming, phonological decoding, phonological awareness, morphological awareness, and working memory) have direct effects or if they are mediated through word reading and reading fluency. A sample of 67 typical adult Portuguese readers participated in this study. The SVR model accounted for 27% of the variance in reading comprehension, with oral language comprehension displaying a larger contribution than word reading. In the extended SVR model, reading fluency and vocabulary provided an additional and significant contribution of 7% to the explained variance. Moreover, vocabulary influenced reading comprehension directly and indirectly, *via* oral language comprehension. In the final mediation model, the total mediation hypothesis was rejected, and only morphological awareness showed a direct effect on reading comprehension. These results provide preliminary evidence that the SVR (with the possible addition of vocabulary) might be a reliable model to explain reading comprehension in adult typical readers in a semitransparent orthography. Furthermore, oral language comprehension and vocabulary were the best predictors in the study, suggesting that remediation programs addressing reading comprehension in adults should promote these abilities.

Keywords: reading comprehension, simple view of reading, path-analysis, adult typical readers, European Portuguese

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INTRODUCTION

Reading comprehension is the ultimate goal of reading, although it remains an understudied subject when compared to word-level processes (Barquero and Cutting, 2021). One can define reading comprehension as the ability to draw and construct meaning from the text (Snow and RAND Reading Study Group, 2002) through an interactive process whereupon the reader extracts explicit information or infers implicit information through textual cues or the activation of background knowledge (Day and Park, 2005). Adequate reading comprehension is essential for academic achievement, social and cultural participation, and successful functioning in contemporary societies (Cavalli et al., 2019; Hjetland et al., 2020).

Despite its central importance in adults' everyday life, most reading comprehension studies focus on children, both with and without learning disorders (Earle and Del Tufo, 2021). However, children and adults might differ significantly in the way they achieve reading comprehension. Adults have been exposed to a larger quantity of textual material, because of their extended life experience. Adults also have a greater understanding of the different domains, such as vocabulary, morphological and syntactic knowledge, and logical reasoning, that support comprehension (Thompkins and Binder, 2003). On the other hand, children allocate most of their cognitive resources to decoding, since they are still learning the rules of grapheme-phoneme conversion, leaving fewer resources available for meaning extraction. The allocation of cognitive resources to comprehend seems therefore to be different in these age groups. Greenberg et al. (2002) compared adult literacy students to school-aged children, matched for reading level. When analyzing the groups' performance on word and non-word reading, spelling, and rhyme word detection tasks, the authors found that children relied mostly on phonological skills, whereas adults were more likely to call upon orthographic knowledge and visual memory strategies. Thus, when confronted with a word that could not be immediately read, children would try to read it through grapheme-phoneme conversion, while adults would typically try to guess the word by comparing it to other words stored in their lexicon. The use of distinct strategies by adults and children might reflect the different cognitive processes that children and adults rely on when reading. Models of reading comprehension should therefore take these differences into account since models developed for children might not be appropriate for adults.

The Simple View of Reading (SVR; Gough and Tunmer, 1986) is a prominent model of reading comprehension, based on English-speaking school-aged children, that has been applied to adults. The SVR postulates that decoding accuracy and oral language comprehension can account for all the variance in reading comprehension: while decoding skills translate print into oral language, oral language comprehension skills make sense of what is read (Gough and Tunmer, 1986). In children, this combination has been shown to capture between 65 and 85% of the variance in reading comprehension (Catts et al., 2005). In adults, the SVR model accounted for a somehow smaller fraction of the reading comprehension variance (34% for a sample of college students; Macaruso and Shankweiler, 2010; and between 64 and 74%, for samples of struggling adult readers; Braze et al., 2007; Sabatini et al., 2010; Talwar et al., 2020).

However, the SVR has often been considered too "simple" to explain such a complex construct as reading comprehension and, consequently, several authors have proposed augmented versions of the original model. Catts (2018) identified two main research lines that argue for expanding the SVR model by adding vocabulary and reading fluency, respectively. Vocabulary is a subcomponent of oral language comprehension, and there is no consensus if its contribution should be subsumed within oral language comprehension or be considered as a distinct component on its own. Gottardo et al. (2018) "unpacked" oral language comprehension into three subcomponents (vocabulary, morphology, and syntax) and found that each of them captured both unique and shared amounts of variance in reading comprehension. Using hierarchical regression models, Braze et al. (2007) also found that vocabulary accounted for unique variance in young adults reading comprehension, independently from word reading and oral language comprehension, thus supporting the addition of vocabulary to the SVR. However, more recent studies, using latent variable analyses, found that the effect of vocabulary on reading comprehension was completely captured by oral language comprehension (Braze et al., 2016; Talwar et al., 2020), thus supporting the opposite view that vocabulary should not be added to the SVR model as a separate component, at least in adults. These contradictory results fail to clarify the role of vocabulary in the SVR, in adults, leaving the issue unresolved.

The SVR model has also been criticized for only considering decoding accuracy but not a speed component such as reading fluency (Fernandes et al., 2017). In children, the inclusion of reading fluency in the SVR yielded inconsistent results, depending on school grade or orthographic transparency (Catts, 2018). In struggling adult readers, both Braze et al. (2007) and Sabatini et al. (2010) found that reading fluency did not provide an additional and significant contribution to reading comprehension, beyond word reading and oral language comprehension. Mellard et al. (2010) used a path analysis approach to test an extended version of the SVR model in low literacy adults and showed that while word reading accuracy had the strongest direct influence on reading comprehension, reading fluency made the second strongest direct contribution, being greater than the oral language comprehension own contribution. Additionally, Macaruso and Shankweiler (2010) found, in a college students' sample, that reading fluency was the only predictor that accounted for unique variance in reading comprehension over and above decoding and listening comprehension. It seems that, for both children and adults, the role of reading fluency in the SVR is controversial.

The SVR also postulates that, as the reader acquires expertise, it is expected that the main source of variability in reading comprehension shifts from decoding accuracy to oral language comprehension skills (Hoover and Gough, 1990). This shift might be explained by the Perfetti's Verbal Efficiency Theory (Perfetti, 1985). According to this theory, the cognitive system has limited capacity for decoding and comprehension simultaneously; only when the reader can decode accurately and fluently, the cognitive system can allocate sufficient free attentional resources to the extraction of meaning from the text. Indeed, Catts et al. (2005) found that the contribution of oral language comprehension to reading comprehension increases, while decoding accuracy contribution decreases, as the child progresses through schooling and acquires reading experience. During adolescence, word reading no longer appears to be an important predictor of individual differences in reading comprehension (Foorman et al., 2015).

Nevertheless, and according to Florit and Cain (2011), this shift from decoding accuracy to oral language comprehension seems to be affected by the transparency of the orthographic system. In more opaque orthographies, learning grapheme-phoneme conversion rules is an arduous process, making fluent reading possible only in later school years (Seymour et al., 2003). Subsequently, decoding accuracy stays as the main source of variability in reading comprehension until later in school, when it begins to be replaced by oral language comprehension (Catts et al., 2005). On the other hand, in more transparent orthographies, grapheme-phoneme conversion is simpler, allowing readers to achieve fluent decoding earlier, and therefore being able to focus on comprehension. In a study addressing reading comprehension in European Portuguese (a semitransparent orthography), results showed that for children in the second and fourth grades, oral language comprehension was the strongest contributor to reading comprehension when compared to decoding (Cadime et al., 2017). Also, in transparent orthographies such as Finnish (Torppa et al., 2016) and Italian (Tobia and Bonifacci, 2015), oral language comprehension comes up as the main source of variability in reading comprehension already in early grades, maintaining its preponderant influence as the individual progresses through schooling. These studies add evidence to the suggestion of Florit and Cain (2011) that the transparency of orthography favors the early contribution of oral language comprehension to reading comprehension.

Besides the two components of the SVR (word reading and oral language comprehension), plus the two usual additions to this model (vocabulary and reading fluency), several other predictors have been considered as relevant for adult reading comprehension. Given the lack of consensus about the relative importance of such reading comprehension predictors, Tighe and Schatschneider (2016) performed a meta-analysis of the available literature and identified 10 constructs that should be considered: morphological awareness, language comprehension, reading fluency, oral vocabulary knowledge, real word decoding, working memory, pseudoword decoding, orthographic knowledge, phonological awareness, and rapid automatized naming (RAN). Although only using correlational evidence from a small number of studies, this is the first systematic review addressing the most important reading-related predictors of reading comprehension in adulthood, and it reveals the importance of considering other predictors to reading comprehension beyond the ones assumed by the SVR model (both standard and typically extended versions).

In the present study, we aim to examine the relevance of several predictors to reading comprehension in European Portuguese adult typical readers. Therefore, the SVR model (**Figure 1**) and an extended SVR model (**Figure 2**) were tested, the latter including the addition of vocabulary and reading fluency components. Following the suggestion of Tighe and Schatschneider (2016) regarding the most relevant predictors, we also included measures of RAN, phonological decoding, phonological awareness, morphological awareness, and working memory. Measures of orthographic knowledge were not included in the analysis due to excessive low reliability. These variables were tested for their direct and indirect effects on reading comprehension (through both reading measures: word reading and reading fluency).

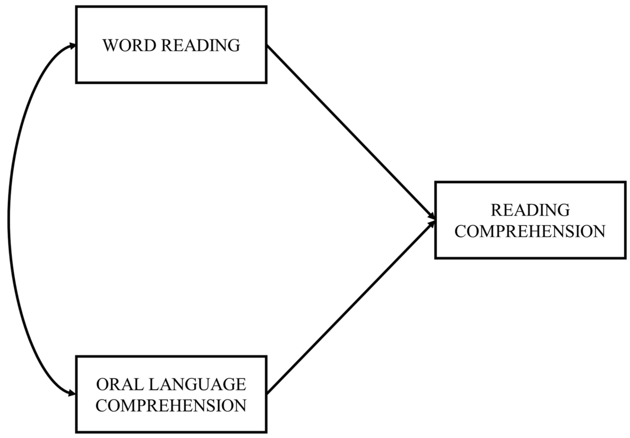

FIGURE 1 | SVR model.

For the SVR model (**Figure 1**), we expect that oral language comprehension contributes more to reading comprehension than word reading. Since European Portuguese is a relatively transparent orthography for reading, fluent decoding is expected in adult typical readers and, consequently, the main source of variability in reading comprehension would probably be oral language comprehension individual differences.

In the extended SVR model (**Figure 2**), word reading appears as an exogenous variable, with paths leading to reading fluency, vocabulary, and reading comprehension. The more accurate the reader is, the faster he is expected to read (Fernandes et al., 2017), thus explaining the first predicted path. Word reading experience contributes to the acquisition of new word meanings, both in context and isolated (Duff et al., 2015), and thus we predict a path from word reading to vocabulary. Lastly, the path from word reading to reading comprehension expresses the role of decoding accuracy in the SVR (Gough and Tunmer, 1986). Reading fluency was considered as an intermediate variable, with a path leading to reading comprehension because when reading is fluent, the cognitive system can free enough attentional resources for the reader to focus on comprehension (Perfetti, 1985; Fernandes et al., 2017). Vocabulary was another intermediate variable in the model, with paths leading to reading fluency, oral language comprehension, and reading comprehension. A larger lexicon leads to a greater number of words the reader understands and recognizes, contributing to a more fluent reading (Kirby et al., 2008; Yildirim et al., 2013). Moreover, vocabulary is known to influence comprehension, since the knowledge of a word's meaning in context aids in understanding and inference making, both in oral and written modalities (Braze et al., 2007). Oral language comprehension was the last intermediate variable considered. Only one path was tested, from oral language comprehension to reading

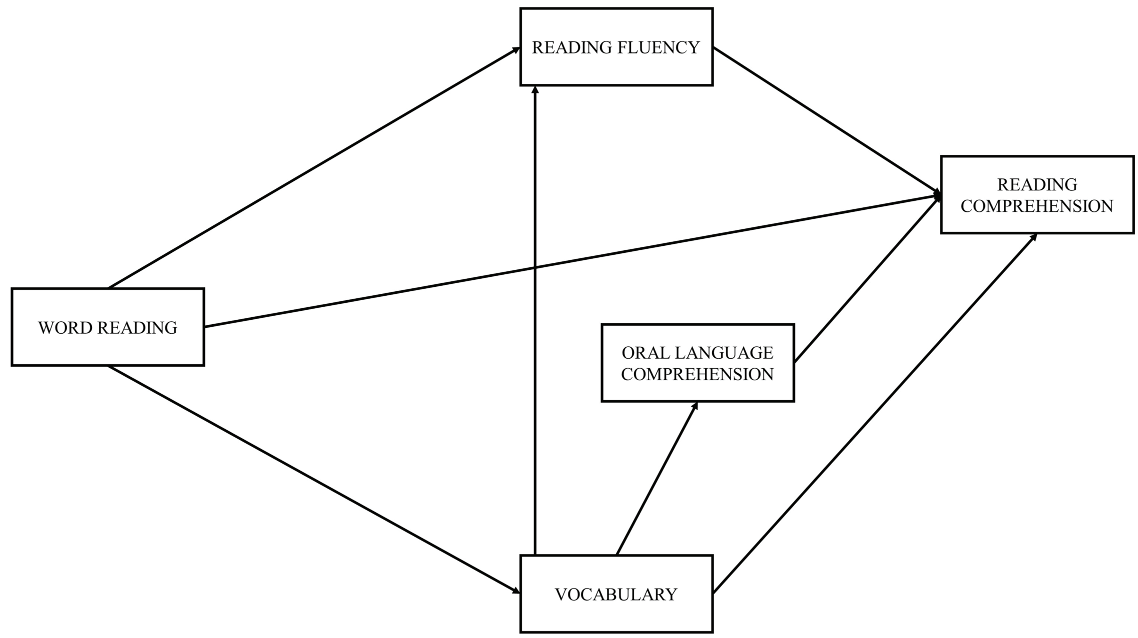

FIGURE 2 | Extended SVR model.

comprehension, reflecting the role of oral language comprehension in the original SVR model.

The remaining predictors were tested for their putative mediated effects on reading comprehension. Thus, we hypothesized that the effects of RAN, phonological decoding, phonological awareness, and working memory on reading comprehension are completely mediated by word reading and reading fluency. This prediction arises from the role of such variables in word reading as well as the absence of evidence for their direct effects on reading comprehension in typical adult readers. Conversely, there is evidence of a direct contribution of morphological awareness, both in children (e.g., Gottardo et al., 2018) and adults (e.g., Guo et al., 2011), suggesting that the effect of this skill on reading comprehension is still important in adulthood. Accordingly, we hypothesized that the effect of morphological awareness will not be completely mediated by word reading and reading fluency, showing a direct path to reading comprehension.

In short, the present study aims to investigate an extended SVR model for reading comprehension in European Portuguese adult typical readers. It is relevant to recognize which abilities reading comprehension relies on to contribute to the identification of worthy targets of intervention to promote reading comprehension.

MATERIALS AND METHODS

Participants

Sixty-seven adults (54 females, 80.6%), with ages ranging from 19 to 47 years old (*mean ± standard deviation*: 21.9 ± 4.4) participated in this study. All participants had European Portuguese as their first language. Formal schooling ranged from 12 to 23 years (*mean ± SD*: 14.4 ± 1.7). Most participants were college students (86.6%).

Exclusion criteria for participants were (1) previous diagnosis of reading, neurological, psychiatric or psychologic disorder and (2) scoring above 60 in the Adult Reading History Questionnaire (Lefly and Pennington, 2000; Portuguese version: *Questionário de Hábitos de Leitura*, Alves and Castro, 2005), a self-reported measure of reading difficulties.

Measures

Reading Comprehension

A reading passage (Stocker, 2016) was translated into Portuguese and further adapted. The text had 495 words and was titled "Anne Frank." Reading comprehension questions were developed according to the taxonomy of Day and Park (2005) and scoring criteria were agreed upon between the authors.

Three domains of reading comprehension were assessed: literal, inferential, and vocabulary. Literal comprehension questions were about facts in the text (eight questions). Inferential comprehension questions were divided into those where the participant had to infer based on implicit textual information (intratextual inference; four questions) and those where the participant had to activate background knowledge (extratextual inference; four questions). Vocabulary questions assessed the ability to deduce the meaning of an ambiguous word in context (four questions). Each one of four vocabulary words had two or more possible meanings, and only one was considered correct for the respective context.

Participants had to silently read the text and then answer aloud to comprehension questions. Silent reading was chosen because it is expected to foster comprehension, as the reader can allocate most cognitive resources to extracting meaning, instead of pronunciation or prosody (Hale et al., 2011). Participants could refer back to the text at any time during questioning and questions could be repeated if the participant did not understand them. The order of the questions was fixed for all participants and there was no time limit to answer.

Answers were scored with 0, 1, or 2 points, if the answer was completely incorrect, partially correct, or completely correct, respectively. Reading comprehension was computed as the sum of the obtained points, with a possible maximum score of 40. Cronbach's alpha for this measure was 0.49, showing poor reliability. However, this reading comprehension score showed a significant positive correlation with the 1-min TIL ($r = 0.47$; $p < 0.001$), a validated measure of reading comprehension in adults (Fernandes et al., 2017).

Oral Language Comprehension

In studies comparing oral language and reading comprehension, measures should be well-calibrated with one another (Braze et al., 2007). Thus, an effort was made to equate these tasks, regarding the assessed domains (literal, inferential, and vocabulary) as well as the scoring procedure. For this task, six passages about the Portuguese poet Fernando Pessoa's biography were adapted from Vilas-Boas and Vieira (2017). All passages had a similar length (*mean* number of words ± SD = 42.17 ± 8.4, *range* = 35–55). Twelve comprehension questions were created, two for each passage. However, questions 1 (passage 1) and 5 (passage 3) were later removed from the analysis due to clear ceiling effects. The questions assessed literal comprehension (two questions), knowledge of vocabulary in context (three questions), intrapassage inference (inference based on the information present on the passage; three questions), and extrapassage inference (inference based on previous knowledge; two questions). The selected vocabulary words had two or more possible meanings, and only one was considered correct. The frequency of these vocabulary words was similar for Oral Language and Reading Comprehension tasks (*mean* = 17.5 and 21.8 occurrences per million, respectively, according to the P-PAL lexical database; Soares et al., 2018).

The passages were recorded by a male voice and played twice through headphones. The passages were repeated to reduce working memory constraints. The instructions and auditory stimuli were presented using the Presentation® software (version 21.1). A sheet with the comprehension questions was provided to the participants, at the beginning of the task. It was explained that they had to respond orally to those questions, based on the information present on auditory passages. The participants could silently read the questions beforehand and during the listening of the passages to scan them for relevant information. After answering the questions for a specific passage, participants pressed the space bar to listen to the next passage.

Answers were scored with 0, 1, or 2 points. The sum of the obtained points (maximum of 20) was taken as an oral language comprehension measure. This composite score showed poor reliability (Cronbach's alpha = 0.40).

Word Reading

The Reading Fluency Subtest of ADLER Battery (Faísca et al., 2019) was used to assess word reading abilities. This subtest includes five lists (high-frequency words, low-frequency words, consistent words, inconsistent words, and pseudowords) that the participants should correctly read as fast as possible during 30 s. Word reading is an accuracy measure computed as the percentage of correctly read words on the four real word lists; this composite measure showed good internal consistency (Cronbach's alpha = 0.61; Faísca et al., 2019).

Phonological Decoding

Phonological Decoding is an accuracy measure computed as the percentage of correctly read pseudowords on the pseudoword list from the ADLER's Reading Fluency Subtest. Test–retest correlation suggests weak reliability ($r = 0.24$; Faísca et al., 2019).

Reading Fluency

Reading fluency is a speed measure computed as the average number of correctly read items across the five lists from the ADLER's Reading Fluency Subtest. This composite measure has excellent internal consistency (Cronbach's alpha = 0.92) and good temporal stability (test–retest correlation: $r = 0.67$; Faísca et al., 2019).

Phonological Awareness

Three phonological awareness tasks were used (phoneme deletion, spoonerisms, and phonological acronyms; Faísca et al., 2019). All tasks have good reliability (Cronbach's alphas ranging from 0.70 to 0.90) and showed moderate to strong correlations (mean $r = 0.53$; all $p < 0.01$), so a composite measure for phonological awareness was computed based on the average of the z-transformed accuracy scores from each task. This composite measure has excellent temporal stability (test–retest correlation: $r = 0.85$; Faísca et al., 2019).

Rapid Automatized Naming

Digit and letter naming tasks were used (Alves et al., 2007) since RAN alphanumeric measures have been considered as stronger predictors of reading-related skills than non-alphanumeric measures (e.g., Araújo et al., 2015; Donker et al., 2016). As these tasks correlated strongly ($r = 0.74$), a RAN composite was computed, representing the average number of correctly named items per second. The Spearman-Brown coefficient was $r = 0.84$, indicating good reliability for this measure.

Morphological Awareness

Two morphological awareness computer-driven tasks were developed based on Cavalli et al. (2017): the Suffixation Decision Task and the Suffixed Word Detection Task. These tasks were designed to assess explicit morphological awareness since they required extracting the stem word from a derived form (Martin et al., 2014).

In these tasks, all words were nouns, in the singular form, and had a regular grapheme-phoneme conversion, to ensure that performance was based exclusively on morphology.

Suffixation stimuli were matched for phonological/orthographic shift (Wilson-Fowler and Apel, 2015), as well as for word length (3–4 syllables).

All the words were audio-recorded and played through headphones to prevent the participants to extract the stem word through orthographic analysis of the stimulus, and thus avoiding possible cofounding with word reading skills (Cavalli et al., 2017). Before performing the morphological awareness tasks, all participants were instructed on the definitions of stem words, affixes (suffixes and prefixes), suffixed and prefixed words, and pseudosuffixed and pseudoprefixed words. Morphological awareness tasks were always presented in the same order.

Suffixation Decision Task

Thirty-two words were used as auditory stimuli, half being morphologically complex and suffixed (e.g., "carteiro"/postman) and half being morphologically simple and pseudosuffixed (e.g., "dinheiro"/money). Pseudosuffixed words have a suffix-like ending (e.g., "-eiro") but are monomorphemic. Frequency and word length were matched between suffixed and pseudosuffixed items. Immediately after the auditory presentation of each stimulus, participants should decide as fast and accurately as possible if the word was suffixed or not. The item presentation order was pseudorandomized and fixed across participants. Before the task, participants were trained with four examples, and oral feedback was given. Accuracy scores were calculated as the percentage of correctly answered items.

Suffixed Word Detection Task

Words were organized in 12 triplets (groups of three words), comprising one suffixed word and two pseudosuffixed words (e.g., "ossada, geada, cilada"/bone, frost, trap, being "ossada" the suffixed target). Frequency and word length were matched between suffixed and pseudosuffixed items. Words within triplets were auditorially presented one by one, with a one-second pause between words. Triplets were always presented twice, with 2 seconds between them, to avoid working memory constraints. Immediately after hearing the triplet for the second time, participants had to detect the word that was suffixed, by pressing either the 1, 2, or 3 button keys on the computer keyboard, if the target suffixed word was the first, second, or third item of the triplet. Participants were instructed to respond as fast and accurately as possible with their preferred hand. The presentation order of the triplets was pseudorandomized and fixed across participants. Before the task, participants trained with two example triplets, and oral feedback was given. Accuracy scores were calculated as the percentage of correctly answered items.

The morphological awareness score was computed averaging the z-transformed accuracy scores obtained in the Suffixation Decision and the Suffixed Word Detection Tasks.

Auditory Working Memory

The backward condition of the Digit Span subtest of the WAIS-III (Portuguese version; Wechsler, 2008) was used to assess working memory, considering that this task requires storage and manipulation of auditory information (Novaes et al., 2019). The raw scores were used as a working memory measure.

Vocabulary

The Vocabulary subtest of the WAIS-III (Portuguese version; Wechsler, 2008) was used to measure oral vocabulary knowledge. In the present work, raw scores were converted to standardized scores, based on the WAIS-III age groups and used as a vocabulary knowledge measure.

Procedure

This study is part of a larger research project aiming at the development and validation of a battery of tests to assess reading and reading-related skills in European Portuguese adults (the ADLER Battery; Faísca et al., 2018, 2019). The participants were recruited among those who were being assessed in the ADLER sessions. Typical adult readers were selected and asked to collaborate in the present study. For those who agreed, an additional session took place, to administer the new tasks not included in the ADLER Battery (reading comprehension, oral language comprehension, and morphological awareness). The order of administration of the tasks was fixed for all participants.

Before the administration of the tasks, participants gave their informed consent, according to the current Portuguese personal data protection law. Participants also filled a questionnaire with relevant sociodemographic information.

Data Analysis

Regression and path analyses approaches were used to test SVR and mediation models. Path analysis is a statistical method developed to study simultaneously the direct and indirect effects of a set of independent variables on one or more dependent variables (Streiner, 2005), providing estimates of the magnitude of the hypothesized relationships (*paths*) among variables.

Path coefficients point estimates (unstandardized and standardized) were complemented with bootstrap percentile confidence intervals, BPCI (based on 2,000 samples). To assess the goodness-of-fit of the path models, we used the Chi-squared statistic (X^2), the Comparative Fit Index (CFI), and the Root Mean Square Error of Approximation (RMSEA). CFI values higher than 0.9 indicate an acceptable fit, while RMSEA should be lower than 0.05 to verify a good fit, with values between 0.05 and 0.08 suggesting a reasonable fit (Hu and Bentler, 1999).

To test the mediation hypothesis, a full mediation model (direct effects were restricted to zero, except those involving the mediator) was estimated first, to check for non-null indirect effects. If indirect effects existed, the full mediation model was compared to the partial mediation model (where direct effects are freed). Significant goodness-of-fit differences between both models would indicate that restricting the direct effects to zero hinders the model's adjustment, and so the total mediation model cannot be accepted, and direct paths should be maintained (partial mediation). Contrarily, non-significant differences between models would indicate that restricting the direct effects to zero does not hinder the model's adjustment and so full mediation can be assumed. Chi-squared tests were used to assess the significance of the difference between the goodness-of-fit of nested models.

Besides the path analyses, descriptive and correlational statistics were performed. The guidelines of Cohen (1988) for the strength of correlations in behavioral sciences were followed. All data were processed using the IBM SPSS Statistics (v.26) and IBM SPSS AMOS (v.26) software.

RESULTS

Descriptive Statistics

Table 1 shows the descriptive statistics for all variables in the study. According to Kline's (2005) suggestion, the skewness and kurtosis coefficients indicate no severe deviation from normality in the variable distributions. Scores on morphological and phonological awareness measures were somewhat skewed to the left, but the visual inspection of their distribution (boxplot and histogram) indicates that the relatively high concentration of scores on the right may not be considered a ceiling effect.

Z-scores for measures of phonological decoding (*mean* = 0.18, min = −2.58, max = 1.36), word reading (*mean* = 0.19, min = −3.20, max = 2.06) and reading fluency (*mean* = 0.13, min = −2.65, max = 3.00) were computed based on the scores of 150 typical adult readers (Faísca et al., 2019) and they indicate that, on average, the present sample does not deviate from the expected performance level on these tasks.

Pearson correlations among predictors were always positive (except for the null correlation between RAN and morphological awareness, $r = -0.01$, $p = 0.918$), but not always significant. Significant correlations among predictors ranged from weak to moderate ($0.25 < r < 0.50$). Predictors correlated significantly with reading comprehension, with the exceptions of phonological decoding and RAN. All significant correlations between predictors and reading comprehension were positive and moderate, ranging from 0.30 (reading fluency) to 0.47 (oral language comprehension).

SVR Model

The SVR model (**Figure 3**) is a saturated model (degrees of freedom = 0), so the goodness of fit indexes could not be computed. Both word reading (standardized coefficient $\beta = 0.227$; 95% BPCI [0.038, 0.391]) and oral language comprehension (standardized coefficient $\beta = 0.405$; 95% BPCI [0.157, 0.713]) have a significant direct effect on reading comprehension. Together, these two predictors explained about 27% of the variance in reading comprehension ($R^2 = 0.266$). Although the standardized coefficient for oral language comprehension seems to express a somehow greater effect on reading comprehension compared to word reading, pairwise parameter comparison showed that this difference was non-significant (critical ratio = 0.27, $p > 0.7$). Confidence intervals for path coefficients were rather wide and overlapped, suggesting

TABLE 1 | Correlation matrix (Pearson product–moment correlation coefficients) and descriptive statistics.

	1	2	3	4	5	6	7	8	9	10
1. RAN	1									
2. Morphological awareness	−0.01	1								
3. Phonological decoding	0.08	0.17	1							
4. Phonological awareness	0.09	0.35**	0.33**	1						
5. Working memory	0.06	0.05	0.19	0.50**	1					
6. Word reading	0.06	0.18	0.40**	0.29*	0.26*	1				
7. Reading fluency	0.47**	0.15	0.23	0.26*	0.34**	0.34**	1			
8. Vocabulary	0.14	0.15	0.02	0.35**	0.34**	0.36**	0.31*	1		
9. Oral lang. comprehension	0.07	0.23	0.00	0.23	0.37**	0.27*	0.25*	0.27**	1	
10. Reading comprehension	0.11	0.34**	0.06	0.35**	0.36**	0.34**	0.30*	0.42**	0.47**	1
Mean	3.04	0.00	93.77	0.00	7.13	96.83	1.67	10.67	11.47	24.34
standard deviation	0.46	0.83	5.15	0.83	2.12	1.55	0.26	2.56	2.35	4.23
Skewness	0.326	−1.028	−0.638	−2.034	0.105	−0.860	−0.033	0.010	0.164	0.144
Kurtosis	−0.592	2.455	−0.266	6.527	−0.066	2.271	−0.317	2.603	−0.218	−1.025

*RAN – Number of correctly named items per second; Morphological Awareness – Accuracy (z-scores); Phonological Decoding – Percentage of correctly read pseudowords; Phonological Awareness – Accuracy (z-scores); Working Memory – Raw scores (max = 14); Word Reading – Percentage of correctly read words; Reading Fluency – Number of correctly read words per second; Vocabulary - Standardized scores; Oral Language Comprehension – Number of correct answers (max = 20); Reading Comprehension – Number of correct answers (max = 40); *p < 0.05 and **p < 0.01.*

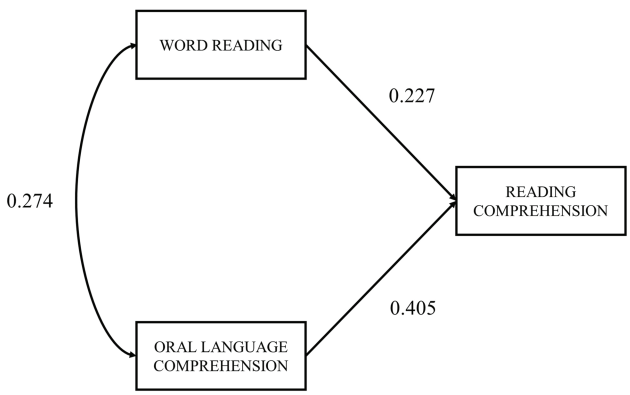

FIGURE 3 | SVR model with standardized path coefficients. All paths are significant ($p < 0.05$).

that the magnitude of these effects cannot be considered reliably different.

Extended SVR Model

A hierarchical regression analysis with two blocks was used to test if reading fluency and vocabulary could add a significant contribution to the SVR model. The first block contained the two main components of the SVR (word reading and oral language comprehension), and the second block included the reading fluency and vocabulary measures. This regression model provided a significant addition of near 7% above the reading comprehension variance explained by the SVR model [$R^2 = 0.335$; R^2 change = 0.069; F change $(2, 62) = 3.2$, $p = 0.046$]. In this extended model, the effect of vocabulary on reading comprehension was significant ($\beta = 0.256$, $p = 0.030$) but the effect of reading fluency was not ($\beta = 0.091$, $p = 0.429$). Also, the effect of word reading on reading comprehension was attenuated, losing its significance when reading fluency and vocabulary were considered ($\beta = 0.227$, $p = 0.045$ in the first block and $\beta = 0.122$, $p = 0.297$ after including the second block). The effect of oral language comprehension on reading comprehension maintains its significance even in the presence of reading fluency and vocabulary ($\beta = 0.342$, $p = 0.003$).

The path analysis of the extended SVR model (**Figure 4**) helps to elucidate the consequences of including reading fluency and vocabulary as predictors of reading comprehension. While chi-square goodness-of-fit statistic [$X^2\ (2) = 3.8$, $p = 0.149$] and the CFI = 0.961 suggests a good model fit, the RMSEA = 0.117 indicates poor adjustment. However, considering that RMSEA is known to be too restrictive when the model has a small number of degrees of freedom and the sample size is small (Kenny et al., 2015), and considering the Chi-square and CFI indexes, we can assume that the extended SVR model depicted in **Figure 4** represents the sample data adequately.

Five out of the eight hypothesized paths of the extended SVR model were significant (**Table 2**). Lastly, **Table 3** shows the standardized direct, indirect, and total effects of the variables on reading comprehension. Overall, word reading does not have a direct effect on reading comprehension, exerting its indirect influence mainly through vocabulary. Vocabulary influences reading comprehension both directly and through oral language comprehension.

Effects of the Remaining Predictors on Reading Comprehension

Since RAN and phonological decoding did not correlate significantly with reading comprehension, both measures were not included in the mediation analyses. Thus, the effects of phonological awareness, morphological awareness, and working memory on reading comprehension were tested, to verify if direct effects on reading comprehension do exist, or if these effects were totally mediated by word reading and reading fluency. To test our mediation hypotheses, two models were tested: full mediation through word reading and reading fluency (model 1a, **Figure 5**) and partial mediation through word reading and reading fluency (model 1b, **Figure 6**).

Chi-square statistics were significant for both models ($p < 0.05$), indicating a poor fit (**Table 4**). CFI indicated a good fit only for the partial mediation model (CFI > 0.9). Again, as expected due to the small number of degrees of freedom (Kenny et al., 2015), the RMSEA index suggests a poor fit (RMSEA > 0.2) for both models. However, the crucial step in this analysis is to compare the full and partial mediation models. The difference in chi-square statistics between the two models was significant ($p = 0.011$), suggesting that word reading and reading fluency did not completely mediate the effects that morphological awareness, phonological awareness, and working memory may have on reading comprehension.

In the full mediation model, all indirect effects on reading comprehension through word reading and reading fluency were non-significant, except for working memory (model 1a; $\beta = 0.110$, $p = 0.045$). When direct effects were allowed (model 1b), only morphological awareness revealed a significant direct impact on reading comprehension (model 1b; $\beta = 0.259$, $p = 0.023$). Phonological awareness showed no significant direct or indirect effects on reading comprehension (**Table 5**).

DISCUSSION

Research on the predictors of reading comprehension has been largely focused on school-aged children, and in more opaque orthographies, such as English. These studies cannot be fully generalized to adults typical readers, that rely on different cognitive processes when reading (Greenberg et al., 2002), or to more transparent orthographies, as transparency affects the weight of the contribution of predictors on reading comprehension (Florit and Cain, 2011). Moreover, the SVR model, despite some cases of high percentages of explained variance of reading comprehension in both children (e.g.,

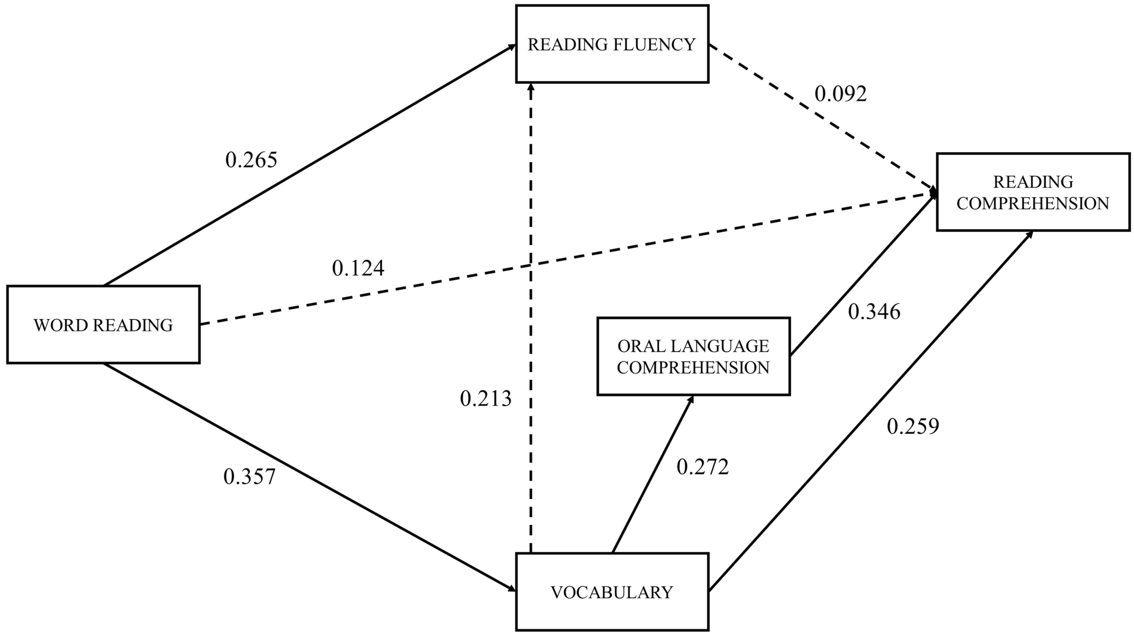

FIGURE 4 | Extended SVR model with standardized path coefficients. χ^2 (2) = 3.814, p = 0.149; CFI = 0.961; RMSEA = 0.117. Dashed lines represent non-significant paths; solid lines represent significant paths (p < 0.05).

TABLE 2 | Unstandardized and standardized path coefficients for the extended SVR model.

Paths	Unstandardized	Standard error	Standardized	*p*
Word reading → Reading fluency	0.045	0.020	0.265	0.028
Word reading → Vocabulary	0.592	0.190	0.357	0.002
Vocabulary → Reading fluency	0.022	0.012	0.213	0.078
Vocabulary → Oral language comprehension	0.250	0.109	0.272	0.021
Word reading → Reading comprehension	0.079	0.072	0.124	0.272
Reading fluency → Reading comprehension	0.349	0.421	0.092	0.407
Vocabulary → Reading comprehension	0.100	0.044	0.259	0.024
Oral lang. comprehension → Reading comprehension	0.145	0.044	0.346	0.001

Catts et al., 2005) and adults (e.g., Sabatini et al., 2010), has been often criticized for being too simplistic, and other components have been suggested, such as vocabulary and reading fluency.

In this study, we set out to examine the relations between several reading-related predictors and reading comprehension in European Portuguese-speaking adults. For that, we selected a set of predictors identified in the meta-analysis of Tighe and Schatschneider (2016), namely oral language comprehension and word reading (as it is assumed in SVR), vocabulary and reading fluency (frequently included in SVR extended models), and phonological decoding, phonological awareness, rapid automatized naming, working memory and morphological awareness. As expected, our results showed that all these predictors correlated significantly, positively, and moderately with reading comprehension, with the exceptions of phonological decoding and RAN. The absence of a significant correlation between phonological decoding and reading comprehension could be partially explained by the relative transparency of the European Portuguese orthography in the print-to-read conversion. In semitransparent orthographies such as Portuguese, the grapheme-phoneme conversion is simpler, allowing readers to achieve fluent decoding in the first school years (Seymour et al., 2003). When fluent reading is achieved, reading performance no longer depends on grapheme-phoneme conversions, and therefore correlations between phonological decoding and reading comprehension lose strength. This might explain the null correlation between phonological decoding and reading comprehension in the present study.

The absence of correlation between RAN and reading comprehension could result from reading expertise. Tighe and Schatschneider (2016) contrasted the correlations in their meta-analysis with correlations reported in a large meta-analytical study addressing the predictors of reading comprehension in early childhood and kindergarten (National Early Literacy Panel, 2008). The authors found that RAN was weakly related to reading comprehension in their reviewed studies with adult readers (average $r = 0.15$), but this correlation had a moderate magnitude in the studies reviewed by the National Early Literacy Panel (2008) (average $r = 0.43$). These findings suggest that the association between RAN and reading comprehension loses its strength in adulthood and that this association depends on reading expertise. Since RAN is a well-known predictor of reading fluency (Savage and Frederickson, 2005), it will affect reading comprehension probably in an indirect manner, *via* reading fluency. In early school years, while fluent reading is not yet achieved, reading fluency and RAN prove to be important predictors of reading comprehension. However, in higher grades, readers have already achieved proficient reading, and consequently reading fluency will show a reduced effect on comprehension. If this is the case, it might explain why the effect of RAN on reading comprehension is absent in our adult sample.

Regarding the simple SVR model, our results demonstrated that both word reading and oral language comprehension displayed direct and significant effects on reading comprehension, with the latter showing a stronger effect, and apparently confirming our hypothesis. However, inferential procedures indicate that this difference cannot be considered as statistically reliable (perhaps due to the lack of statistical power). Despite that, there is a clear tendency that arose from previous studies (e.g., Florit and Cain, 2011; Cadime et al., 2017) that allow us to suggest that in a sample with advanced grade levels and for an orthography of intermediate transparency, oral language comprehension should provide a significantly higher contribution than word reading to reading comprehension.

The two components of the SVR model only explained about 27% of the variance in reading comprehension, contrasting with the values found in the literature, usually higher (e.g., 74% in Braze et al., 2007; 64% in Sabatini et al., 2010). A possible explanation for such differences might result from the samples used in previous studies, namely English adult struggling readers, whose reading comprehension might still be strongly dependent on word decoding processes. Therefore, the comparison with such populations of struggling readers should be done with precaution. In typical English adult readers, the SVR model explains a fraction of the reading comprehension variance similar to the observed in our sample (34% of the explained variance; Macaruso and Shankweiler, 2010). Another possible explanation is the exclusive reliance on observable variables (e.g., Sabatini et al., 2010; Braze et al., 2016), an approach that diminishes measurement error and allows more reliable measures. Furthermore, reliability coefficients for our oral language and reading comprehension tasks were low (Cronbach's alpha = 0.40 and 0.49, respectively), so in the future, we should consider adopting methods to improve the reliability of our measures, to lessen measurement errors and hence

TABLE 3 | Standardized direct, indirect, and total effects of predictors on reading comprehension, in the extended SVR model.

Predictors	Direct (*p*)	Indirect (*p*)	Total (*p*)
Word reading	0.124 (0.169)	0.158 (0.019)	0.281 (0.017)
Reading fluency	0.092 (0.438)	-	0.092 (0.438)
Vocabulary	0.259 (0.018)	0.114 (0.035)	0.373 (0.010)
Oral language comprehension	0.346 (0.019)	-	0.346 (0.019)

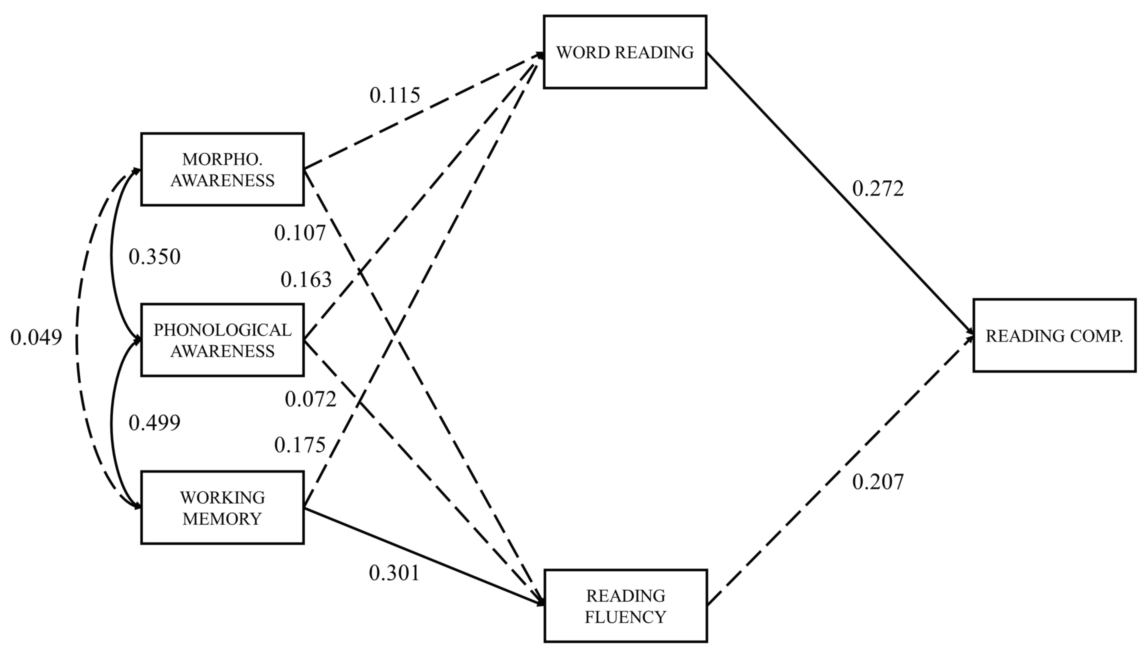

FIGURE 5 | Full mediation by word reading and reading fluency model, with Standardized path coefficients. χ^2 (4) = 15.641, $p = 0.004$; CFI = 0.800; RMSEA = 0.210. Dashed lines represent non-significant paths; solid lines represent significant paths ($p < 0.05$).

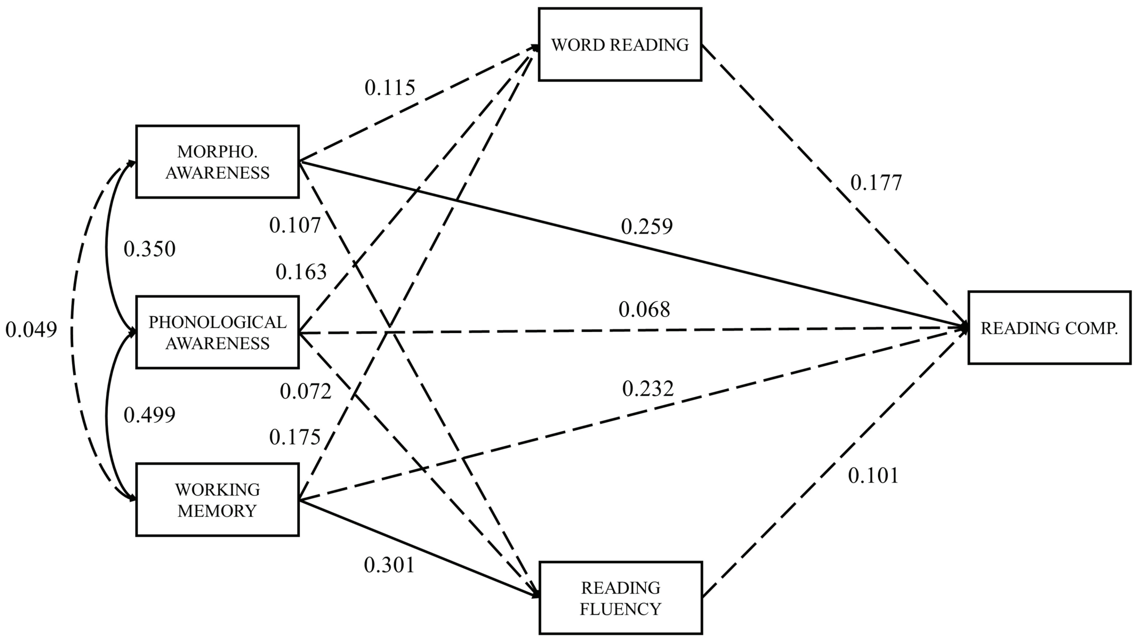

FIGURE 6 | Partial mediation by word reading and reading fluency model with standardized path coefficients. χ^2 (1) = 4.417, p = 0.036; CFI = 0.941; RMSEA) = 0.228. Dashed lines represent non-significant paths; solid lines represent significant paths (p < 0.05).

TABLE 4 | Goodness-of-fit indexes for the mediation models and comparison between full and partial mediation models.

Models	χ^2(df), p	CFI	RMSEA	Comparisons
1a – Full mediation by word reading and reading fluency	15.6 (4), 0.004	0.800	0.210	-
1b – Partial mediation by word reading and reading fluency	4.4 (1), 0.036	0.941	0.228	$\Delta\chi^2$ = 11.224, Δdf = 3, p = 0.011

df = degrees of freedom; CFI = Comparative Fit Index; RMSEA = Root Mean Square Error of Approximation.

proving more accountability for the variance in reading comprehension.

The extended SVR model included reading fluency and vocabulary and provided a significant addition to the explained variance in reading comprehension (7%). Nonetheless, vocabulary was the only one of the two added variables that showed a significant individual contribution to reading comprehension. The inclusion of these new variables also caused the direct effect of word reading to become non-significant, demonstrating that word reading only affects reading comprehension indirectly. A more detailed analysis showed that this indirect effect happens mostly *via* vocabulary. Thus, at least in our adult sample, word reading accuracy effects on reading comprehension might reflect the reciprocal association between reading accuracy and the acquisition of new word meanings (Ricketts et al., 2007; Mellard et al., 2010).

The direct effect of vocabulary on reading comprehension was expected. A study performed with Portuguese children suggests that while reading fluency remains important from the first to the sixth grade, vocabulary emerges as a significant predictor in the second grade, gaining importance throughout the school years, as reading fluency loses relevance (Fernandes et al., 2017). By the sixth grade, vocabulary's importance catches up with reading fluency's, and this tendency could go on as the reader advances in schooling, with reading becoming more fluent and vocabulary size increasing. Indeed, in our sample, reading fluency was not a significant predictor of reading comprehension, while vocabulary showed significant direct and indirect effects (through oral language comprehension). Once again, this suggests that, at least in more transparent orthographies, decoding skills are important in early school years, until reading becomes fluent. Then, higher-order skills such as vocabulary emerge and remain important to achieve reading comprehension, throughout schooling and adulthood.

The effect of vocabulary on reading comprehension, in our study, provides support for its addition as a separate component in the SVR model. Other studies that used path analysis (e.g., Mellard et al., 2010) or regression models (e.g., Braze et al., 2007) also support this idea. However, Braze et al. (2016) proposed that the observed effect of vocabulary on reading comprehension could be explained by the typical low-reliability of oral language comprehension measures, which might not be capturing all aspects that are relevant for reading comprehension, which in turn might be apprehended by the more reliable vocabulary measures. Since our oral language comprehension measure presented low reliability, this may be also

TABLE 5 | Standardized direct, indirect, and total effects of predictors on reading comprehension, in the full mediation (1a) and partial mediation (1b) models.

Predictors	Model 1a			Model 1b		
	Direct (*p*)	Indirect (*p*)	Total (*p*)	Direct (*p*)	Indirect (*p*)	Total (*p*)
PA	-	0.059 (0.273)	0.059 (0.273)	0.068 (0.575)	0.036 (0.259)	0.104 (0.436)
MA	-	0.053 (0.282)	0.053 (0.282)	0.259 (0.023)	0.031 (0.280)	0.291 (0.025)
WM	-	0.110 (0.045)	0.110 (0.045)	0.232 (0.114)	0.062 (0.109)	0.293 (0.032)
WR	0.272 (0.035)	-	0.272 (0.035)	0.177 (0.167)	-	0.177 (0.167)
RF	0.207 (0.073)	-	0.207 (0.073)	0.101 (0.382)	-	0.101 (0.382)

PA = Phonological Awareness; MA = Morphological Awareness; WM = Working Memory; WR = Word Reading; RF = Reading Fluency. Model 1a – full mediation through word reading and reading fluency; Model 1b – partial mediation through word reading and reading fluency.

the case for our study. Thus, this significant effect of vocabulary on reading comprehension should be interpreted with caution, until other studies, with different statistical procedures or more reliable measures of oral language comprehension, can confirm vocabulary relevance in the SVR model for the studied population.

Although the results of the present study show that the SVR model (with the possible addition of vocabulary) can reliably predict reading comprehension in adults, the percentage of explained variance by the model is smaller than the reported in previous studies with English struggling adult readers. This difference might be due to both the different levels of reading expertise of the studied samples or to the orthographies' transparency. More studies are needed to verify the SVR's adequacy in adult typical readers, and they should include proposals for additional inclusions as a way of increasing the percentage of explained variance of reading comprehension. Recent studies have suggested the inclusion of higher-order cognitive skills (e.g., inference making, perspective-taking, and comprehension monitoring; Kim, 2017, 2020), text characteristics (e.g., sentence length and frequency of the words; Francis et al., 2018), and variables of self-regulation when reading (e.g., motivation, engagement, and the use of reading strategies; Duke and Cartwright, 2021).

In the final mediation analyses, we tested if the effects of the remaining variables at study (morphological awareness, phonological awareness, and working memory) on reading comprehension were direct or mediated by word reading and reading fluency. The total mediation hypothesis was rejected, suggesting that word reading and reading fluency did not completely mediate the contribution of these predictors. As expected, morphological awareness was the only variable that presented a significant direct effect on reading comprehension. In the meta-analysis of Tighe and Schatschneider (2016), morphological awareness was the strongest predictor of reading comprehension. According to Kirby et al. (2008), this skill gains importance as the reader progresses to more advanced levels of schooling. As text exposure increases, so does the number of morphologically complex words that the reader is exposed to, providing more opportunities for the use of morphological awareness skills. The direct effect of morphological awareness on reading comprehension, in adults, can be observed in more opaque orthographies such as English (see, for example, Wilson-Fowler and Apel, 2015; Fracasso et al., 2016). In such orthographies, since grapheme-phoneme conversion is not consistent, the ability to manipulate morphemes aids in accurately reading morphologically complex words and comprehending texts. In more transparent orthographies, such as Portuguese, decoding is easier, since grapheme-phoneme conversion is more consistent, and therefore morphological awareness is not so relevant to accurate reading, but still plays an important role in meaning-extraction to achieve comprehension of what was read.

Working memory showed a significant total effect on reading comprehension, in the final mediation models, although individual direct and indirect paths were non-significant. This is an indicator that individual effects might be important, as their sum reaches statistical significance. Indeed, a direct effect of working memory on reading comprehension would be expectable, since working memory allows readers to store and manipulate information from the text as they read and integrate it with previously stored knowledge (Daneman and Merikle, 1996). In addition, an indirect effect of working memory on reading comprehension, through word reading and reading fluency, makes theoretical sense. The larger the amount of information that readers can store and process continuously, the more accurate and faster they can read since they can quickly retrieve word pronunciations and meanings from their long-term memory.

Surprisingly, phonological awareness did not show a significant direct or indirect path of influence to reading comprehension in the final mediation models, even though it correlated significantly with reading comprehension. An explanation we could provide for this is that phonological awareness and working memory correlated moderately ($r = 0.50$, $p < 0.01$), sharing explained variance. This correlation probably reflects the working memory demands of phonological awareness tasks, where participants typically need to store and manipulate verbal information of increasing difficulty. In this way, phonological awareness could be reflecting the effects of working memory on reading comprehension, lessening its effect when the two predictors are considered together. In the future, other studies should try to disentangle the relations between these variables and reading comprehension.

This study was the first one to investigate the predictors of reading comprehension in a sample of European Portuguese-speaking adults, and so several measures were specifically tailored for this study. Consequently, our findings should be interpreted taking into account the low reliability of some tasks. Also, our relatively small sample size only provided statistical power to detect moderate effects on reading comprehension. A larger sample should contribute with sufficient statistical power to detect smaller but still relevant effects. Additionally, considering the predominance of female participants in our study, our results should be confirmed in a more gender-balanced sample.

We consider that the greatest implication of the present work is that it provides a re-thinking about the models of reading comprehension for typical adult readers, in a less opaque orthography such as European Portuguese. Future investigations might use these results as a term of comparison with other age-groups, education levels, reading skills, and orthographies, or as a way of identifying relevant targets of intervention for the improvement of reading comprehension levels in Portuguese adults. Oral language comprehension and vocabulary were the best predictors of reading comprehension in the present study and therefore these abilities can be the target of remediation programs to increase reading comprehension levels, in adults.

In sum, this study adds evidence that the transparency of the orthography and reading expertise affect the relative contribution of predictors on reading comprehension. Results show that the SVR model (with the significant addition of vocabulary) could be an adequate model to predict reading comprehension in typical adult readers in a semitransparent orthography, even though other variables could probably increase the percentage of explained variance in reading comprehension.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

FG, AR, and LF: conceptualization and methodology. FG, IS, and LF: investigation and formal analysis. FG, AR, FI, and LF: writing – original draft. AR, FI, and LF: writing – review and editing. AR: funding acquisition. All authors contributed to the article and approved the submitted version.

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Is There a (Dis-)Fluency Effect in Learning With Handwritten Instructional Texts? Evidence From Three Studies

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The disfluency effect postulates that intentionally inserted desirable difficulties can have a beneficial effect on learning. Nevertheless, there is an ongoing discussion about the emergence of this effect since studies could not replicate this effect or even found opposite effects. To clarify boundary effects of the disfluency effect and to investigate potential social effects of disfluency operationalized through handwritten material, three studies (N_1 = 97; N_2 = 102; N_3 = 103) were carried out. In all three experiments, instructional texts were manipulated in terms of disfluency (computerized font vs. handwritten font). Learning outcomes and cognitive load were measured in all experiments. Furthermore, metacognitive variables (Experiment 2 and 3) and social presence (Experiment 3) were measured. Results were ambiguous, indicating that element interactivity (complexity or connectedness of information within the learning material) of the learning material is a boundary condition that determines the effects of disfluency. When element interactivity is low, disfluency had a positive effect on learning outcomes and germane processes. When element interactivity increases, disfluency had negative impacts on learning efficiency (Experiment 2 and 3) and extraneous load (Experiment 3). In contrast to common explanations of the disfluency effect, a disfluent font had no metacognitive benefits. Social processes did not influence learning with disfluent material as well.

Keywords: disfluency, handwritten font, metacognition, element interactivity, social presence

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INTRODUCTION

When managing complex and challenging learning tasks in multimedia environments, instructors should be aware that a high cognitive load hampers learning progress (Sweller et al., 2019). In this vein, research on designing appropriate instructional materials and procedures for multimedia learning has gained a lot of attention over the years. The aim is to support the learner to concentrate solely on learning and to eliminate unnecessary burdens (or unnecessary cognitive load) as far as possible. Nevertheless, there is an ongoing research on positive effects of designing learning material in a way that it is intentionally difficult to perceive. One approach is providing texts with a difficult-to-read font. What sounds paradox, however, has been established as the disfluency effect in educational research (Alter et al., 2007). The intentional insertion of disfluency, in this case, a difficult-to-read font can improve memorization skills because of metacognitive processes. This study focuses on investigating the disfluency effect operationalized through a handwritten text font. Disfluency is defined and discussed in the context of desirable difficulty, cognitive load, and social processes. Three experiments outline the role of disfluent materials and causal mechanisms of text design on learning processes.

LITERATURE REVIEW

Disfluency as Desirable Difficulty

The concept of disfluency can be traced back to research from James (1950) as well as Kahneman and Frederick (2002), who stated that human processing consists of two distinct cognitive systems. System one is quick, effortless, associative, and intuitive while system two is slow, effortful, analytic, and deliberate (Kühl and Eitel, 2016). Depending on the perceived task difficulty, one of the two systems is activated (Alter et al., 2007). If the learner perceives the information as easy to process, system one operates (Alter and Oppenheimer, 2009). Accordingly, system two will be stimulated when the information processing is perceived as difficult and requires deeper analytic processing. In this case, the learner invests more mental effort (Eitel et al., 2014). Alter et al. (2007) have shown that experienced difficulty motivated learners to process tasks more analytically. In this vein, intentionally inserted desirable difficulties (e.g., an illegible learning material) can have a beneficial effect on learning (Pashler et al., 2007; Bjork, 2013). When learners are facing a challenging design of the learning material, they invest more mental effort while processing the information more deeply (Strukelj et al., 2016). As difficult perceived tasks engage the learner to activate more elaboration strategies (Alter et al., 2007; Xie et al., 2018).

Adding difficulties to the learning material is also possible by manipulating the legibility of the text-font presented (e.g., Alter and Oppenheimer, 2009; Beege et al., 2021). It is assumed that "making text slightly harder-to-read fosters retention and understanding" (Eitel and Kühl, 2016, *p*. 108). When learners are confronted with hard-to-read learning materials, such difficulties motivate to process the information more deeply than it would be the case in easy-to-read learning materials (Xie et al., 2018). "With disfluent learning material learners perceive the task as more difficult and metacognitively regulate their learning approach by activating system two" (Seufert et al., 2017, *p*. 222). The cognitive task of encoding a text, therefore, relates to a metacognitive experience. Thus, metacognitive activities should be taken into account. Three main types of judgments are measured when discussing metacognitive activities in learning contexts (Nelson and Narens, 1990): ease of learning (EOL) judgments are made at the beginning of the learning period, after seeing the material for the first time which affects the allocation of study-time (Son and Kornell, 2008). Ease of learning judgments are particularly affected by the text font since no information about the complexity of the learning content is available at the time the judgment is made. Judgments of learning (JOL) are made after learning from the text and predict future memory performance (Dunlosky and Metcalfe, 2009). Finally, retrospective confidence (RC) assesses the confidence of the performance in a learning test (Dinsmore and Parkinson, 2013). These variables are used to calculate metacognitive accuracy scores to determine how accurate learners assume their performance in relation to their abilities and how learners adapt their strategies during learning (Pieger et al., 2016). Pieger and colleagues pointed out that disfluency enhanced absolute metacognitive accuracy, since more analytic metacognitive processes were initiated. Perceptual fluency might be a dominant cue for improving monitoring processes which led to more accurate judgements of learning performance.

The impetus for this field of research was provided by Diemand-Yauman et al. (2011) who investigated the effect of disfluency on memory performances more closely. Across two experiments with different samples (university students and high school students) they confirmed that texts with hard-to-read fonts (e.g., Hattenschweiler) led to better learning performances than presenting text with easy-to-read fonts (e.g., Arial). In another study, Eitel et al. (2014) tried to apply the disfluency effect to multimedia learning across four experiments. However, a benefit for disfluent material could be found only in the first experiment. The manipulation of the text and the pictures in Experiment 1 is of particular interest. The disfluent text was presented in the same way as in the study by Diemand-Yauman et al. (2011). Pictures in a less legible format were operationalized as a low-quality photocopy. An ANCOVA with spatial ability as covariate showed that participants with disfluent text outperformed participants with fluent text regarding transfer. However, no significant differences between the groups could be detected for retention. In line with assumptions of desirable difficulties, learners receiving less legible texts invested significantly more mental effort than learners confronted with legible texts. However, the Experiments 2, 3, and 4 were not able to replicate the learning-beneficial effect of disfluency.

Making texts perceptually harder-to-read can also be implemented by handwritten texts. For instance, a study by Geller et al. (2018) examined the impact of cursive text on students' performance in a recognition memory task. Participants studied the learning material (word list) either with text in type-print, easy-to-read cursive, and hard-to-read cursive. The results confirmed that "cursive words were better remembered than type-print words, indicating that cursive script serves as a desirable difficulty" (Geller et al., 2018, *p*. 1114). However, the difference between easy-to-read and hard-to-read cursive script did not reach significance. The degree of disfluency, therefore, does not seem to be sufficient as a theoretical explanatory approach. Two additional experiments confirmed that the memory effect is also stable across different list designs and after a 24 h delayed learning test.

To sum up, empirical evidence for the learning beneficial effect of hard-to-encode instructional materials is not conclusive. Several experimental studies came to debilitating results and could not find any benefit for disfluency (e.g., Faber et al., 2017; İlïc and Akbulut, 2019; Rummer et al., 2016; Yue et al., 2013). A meta-analysis by Xie et al. (2018) also questions the robustness of the disfluency effect in text-based educational settings. In this vein, no significant effects of perceptual disfluency were found on recall (d = –0.01) and transfer (d = 0.03) outcomes. Furthermore, the theoretical foundation, postulated by Alter et al. (2007) is questioned as well. Thompson et al. (2013) found that perceptual fluency had no impact on metacognitive judgements and metacognitive accuracy. In consequence, boundary conditions or further explanations have to be taken into account to explain these inconsistent findings.

Disfluency as Extraneous Cognitive Load

An explanation for the rather inconsistent findings in disfluency research can be provided by considering the Cognitive Load Theory (CLT; Sweller, 1988, Sweller, 2010), which represents a well-established and empirically verified framework. The goal is to provide instructional guidelines and design recommendations that efficiently use the limited working memory to promote learning (Paas et al., 2003; Sweller et al., 2019). The load imposed on the cognitive structures can be divided into three types (intrinsic, extraneous, and germane cognitive load; Paas et al., 2003; Sweller et al., 1998). However, recent publications assumed a two-factor model including intrinsic and extraneous load (e.g., Sweller et al., 2019; Jiang and Kalyuga, 2020). First, intrinsic cognitive load (ICL) can be defined as the internal complexity of the learning material (Kalyuga, 2011). It is determined by the task's inherent element interactivity and the learner's domain-specific prior knowledge (Sweller et al., 2019). The concept of element interactivity relates to the complexity of the information to be learned and can be classified on a continuum between low to high. More concretely, interactivity refers to the number of elements that must be processed simultaneously in working memory (Sweller, 1994). Working memory load is not only caused by the task's inherent complexity, but also by a suboptimal design of the learning material. An inappropriate designed instructional format imposes extraneous cognitive load (ECL) and does not contribute to learning (Paas and Sweller, 2014). To facilitate schema construction and automation, extraneous processing should ideally be avoided (De Jong, 2010). Consequently, the instructional designer can manipulate the ECL while preparing learning materials (Klepsch et al., 2017). Intrinsic and extraneous cognitive load are in an additive relationship to each other and should be considered accordingly in the design (Paas and Sweller, 2014). When appropriate design principles ensure a reduction of the ECL, working memory capacities are freed for managing the tasks immanent element interactivity. However, meaningful learning is also possible, when comparatively low ICL does not require many working memory resources. In this case, high levels of ECL can be managed (Paas and Sweller, 2014). The third component, germane cognitive load (GCL), has experienced a redefinition over the years. Whereas older publications assumed that the GCL describes the required working memory capacities for managing the intrinsic load, current research attributes the GCL as a redistribution function (Sweller et al., 2019) and as active processing (i.e., mental effort; Jiang and Kalyuga, 2020). More precisely, GCL does not contribute to the whole load, but it rather allocates working memory capacities to activities being relevant for learning (Kalyuga, 2011).

The disfluency assumption can be seen as a counterpart to the CLT (Eitel et al., 2014; Lehmann et al., 2016; Xie et al., 2018). Implementing handwritten texts into the learning material might not be adequate for learning in general. In particular, when handwriting is hard to read (i.e., high disfluency), encoding errors can occur (Hartel et al., 2011). Hard-to-read handwriting affects the ECL since additional cognitive resources are required to deal with the inadequate instructional design (Seufert et al., 2017). In line with the CLT, illegible fonts must first be deciphered before learning can take place. In consequence, resources not relevant to learning are expended. Accordingly, receiving learning texts with rather hard-to-read letters induce extraneous load (Beege et al., 2021). A study by Seufert et al. (2017) proved that a high level of disfluency, where the text is barely legible, impedes learning success. Moderate levels of disfluency on the other hand can be quite conducive to learning, for example in terms of lower extraneous load perceptions, higher engagement, and better recall performances. Nevertheless, the authors emphasize the ambiguity about the learning-beneficial degree of disfluency, especially concerning extraneous load. İlīc and Akbulut (2019) could also show that the combination of disfluent texts and animations causes higher extraneous cognitive load than the same representations in a fluent form. However, there are several studies that could not detect significant effects of disfluency on extraneous load (e.g., Eitel et al., 2014; Kühl et al., 2014).

Disfluency as Social Cue

Recent findings in the field of educational research suggest considering learning not as an exclusively cognitive process. Motivational, affective, meta-cognitive, and social impacts should also be taken into account, since learning engagement is determined by these factors (e.g., Moreno et al., 2001; Mayer et al., 2003; Moreno and Mayer, 2007). A recent framework regarding multimedia learning explicitly includes social variables (CASTLM; Schneider et al., 2018).

As outlined, disfluency can be operationalized as writing instructional test in handwritten form. In this context, disfluent texts can be viewed as encounters for social processes. Triggering social responses with handwritten texts can be explained with the embodiment principle (Mayer, 2014). It is assumed that the implementation of humanlike entities can lead to the feeling of social presence and being in a social communication situation. By activating a social reaction, an increase in active cognitive processing results in better retention outcomes (Mayer et al., 2004; Mayer, 2014). Unlike other techniques (e.g., interactive learning environments; Moreno and Mayer, 2007), presenting handwritten texts is a comparatively simple possibility to induce the perception of a social event (Reeves and Naas, 1996). Accordingly, the learning environment thus fulfills two functions: First, it delivers information about a certain topic to the learner (Mayer, 2001); and second, it induces the feeling of being in a social interaction with the computer (Mayer et al., 2003). When learners receive font as human-like, the trust mechanism could also have a learning-promoting effect. For instance, a learning situation in which the instructor has written the text could be created. Thus, using disfluent text should not only be discussed in the context of desirable difficulty or cognitive load. Disfluent text, under circumstances, should be discussed considering social learning theories as well since several studies prove the beneficial effect of social cues on learning (e.g., for the voice principle, Mayer et al., 2003; for the politeness effect, McLaren et al., 2011).

Hypotheses

As outlined, operationalizing disfluency through a handwritten font can have beneficial as well as detrimental effects on learning. In three experiments, the role of disfluency in learning scenarios should be specified considering cognitive, metacognitive, and social processes.

Hypothesis 1: From the perspective of disfluency as a desirable difficulty, a handwritten text font leads to more elaborated metacognitive activities since difficulties engage to process the information more deeply than it would be the case in easy-to-read learning materials (Alter et al., 2007; Xie et al., 2018). According to explanations provided by Pieger et al. (2016), disfluency should enhance absolute metacognitive accuracy since perceptual fluency might be crucial for more accurate judgements of learning performance. Thus, absolute metacognitive accuracy should be positively influenced by a harder-to-read, handwritten text font.

H1: Learners receiving an instructional text with a handwritten (hard to read) text font achieve a higher absolute metacognitive accuracy than learners receiving an instructional text with a computerized (easy to read) text font.

Hypothesis 2: From the perspective of disfluency as extraneous cognitive load, a handwritten text font negatively affects ECL since additional cognitive resources are required to read the information (Seufert et al., 2017). Illegible fonts must first be deciphered before learning can take place. In consequence, resources not relevant to learning are expended (Beege et al., 2021).

H2: Learners receiving an instructional text with a handwritten (hard to read) text font perceive higher extraneous cognitive load than learners receiving an instructional text with a computerized (easy to read) text font.

Hypothesis 3: From the perspective of disfluency as a social cue, a handwritten text font can trigger social processes and function as a cue for perceived social presence (embodiment principle; Mayer, 2014), by activating a social reaction an increase in active cognitive processing (Mayer et al., 2004; Mayer, 2014). When learners perceive a font as human-like, the trust mechanism could also have a learning promoting effect.

H3: Learners receiving an instructional text with a handwritten (hard to read) text font perceive higher social presence than learners receiving an instructional text with a computerized (easy to read) text font.

Hypothesis 4: Because of these opposing perspectives, it is difficult to postulate an effect of using handwritten text on learning. Furthermore, research findings are ambiguous. Some studies support a disfluency effect (e.g., Diemand-Yauman et al., 2011; Geller et al., 2018). Consequently, the metacognitive or social benefits when using handwritten fonts are more significant for learning processes than the detrimental effect of the increased ECL. Other experiments found opposing effects or no effects of disfluency on learning (e.g., Faber et al., 2017; İlïc and Akbulut, 2019), indicating that the detrimental effects of ECL are more significant for learning or at least as significant as metacognitive and social benefits. In consequence, boundary conditions seem to determine which effect occurs most dominantly. In the current experiments, the element-interactivity of the learning material was investigated as a potential moderator of the effect. In a rather simple learning environment, metacognitive benefits can unfold since the working memory has enough capacity for encoding the disfluent font and the rising ECL does not significantly influence learning. If the material has a high element-interactivity, no resources are available for encoding the disfluent font and thus, the rising ECL leads to an overload which is dominant despite possible metacognitive or social benefits. Thus, two hypotheses are outlined.

H4a: Learners receiving an instructional text with a low element interactivity and a handwritten (hard to read) text font achieve higher learning outcomes than learners receiving an instructional text with a high element interactivity and a computerized (easy to read) text font.

H4b: Learners receiving an instructional text with a high element interactivity and a handwritten (hard to read) text font achieve lower learning outcomes than learners receiving an instructional text with a low element interactivity and a computerized (easy to read) text font.

To get first insights into learning with handwritten, disfluent texts, a first exploratory experiment with a low element interactivity was carried out. Learning outcomes and cognitive load was measures (Hypothesis 2 and 4). Because of the encouraging results, two additional experiments were conducted with more dependent measures to provide detailed insight. Whereas the first experiment explored the cognitive effects of a disfluent font as well as learning outcomes, the second experiment further included metacognitive variables (Hypotheses 1, 2, and 4). The third experiment further included social variables (Hypotheses 1, 2, 3, and 4). Additionally, exploratory mediation analyses are in the focus of the third main experiment, to determine if learning outcomes are causally effected by rather cognitive, metacognitive, or social processes and thus, to provide general theoretical implications of the emergence of a disfluency effect.

EXPERIMENT 1

Methods

Participants and Design. Overall, the discussed studies on the disfluency effect provided diverse effect sizes. Studies that supported the disfluency effect reported small to medium effect sizes (e.g., Eitel and Kühl, 2016) or medium to high effect sizes (e.g., Seufert et al., 2017). To detect, at least, a medium effect size concerning an one-factorial experiment with two factor levels, an a-priori power analysis ($f = 0.25$; $\alpha = 0.05$; $1 - ß = 0.80$) revealed that 102 participants must be acquired. With respect to this analysis, 97 secondary students (48.5% female; age: $M = 11.79$, $SD = 0.48$) participated in Experiment 1. Students were in the 5th (22.7%) or 6th (77.3%) grade. Prior

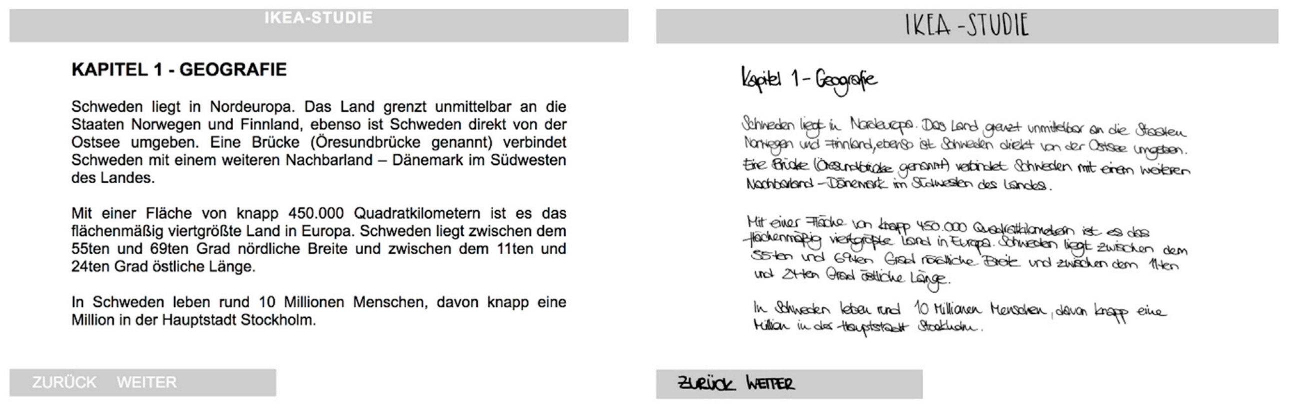


FIGURE 1 | Screen example of the learning material of Experiment 1 (left: fluent; right: disfluent).

knowledge of the participants (M = 0.76, SD = 0.74; with a maximum of five points) was low. Students attended secondary schools (*Gymnasium*) in XXX.

The participants were randomly assigned to two experimental conditions (handwritten font vs. computerized font) of a between-subjects design by drawing lots. Forty-seven students were assigned to the condition with handwritten font and 50 students were assigned to the condition with computerized font. For the experimental conditions, no significant differences existed in terms of age or prior knowledge, $t(95)$ = [0.04, 0.13]; p = [0.90, 0.97] as well as gender, χ^2 = 2.95; p = 0.09.

Materials. The learning material consisted of an instructional text. The text dealt with the geography, climatic characteristics, politics, culture, and language of the country Sweden. The topic was chosen since it was not part of the curriculum of these secondary students. Thus, prior knowledge was assumed to be low. The text had 672 words and was divided into five segments, which were presented on different web-pages. On average, 134.4 words were presented per segment. The participants could click on the forward or backward buttons to navigate through the web-pages. They could navigate and re-read the segments as often as they wanted. There was a finish button on the last page. Once this button had been clicked, the learning websites could no longer be accessed. The participants decided themselves how long they wanted to learn. In the computerized condition, the text was displayed in the legible font Arial. For the handwritten condition, the text was printed and traced to ensure that the size of the letters and the arrangement of the text on the page is identical. The used handwritten font was based on the standard school writing to ensure that the font clearly perceived as written by another person and disfluent but not completely illegible. A screen example of the experimental manipulation is shown in **Figure 1**.

Measures. To assess prior knowledge, five open answer questions were presented (ω = 0.37). The questions covered the spectrum of knowledge that was later included in the learning text. Students were able to get one point per question (a maximum of five points). An example was: “What is the most common animal in Sweden?”.

A knowledge test was implemented to assess learning gain. In this vein, twelve multiple-choice questions (ω = 0.41; e.g., “The neighboring countries of Sweden are...”) and four open answer questions (ω = 0.70; e.g., “What is the capital of Sweden?”) were formulated. Multiple-choice questions refer to recognizing the learning content and open answer questions refer to the reproduction of information (e.g., Atkinson and Shiffrin, 1968). The multiple-choice questions consisted of two to four possible answers. From one to all of the answer options could be correct within a question. A participant gained one point if he or she marked the correct answer option or correctly not marked a wrong answer. Participants could reach up to 41 points for the multiple choice-question test. This approach was chosen because explicitly giving points for correctly rejecting false answers reduces blind guessing and leads to higher reliability of the knowledge test (Burton, 2005). Even if reducing guessing in knowledge tests might disadvantage learners with poor metacognitive monitoring skills (Higham and Arnold, 2007), a bias was avoided because of the randomized allocation of students to the experimental groups. The open questions could always be answered with a single or a few words or numbers. A preset of possible answers was created to ensure a rating that was as objective as possible. Overall, students were able to gain a maximum of 14 points. The low reliabilities might be explained by considering item construction. The items of both learning scales were designed to assess different sub-topics. Furthermore, items had different difficulties to create a broad variance in the answer behavior of the participants. In consequence, internal-consistency was restricted.

To measure cognitive load, the scale from Leppink et al. (2014) was implemented. The questionnaire consisted of ten items. Three items measured ICL (ω = 0.77; e.g., “The subjects in the learning environment were complicated”), three items measured ECL (ω = 0.53; e.g., “The explanations in the learning environment were unclear”) and four items measured GCL (ω = 0.85; e.g., “The learning environment improved my understanding of the topic I was working on”). Students were asked to rate these items

TABLE 1 | Means and standard deviations of all dependent variables of Experiment 1.

	Disfluency			
	Fluent		Disfluent	
	M	*SD*	*M*	*SD*
Learning performance				
Recognition	30.72	3.08	33.83	2.94
Reproduction	11.62	1.59	12.87	2.09
Cognitive Load				
ICL	4.64	1.64	5.08	1.70
ECL	5.21	1.15	5.23	1.29
GCL	8.89	1.30	8.08	1.65

Note. *ICL, intrinsic cognitive load; ECL, extraneous cognitive load; GCL, germane cognitive load,* M = *mean,* SD, *standard deviation. Cognitive Load scores ranged from 0 to 10. Recognition score ranged from 0 to 41. Reproduction score ranged from 0 to 14.*

on an 11-point Likert scale ranging from "not correct at all" to "totally correct".

Procedure. The experiment was carried out in a computer lab parallel to normal school activity. Thus, the experiment was embedded in a school lesson and lasted 45 min. One class participated per experimental run (20–25 students). The working stations were prepared by opening the learning environment on the computer desktop (screen was turned off) and by placing the paper-pencil questionnaire on the desks. Students started with the paper-pencil questionnaire by completing the prior knowledge test. Afterward, the learning phase took place. Participants were instructed to turn on the monitor with the pre-opened learning material. Students read and navigated through the web pages. Finally, the dependent variables were assessed on the paper-pencil questionnaire in the following order: cognitive load, knowledge test, demographic questions.

Results

In the analyses of data, multivariate analyses of variance (MANOVAs) and univariate analyses of variance (ANOVAs) were conducted to assess differences between groups. For all variance analyses, disfluency (handwritten font vs. computerized font) was used as independent variable. Since no other variable (i.e., age, gender, prior knowledge) significantly differed among the experimental groups, no covariate was used for the analyses. Pre-defined test assumptions were only reported if significant violations occur. Descriptive results for all dependent variables are outlined in **Table 1**.

Learning Outcomes. A MANOVA was conducted with recognition (multiple-choice) and recall (open ended questions) as dependent variables. A significant main effect with a large effect size was found for disfluency; Wilk's $\Lambda = 0.70$; $F(2, 94) = 19.92$, $p < 0.001$, $\eta_p^2 = 0.30$.

Follow-up ANOVAs were conducted to get deeper insights into the significant main effect. A significant effect was found for the multiple-choice questions; $F(1, 95) = 25.80$, $p < 0.001$, $\eta_p^2 = 0.21$ and the open-ended questions; $F(1, 95) = 11.11$, $p = 0.001$, $\eta_p^2 = 0.11$. Students in the handwritten condition achieved higher learning outcomes than students in the condition with the computerized font.

Cognitive Load. A MANOVA was conducted with ICL, ECL and GCL as dependent variables. A significant main effect with a medium effect size was found for disfluency; Wilk's $\Lambda = 0.91$; $F(2, 93) = 3.09$, $p = 0.03$, $\eta_p^2 = 0.09$.

Follow up ANOVAs were conducted in order to get deeper insights into the significant main effect. A significant effect was found for GCL; $F(1, 95) = 6.11$, $p = 0.02$, $\eta_p^2 = 0.06$. Students in the handwritten condition reported a higher GCL than students in the condition with the computerized font. No effects could be found with regard to ICL; $F(1, 95) = 1.48$, $p = 0.23$, $\eta_p^2 = 0.02$ and ECL; $F(1, 95) = 0.01$, $p = 0.93$, $\eta_p^2 < 0.001$.

Discussion

This first exploratory experiment was carried out to investigate the effects of a handwritten font in contrast to a computerized font. Results partly support the disfluency effect, since learning outcomes as well as active, generative processing were enhanced in the handwritten (disfluent) condition. This might be a first hint that using a handwritten font in educational settings can foster learning processes. In particular, when students are familiar with handwritten fonts (Ito et al., 2020) and if the degree of disfluency in handwritten fonts is rather low (Geller et al., 2018), handwritten fonts can foster learning. Since 5th and 6th graders often study with handwritten texts, disfluency through handwritten fonts can be effectively included in learning materials. Nevertheless, several limitations have to be discussed.

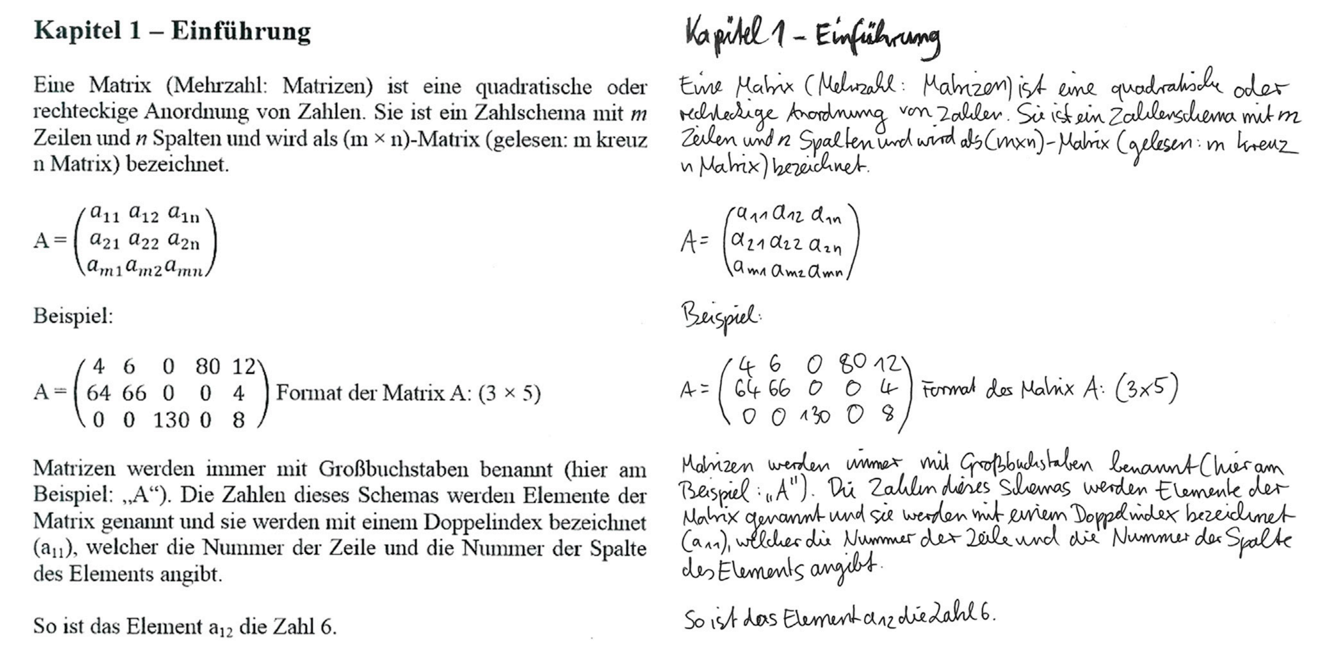
First, because of the exploratory nature of the study, several process variables were not assessed. Thus, no statements about metacognitive or social variables can be postulated. Furthermore, no effect regarding ECL could be observed. An explanation is the use of the CL questionnaire. ECL was assessed with items like "The explanations in the learning environment were unclear." Thus, the scale was rather misleading and did not cover ECL regarding the used test font. Additionally, reliabilities of the multiple-choice questionnaire and the ECL subscale was rather low. Thus, results have to be interpreted with caution and might be explained by methodical flaws. Additionally, more data was necessary to generalize the findings across other knowledge domains and other study samples. Nevertheless, these first exploratory results were encouraging. In order to resolve the methodological problems of Experiment 1, two additional experiments were carried out.

In Experiment 2 and 3, the disfluency effect was investigated with a student sample to increase generalizability of the results. Furthermore, the learning topics were changed in the following two experiments. In Experiment 2, a mathematical topic and in Experiment 3, a natural-scientific topic was used as learning material.

EXPERIMENT 2

Methods

Participants and Design. Concerning the power-analysis conducted in Experiment 1, the acquisition of 102 participants



Kapitel 1 – Einführung

Eine Matrix (Mehrzahl: Matrizen) ist eine quadratische oder rechteckige Anordnung von Zahlen. Sie ist ein Zahlschema mit m Zeilen und n Spalten und wird als (m × n)-Matrix (gelesen: m kreuz n Matrix) bezeichnet.

$$A = \begin{pmatrix} a_{11} & a_{12} & a_{1n} \\ a_{21} & a_{22} & a_{2n} \\ a_{m1} & a_{m2} & a_{mn} \end{pmatrix}$$

Beispiel:

$$A = \begin{pmatrix} 4 & 6 & 0 & 80 & 12 \\ 64 & 66 & 0 & 0 & 4 \\ 0 & 0 & 130 & 0 & 8 \end{pmatrix} \text{ Format der Matrix A: } (3 \times 5)$$

Matrizen werden immer mit Großbuchstaben benannt (hier am Beispiel: „A“). Die Zahlen dieses Schemas werden Elemente der Matrix genannt und sie werden mit einem Doppelindex bezeichnet (a_{11}), welcher die Nummer der Zeile und die Nummer der Spalte des Elements angibt.

So ist das Element a_{12} die Zahl 6.

FIGURE 2 | Screen example of the learning material of Experiment 2 (left: fluent; right: disfluent).

was aimed for. One hundred and five participants (78.1% female; age: M = 23.81, SD = 10.25) participated in the experiment. Participants were university students from the XXXX. Students were enrolled in media communications (73.5%), instructional psychology (22.5%), and other fields of study (3.9%). Students got a 1-h course credit or 5€ as a reward for participating. Prior knowledge of the participants (M = 0.49, SD = 0.68; with a maximum of five points) was low.

The participants were randomly assigned to one of two experimental conditions (handwritten font vs. computerized font) of a between-subjects design by an online randomization software. Forty-seven students were assigned to the condition with handwritten font and 58 students were assigned to the condition with the computerized font. For the experimental conditions, no significant differences existed in terms of gender and field of study, χ^2 = [0.11, 0.33]; p = [0.74, 0.85]. There were significant differences in terms of age, $t(103) = 2.31$; $p = 0.02$ and prior knowledge, $t(103) = 2.12$; $p = 0.04$ indicating that participants in the handwritten condition were younger and had more prior knowledge. Thus, age, as well as prior knowledge, were included as covariates in all analyses.

Materials. The learning material consisted of an instructional text which dealt with matrix calculation. Again, the topic was chosen, since prior knowledge of the participants was considered low. Furthermore, the change of subject might show to what extent the results of Experiment 1 can be generalized. The text had 725 words and was divided into eleven segments, which were presented on different pages. On average, 68.4 words were presented per segment. The material did not only consist of the instructional text. Mathematical formulas were presented to illustrate exemplary calculations. The participants could click on the forward or backward buttons to navigate through the websites. They could navigate and re-read the segments as often as they wanted and there was a finish button on the last page. Once this button had been clicked, the websites could no longer be accessed. The participants decided themselves how long they wanted to learn. In the computerized condition, the text was displayed in the legible font Times New Roman. For the handwritten condition, the text was printed and traced to ensure that the size of the letters and the arrangement of the text on the page is identical. A screen example of the experimental manipulation is shown in **Figure 2**.

Measures. To assess prior knowledge ($\omega = 0.62$), six open answer questions were presented. Because of the low inter-rater reliability, one item was excluded from the analyses (new reliability: $\omega = 0.68$). The questions covered the spectrum of knowledge that was later included in the learning text. Students were able to get one point per question (a maximum of five points). An example was: “How do you multiply matrices?”. Inter-rater reliability of two independent rater with regard to the remaining five items was high, ICC (1, k) = [0.35, 0.96], F(104, 104) = [2.10, 47.85], $p < 0.001$.

A knowledge test was implemented to assess learning gain. In this vein, eight multiple-choice (retention) questions ($\omega = 0.58$; e.g., “What is a vector?”) and seven arithmetic (transfer) problems ($\omega = 0.52$; e.g., “Multiply the following vectors”) were formulated. Retention, as well as transfer, was measured to get a deeper insight into rather basal and more complex learning processes. According to Mayer (2014), retention can be defined as “remembering” content, which has been explicitly presented in an instructional text. Transfer knowledge is defined as “understanding.” The learners had to solve novel problems that were not explicitly presented in the instructional text by using the acquired knowledge (Mayer, 2014). The multiple-choice questions were designed as in Experiment 1. Participants could reach up to 32 points. The arithmetic problems had to be solved and calculated by the participants without additional tools. Students could reach one point per correct solution. Overall, students were able to gain a maximum of seven points.

In contrast to Experiment 1, cognitive load was measured with the questionnaire from Klepsch et al. (2017), which was chosen because the ECL subscale explicitly refers to recognition of information. Furthermore, the scale was found to be valid in various learning situations (Klepsch and Seufert, 2020). Two items measured ICL (ω = 0.84; e.g., "This task was very complex"). Three items measured ECL (ω = 0.78; e.g., "During this task, it was exhausting to find the important information"). Theoretically, germane processes (GCL) are subsumed under the facet of ICL (two-factor model; Jiang and Kalyuga, 2020). In the used questionnaire, ICL items rather refer to the complexity of the learning material and GCL items refer to active processing and mental effort (Klepsch et al., 2017). Thus, the GCL facet of the questionnaire was included separately. Two items measured germane processes (ω = 0.75; e.g., "My point while dealing with the task was to understand everything correct"). The participants had to rate the items on a 7-point Likert scale ranging from 1 (completely wrong) to 7 (completely correct).

The procedure for assessing metacognitive judgments and metacognitive accuracy was based on Pieger et al. (2016). Ease of learning (EOL) was measured by the question, "How easy or difficult will it be to learn the text?" on a scale from 0 (very difficult) to 100 (very easy). Judgments of learning (JOL) were measured twice, to assess if they could answer retention questions ("What percentage of the questions about the text will you answer correctly?") and solve arithmetic problems (transfer performance; "What percentage of the arithmetic problems will you solve correctly?") on a scale from 0 (no questions) to 100 (all questions). Retrospective confidence (RC) was measured by the question, "How confident are you that your answer is correct?" on a scale from 0 (unconfident) to 100 (confident). In line with the JOL questions, RC questions were implemented after the retention as well as transfer questionnaire. Metacognitive accuracy was calculated as absolute. The five metacognition scores (EOL, JOL [retention and transfer], and RC ratings [retention and transfer]) and the learning scores were z-standardized prior to analyses. Z-standardization was carried out for the whole sample in order to examine differences in metacognitive judgments and their relation to performance between the experimental groups. For the absolute accuracy calculation, the performance scores were subtracted from the five metacognition scores (Pieger et al., 2016). Non-standardized accuracy scores (differences between judgments and performance) can be found in **Supplementary Appendix B**.

Finally, the learning time in seconds and navigation (the number of switches between the web-pages) were tracked to get insight into the learning behavior of the participants. Concerning learning time, an efficiency score was conducted based on the formula from Van Gog and Paas (2008).

$$Efficiency = \frac{zP - zT}{\sqrt{2}}$$

TABLE 2 | Means and standard deviations of all dependent variables of Experiment 2.

	Disfluency			
	Fluent		Disfluent	
	M	*SD*	*M*	*SD*
Learning performance				
Retention	23.05	3.60	19.96	4.41
Transfer	3.71	1.42	3.76	1.45
Cognitive Load				
ICL	7.35	3.08	7.22	3.21
ECL	6.95	4.28	7.96	4.88
GCL	5.24	1.47	5.43	1.25
Metacognition				
EOL	49.60	25.16	52.40	24.88
JOL (retention)	51.45	20.77	54.22	20.50
JOL (transfer)	55.45	20.53	57.11	22.83
RC (retention)	41.45	20.85	42.67	24.53
RC (transfer)	40.18	26.84	45.33	28.25
EOL accuracy (retention)	0.38	0.96	−0.47	1.50
EOL accuracy (transfer)	0.04	1.30	−0.04	1.36
JOL accuracy (retention)	0.39	1.15	−0.48	1.41
JOL accuracy (transfer)	0.05	1.32	0.01	1.00
RC accuracy (retention)	0.36	1.00	−0.43	1.33
RC accuracy (transfer)	0.08	1.14	−0.08	0.96
Learning behavior				
Learning time	484.73	154.03	574.22	202.16
Efficiency (time–retention)	0.38	0.71	−0.45	1.18
Efficiency (time–transfer)	0.13	0.85	−0.16	1.03
Navigation	18.02	8.79	22.84	13.69

Note. *ICL, intrinsic cognitive load; ECL, extraneous cognitive load; GCL, germane cognitive load; EOL, ease of learning; JOL, judgement of learning; RC, retrospective confidence,* M = *mean,* SD, *standard deviation. Cognitive Load scores ranged from 1 to 7. Metacognitive Scores ranged from1 to 101. Retention score ranged from 0 to 32. Transfer score ranged from 0 to 7.*

For *p*, performance scores (retention and transfer) were included and T was the learning time. Learning time as well as performance scores were z-standardized. Efficiency was calculated for retention and transfer performance separately.

Procedure. A computer laboratory at the university with ten identical computers was prepared before each experimental session. The online questionnaire was pre-opened at each workstation. Up to ten participants were tested simultaneously. Sight-blocking partition walls were used to ensure that the students worked independently. At the beginning of the experiment, the participants were told that the experiment was an instructional study on a science topic and were asked to answer the prior knowledge test. Then, they were given the link to the learning material and asked to take a preliminary look at the learning environment and the learning text. After 2 seconds, the participants were automatically redirected to a questionnaire and had to evaluate the EOL item. The learning phase then began. The students had to learn the material at their own pace. They were able to navigate freely between the individual learning segments. When they had finished the learning phase, the students had to rate two JOL items. They should predict how many questions they could possibly answer correctly (retention) and how many arithmetic problems they could possibly solve (transfer). Further, dependent variables were measured after finishing the learning phase. At the beginning of this questionnaire, the cognitive load was assessed. Afterward, retention and transfer were measured. One RC item had to be answered after the retention test and on RC item had to be answered after the transfer test. Finally, the students had to answer a demographic questionnaire. When all the tests had been completed, the participants could leave the room. The experiment lasted a total of 45 min.

Results

In the analyses of data, multivariate analyses of covariance (MANCOVAs) and univariate analyses of covariance (ANCOVAs) were conducted to assess differences between groups. For all variance analyses, disfluency (handwritten font vs. computerized font) was used as the independent variable. Age and prior knowledge were used as covariates in all analyses since these variables significantly differed between the experimental groups. Pre-defined test assumptions were only reported if significant violations occur. Descriptive results for all dependent variables are outlined in **Table 2**.

Learning Outcomes. A MANCOVA was conducted with retention (multiple-choice) and transfer (arithmetic problems) as dependent variables. Prior knowledge; Wilk's $\Lambda = 0.90$; $F(2, 100) = 5.49$, $p = 0.01$, $\eta_p^2 = 0.10$ but not age; Wilk's $\Lambda = 0.99$; $F(2, 100) = 0.34$, $p = 0.71$, $\eta_p^2 = 0.01$ was a significant covariate. A significant main effect with a large effect size was found for disfluency; Wilk's $\Lambda = 0.84$; $F(2, 100) = 9.77$, $p < 0.001$, $\eta_p^2 = 0.16$. Follow up ANCOVAs revealed a significant effect for retention; $F(1, 101) = 19.67$, $p < 0.001$, $\eta_p^2 = 0.16$ but not for transfer; $F(1, 101) = 0.18$, $p = 0.67$, $\eta_p^2 = 0.002$. In contrast to Experiment 1 students in the computerized font condition achieved higher retention outcomes than students in the condition with the handwritten font.

Cognitive Load. A MANCOVA was conducted with ICL, ECL, and GCL as dependent variables. Neither prior knowledge; Wilk's $\Lambda = 0.98$; $F(3, 99) = 0.78$, $p = 0.51$, $\eta_p^2 = 0.02$ nor age; Wilk's $\Lambda = 0.99$; $F(3, 99) = 0.33$, $p = 0.80$, $\eta_p^2 = 0.01$ were significant covariates. No main effect was found for disfluency; Wilk's $\Lambda = 0.98$; $F(3, 99) = 0.82$, $p = 0.82$, $\eta_p^2 = 0.02$.

Metacognition. A MANCOVA was conducted with EOL, JOL (retention and transfer), and RC (retention and transfer) as dependent variables. Prior knowledge; Wilk's $\Lambda = 0.80$; $F(5, 95) = 4.73$, $p = 0.001$, $\eta_p^2 = 0.20$ but not age; Wilk's $\Lambda = 0.97$; $F(5, 95) = 0.55$, $p = 0.74$, $\eta_p^2 = 0.03$ was a significant covariate. No main effect was found for disfluency; Wilk's $\Lambda = 0.99$; $F(5, 95) = 0.24$, $p = 0.95$, $\eta_p^2 = 0.01$.

After analyzing metacognitive measures, metacognitive accuracy scores were investigated. At first, absolute metacognitive accuracy with regard to retention performance was analyzed. A MANCOVA was conducted metacognitive accuracy scores (EOL, JOL [retention], and RC [retention]) as dependent variables. Neither prior knowledge; Wilk's $\Lambda = 0.98$; $F(3, 97) = 0.55$, $p = 0.65$, $\eta_p^2 = 0.02$ nor age; Wilk's $\Lambda = 0.98$; $F(3, 97) = 0.81$, $p = 0.49$, $\eta_p^2 = 0.02$ were significant covariates. A significant main effect with a large effect size was found for disfluency; Wilk's $\Lambda = 0.86$; $F(3, 97) = 5.34$, $p = 0.002$, $\eta_p^2 = 0.14$. Follow up ANCOVAs revealed a significant effect for all accuracy scores; $F(1, 99) = [10.13, 12.20]$, $p = [0.001, 0.002]$, $\eta_p^2 = [0.09, 0.11]$. Students in the computerized condition had positive accuracy scores whereas students in the handwritten condition had negative scores. *T*-tests against zero revealed that students in the computerized condition overestimated their performance regarding all accuracy scores; $t(57) = [2.66–3.22]$, $p = [0.001–0.005]$, $d = [0.35–0.43]$. Students in the handwritten condition underestimated their performance with regard to all accuracy scores; $t(46) = [-2.27–-2.41]$, $p = [0.02–0.03]$, $d = [-0.34–-0.35]$. Second, absolute metacognitive accuracy with regard to transfer performance was analyzed. A MANCOVA was conducted metacognitive accuracy scores (EOL, JOL [transfer], and RC [transfer]) as dependent variables. Neither prior knowledge; Wilk's $\Lambda = 0.95$; $F(3, 97) = 1.84$, $p = 0.15$, $\eta_p^2 = 0.05$ nor age; Wilk's $\Lambda = 0.99$; $F(3, 97) = 0.44$, $p = 0.73$, $\eta_p^2 = 0.01$ were significant covariates. No main effect was found for disfluency; Wilk's $\Lambda = 0.99$; $F(3, 97) = 0.20$, $p = 0.90$, $\eta_p^2 = 0.01$.

Learning Time and Navigation. A MANCOVA was conducted with learning time and navigation as dependent variables. Neither prior knowledge; Wilk's $\Lambda = 0.98$; $F(3, 97) = 1.84$, $p = 0.15$, $\eta_p^2 = 0.05$ nor age; Wilk's $\Lambda = 0.99$; $F(3, 97) = 0.44$, $p = 0.73$, $\eta_p^2 = 0.01$ were significant covariates. A significant main effect with a small to medium effect size was found for disfluency; Wilk's $\Lambda = 0.93$; $F(3, 97) = 3.67$, $p = 0.03$, $\eta_p^2 = 0.07$. Follow up ANCOVAs were conducted in order to get deeper insights into the significant main effect. A significant effect was found for learning time; $F(1, 98) = 6.70$, $p = 0.01$, $\eta_p^2 = 0.06$. Students in the handwritten condition learned longer than students in the condition with the computerized font. A significant effect was found for navigation; $F(1, 98) = 4.72$, $p = 0.03$, $\eta_p^2 = 0.05$. Students in the handwritten condition navigated more often through the websites than students in the condition with the computerized font.

To analyze learning efficiency, a MANCOVA was conducted with learning efficiency with respect to retention and transfer as dependent variables. Prior knowledge; Wilk's $\Lambda = 0.90$; $F(2, 97) = 5.35$, $p = 0.01$, $\eta_p^2 = 0.10$ but not age; Wilk's $\Lambda = 0.99$; $F(2, 97) = 0.33$, $p = 0.72$, $\eta_p^2 = 0.01$ was a significant covariate. A significant main effect with a large effect size was found for disfluency; Wilk's $\Lambda = 0.80$; $F(2, 97) = 11.98$, $p < 0.001$, $\eta_p^2 = 0.20$. Follow up ANCOVAs showed a significant effect for retention efficiency; $F(1, 98) = 24.03$, $p < 0.001$, $\eta_p^2 = 0.20$. Students in the computerized condition had a higher efficiency than students in the condition with the handwritten font. A significant effect was found for transfer efficiency; $F(1, 98) = 4.99$, $p = 0.03$, $\eta_p^2 = 0.05$. Students in the computerized condition had a higher efficiency than students in the condition with the handwritten font.

Discussion

The second experiment was carried out to shed more light on the emergence of a potential disfluency effect. Interestingly, the results of Experiment 1 could not be replicated. In Experiment 1, learning scores as well as GCL was enhanced in the disfluent condition. These results were in line with the disfluency effect. In contrast, results of Experiment 2 mostly contradicted the disfluency effect. Students in the disfluent (handwritten) condition achieved worse retention outcomes and related to the learning time, students in the disfluent condition had lower accuracy scores than students in the fluent condition. No main effects of the metacognitive monitoring scores could be obtained but metacognitive accuracy scores showed that participants in the disfluent condition underestimated their learning skills at the beginning, during, and after learning. A disfluent font might discourage learners to invest effort into schema construction. Learners were discouraged by encoding this illegible information and consequently, learners might invest less effort into learning because they rated their learning success too low compared to their abilities. Learners were less focused which might lead to longer learning time and the need for additional navigation. This interpretation contradicts the common explanation of the disfluency effect pointing out that using disfluent fonts encourages learners to invest more effort and to use more elaborated learning strategies (Alter et al., 2007). Another explanation would be that, in line with common explanations, learners were encouraged to invest more effort in encoding the font because they realized that there might be a gap between the learning task and their cognitive skills. Though, the additional effort which was invested in encoding consumed too many cognitive resources and not enough resources for schema construction left. Nevertheless, students did not benefit from their additional study time which can be interpreted as a labor-in-vain effect (Nelson and Leonesio, 1988). In line with Experiment 1, no effects regarding ECL could be found. Cognitive effects were more likely to be unconscious or the findings cannot be explained explicitly concerning cognitive variables.

The differences between the results from Experiment 1 and 2 and the pre-study might be explained considering the new learning material. In Experiment 1, a learning material with comparative low element interactivity was used. Information could be learned, recalled, and applied without considering other information from the material. Furthermore, the information was rather surface knowledge since it was adapted to younger learners. The material might be so easy that learners were not engaged. The disfluent font made learners an effort to learn the material whereas students in the computerized condition did not invest many resources in learning the material and the disfluency effect occurred. In Experiment 2, the material was complex and had a high element interactivity. The presentation of this material in a disfluent font overtaxed learners because they have already invested a lot of resources in learning the complex content. The overtaxed learners underestimated their performance and did not compensate for the negative effects of the font through an adequate effort in learning. Altogether, using a disfluent font led to unfavorable learning conditions and learning behavior.

Overall, Experiment 1 and 2 pointed out that there might be no general disfluency effect. Boundary conditions seemed to determine if a handwritten text font has rather positive or negative effects on learning. Furthermore, social effects of handwritten learning material were not investigated in the first two experiments. In consequence, a third experiment was carried out 1) to investigate social variables in addition to cognitive and metacognitive variables, 2) to get additional insights in causal indirect effects on learning by conducting mediation analyses with these multidisciplinary process variables, and 3) to further investigate the influence of element interactivity on learning with disfluent material. Since Experiment 1 used low-interactivity material and Experiment 2 used high-element interactivity material, an instructional text with medium element interactivity was used as learning material.

EXPERIMENT 3

Methods

Participants and Design. Again, the acquisition of 102 participants was aimed for. One hundred and three participants (74.8% female; age: M = 22.71, SD = 2.97) participated in the experiment. Participants were university students from the XXXX. Students were enrolled in media communications (58.3%), instructional psychology (32.0%), and other fields of study (9.7%). Students got a 1-h course credit or they took part in a raffle for a 20€ voucher. Prior knowledge of the participants (M = 0.50, SD = 1.04; with a maximum of thirteen points) was low.

The participants were randomly assigned to two experimental conditions (handwritten font vs. computerized font) of a between-subjects design by an online randomization software. Fifty-seven students were assigned to the condition with handwritten font and 46 students were assigned to the condition with computerized font. For the experimental conditions, no significant differences existed in terms of gender and field of study, χ^2 = [0.03, 1.54]; p = [0.46, 0.86] as well as age and prior knowledge; $t(101)$ = [0.29, 1.03]; p = [0.31, 0.78]. In consequence, no covariates had to be included in further analyses.

Materials. The learning material consisted of an instructional text. The text dealt with the chemical process of pyrolysis. The topic was chosen since prior knowledge of the participants was considered low. The element interactivity of the material was higher than in Experiment 1 since not only basal facts that did not depend on each other were taught. The element interactivity of the material was further not as high as in Experiment 2 since single paragraphs displayed information that depends on each other but subtopics were self-contained. In Experiment 2, all information was necessary to understand the learning material to the end. Consequently, in comparison to Experiment 1 and 2, the material of Experiment 3 had a medium element interactivity. The text had 676 words and was divided into ten segments which were presented on different pages. On average, 67.7 words were presented per segment. The material did not only consist of an instructional text. One table (summarizing information about the different types of pyrolysis) and one figure (illustrating the yield of ethylene) were additionally included in the learning material. The participants could click on the forward button to navigate through the websites and there was a finish button on the last page. Once this button had been clicked, the websites could no longer be accessed. The participants decided how long they wanted to learn themselves. In the computerized condition, the text was displayed in the legible font Arial. For the handwritten condition, the text was printed and traced to ensure that the size of the letters and the arrangement of the text on the page is identical. A screen example of the experimental manipulation is shown in **Figure 3**.

Measures. To assess prior knowledge (ω = 0.71), three open answer and three single choice questions were presented. The questions covered the spectrum of knowledge that was later included in the learning text. Students were able to get three

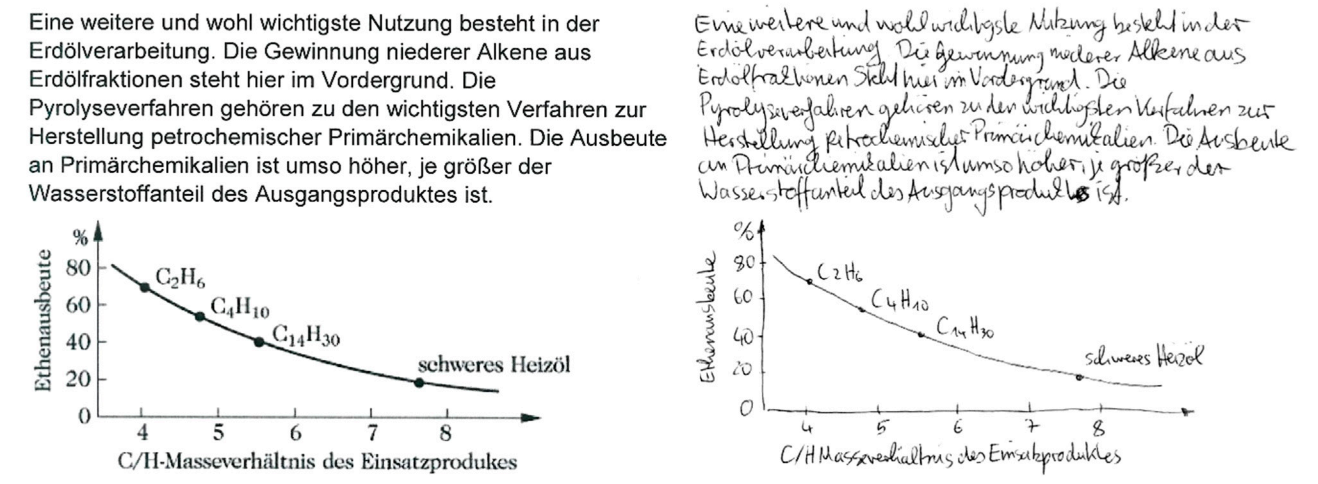


FIGURE 3 | Screen example of the learning material of Experiment 3 (left: fluent; right: disfluent).

to four points per open answer question and one point per single choice question (a maximum of thirteen points). An example was: "Where is pyrolysis used in practice?". Inter-rater reliability of two independent rater with regard to the three open answers was high, ICC (1, k) = [0.55, 0.79], $F(102, 102) = [3.51, 8.52]$, $p < 0.001$ or perfect (ICC = 1).

A knowledge test was implemented to assess learning gain. In this vein, a retention test (ω = 0.65; e.g., "What characterizes the thermo-chemical process of pyrolysis?") consisting of eight multiple-choice questions and two open-answer questions, as well as a transfer test (ω = 0.65; e.g., "please specify, if the following chemical equations are a pyrolysis. Please substantiate your decision") consisting of two multiple-choice questions and five open-answer questions was implemented. The scoring of the multiple-choice questions was similar to Experiment 1 and 2. For the open-answer questions, participants had to remember information that was explicitly in the text (retention) or decide if presented chemical equations are a pyrolysis and explain their decision (transfer). Inter-rater reliability of two independent rater and the three open-answer questions was high, ICC (1, k) = [0.77, 0.94], $F(102, 102) = [8.85, 34.27]$, $p < 0.001$. In sum, students were able to gain 67 points for retention and 18 points for transfer.

Measurement of cognitive load (ICL: ω = 0.71; ECL: ω = 0.83; GCL: ω = 0.63), metacognitive variables and learning time was nearly identical to Experiment 2. The only difference from Experiment 2 is that only one JOL and RC score was assessed after learning phase, since no arithmetic problems had to be solved. Again, non-standardized accuracy scores are displayed in **Supplementary Appendix B**.

In addition to Experiment 2, social presence (ω = 0.73) was measured with a self-created scale based on a scale from Bailenson et al. (2004). Five items (e.g., "The text was impersonal") measured if the participants had the subjective feeling of a social context. Students had to rate the items on a 7-point Likert scale ranging from 1 (absolutely wrong) to 7 (absolutely correct).

TABLE 3 | Means and standard deviations of all dependent variables of Experiment 3.

	Disfluency			
	Fluent		Disfluent	
	M	*SD*	*M*	*SD*
Learning performance				
Retention	25.64	3.78	25.16	5.18
Transfer	8.51	3.11	9.50	2.92
Cognitive Load				
ICL	4.33	1.54	4.27	1.57
ECL	4.55	1.62	5.39	1.43
GCL	4.08	1.08	4.23	1.22
Metacognition				
EOL	44.07	22,76	20.40	16.56
JOL	41.77	18.75	35.19	20.07
RC	30.42	19.15	29.16	19.68
EOL accuracy (retention)	–0.37	0.89	0.29	0.81
EOL accuracy (transfer)	–0.53	0.99	0.44	0.81
JOL accuracy (retention)	–0.10	0.75	0.07	0.70
JOL accuracy (transfer)	–0.26	0.77	0.21	0.83
RC accuracy (retention)	0.01	0.72	–0.01	0.64
RC accuracy (transfer)	–0.15	0.70	0.13	0.74
Learning behavior				
Learning time	375.75	164.66	473.42	290.46
Efficiency (time–retention)	0.19	0.67	–0.17	0.61
Efficiency (time–transfer)	0.03	0.87	–0.02	0.94
Social Presence	3.19	0.98	4.37	1.18

Note. *ICL, intrinsic cognitive load; ECL, extraneous cognitive load; GCL, germane cognitive load; EOL, ease of learning; JOL, judgement of learning; RC, retrospective confidence,* M = *mean,* SD, *standard deviation. Cognitive Load scores and Social Presence ranged from 1 to 7. Metacognitive Scores ranged from1 to 101. Retention score ranged from 0 to 67. Transfer score ranged from 0 to 18.*

Procedure. The procedure was largely identical to the procedure of Experiment 2. The only difference was that the experiment was completely carried out online. In line with Experiment 2, students 1) were instructed, 2) answered the prior knowledge questions, 3) completed the learning phase and the metacognitive items, 4) completed the questionnaire concerning the dependent and demographic variables. The experiment lasted a total of 45 min.

Results

In the analyses of data, multivariate analyses of variance (MANOVAs) and univariate analyses of variance (ANOVAs) were conducted to assess differences between groups. Furthermore, mediation analyses were conducted to get a deeper insight into the causal processes during learning. Mediator analyses were carried out using PROCESS (Model 4; Hayes, 2017) with a bootstrap-sample of $N = 5{,}000$. For all variance analyses, disfluency (handwritten font vs. computerized font) was used as the independent variable. No covariates were used. Pre-defined test assumptions were only reported if significant violations occur. Descriptive results for all dependent variables are outlined in **Table 3**.

Learning Outcomes. A MANOVA was conducted with retention and transfer as dependent variables. No main effect could be found for disfluency; Wilk's $\Lambda = 0.97$; $F(2, 99) = 1.71$, $p = 0.19$, $\eta_p^2 = 0.03$.

Cognitive Load. A MANOVA was conducted with ICL, ECL, and GCL as dependent variables. A significant main effect with a medium effect size was found for disfluency; Wilk's $\Lambda = 0.89$; $F(3, 99) = 4.10$, $p = 0.01$, $\eta_p^2 = 0.11$.

A follow up ANOVA revealed a significant effect for ECL; $F(1, 101) = 8.51$, $p = 0.004$, $\eta_p^2 = 0.08$. Participants in the handwritten font condition reported a higher ECL than students in the computerized condition. No effects were found regarding ICL; $F(1, 101) = 0.01$, $p = 0.92$, $\eta_p^2 < 0.001$ and GCL; $F(1, 101) = 0.12$, $p = 0.73$, $\eta_p^2 = 0.001$.

Metacognition. A MANOVA was conducted with EOL, JOL, and RC as dependent variables. A significant main effect with a high effect size was found for disfluency; Wilk's $\Lambda = 0.71$; $F(3, 99) = 13.21$, $p < 0.001$, $\eta_p^2 = 0.29$.

A follow up ANOVA revealed a significant effect for EOL; $F(1, 101) = 38.051$, $p < 0.001$, $\eta_p^2 = 0.27$. Participants in the handwritten font condition reported a lower EOL (harder to learn) than students in the computerized condition. No effects were found regarding JOL; $F(1, 101) = 3.42$, $p = 0.07$, $\eta_p^2 = 0.03$ and RC; $F(1, 101) = 0.26$, $p = 0.61$, $\eta_p^2 = 0.003$.

At first, absolute metacognitive accuracy with regard to retention performance was analyzed. A MANOVA was conducted metacognitive accuracy scores (EOL, JOL, and RC) as dependent variables. A significant main effect with a large effect size was found for disfluency; Wilk's $\Lambda = 0.85$; $F(3, 94) = 5.69$, $p = 0.001$, $\eta_p^2 = 0.15$. Follow up ANOVAs revealed a significant effect for EOL accuracy; $F(1, 96) = 12.20$, $p = 0.002$, $\eta_p^2 = 0.11$. In contrast to Experiment 2, students in the computerized condition had negative accuracy scores whereas students in the handwritten condition had positive scores. T-tests against zero indicated that students in the computerized condition underestimated their performance; $t(44) = -2.55$, $p = 0.01$, $d = -0.38$ whereas students in the handwritten condition overestimated their performance; $t(52) = 2.62$, $p = 01$, $d = 0.36$. No differences regarding JOL accuracy; $F(1, 96) = 1.01$, $p = 0.32$, $\eta_p^2 = 0.01$ and RC accuracy; $F(1, 96) = 0.05$, $p = 0.82$, $\eta_p^2 = 0.001$ could be observed.

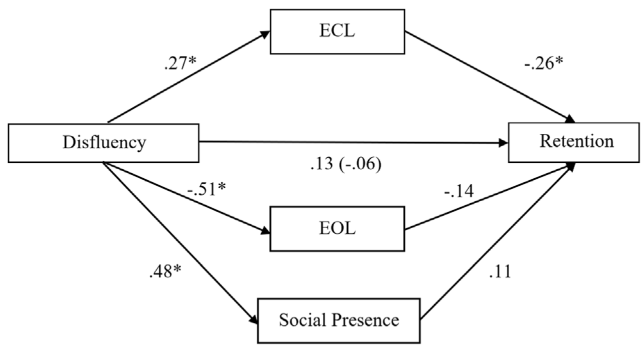


FIGURE 4 | Indirect influence of disfluency on retention (β values are displayed; *p < 0.05); Mediators: ECL (extraneous cognitive load), EOL (ease of learning), social presence.

Second, absolute metacognitive accuracy with regard to transfer performance was analyzed. A MANOVA was conducted metacognitive accuracy scores (EOL, JOL, and RC) as dependent variables. A significant main effect with a large effect size was found for disfluency; Wilk's $\Lambda = 0.77$; $F(3, 93) = 9.47$, $p < 0.001$, $\eta_p^2 = 0.23$. Follow up ANOVAs revealed a significant effect for EOL accuracy; $F(1, 95) = 27.84$, $p < 0.001$, $\eta_p^2 = 0.23$ and JOL accuracy; $F(1, 95) = 8.15$, $p = 0.01$, $\eta_p^2 = 0.08$. Again, t-tests against zero indicated that students in the computerized condition underestimated their performance; $t[43, 44] = [-3.55, -2.19]$, $p = [<0.001, 0.03]$, $d = [-0.54, -0.33]$ whereas students in the handwritten condition overestimated their performance; $t(52) = [1{,}87, 3.91]$, $p = [< 001, 0.03]$, $d = [0.26, 0.58]$. No effect could be found for RC accuracy; $F(1, 95) = 3.51$, $p = 0.06$, $\eta_p^2 = 0.04$ but descriptively, the direction of the effect is similar.

Learning Time. Levene's test indicated unequal variances; $F(1, 101) = 7.44$, $p = 0.01$. Thus, an U test was conducted. No effect for disfluency could be found; $U = 1{,}201.50$, $p = 0.47$.

To analyze learning efficiency, a MANOVA was conducted with learning efficiency with respect to retention and transfer as dependent variables. A significant main effect with a medium effect size was found for disfluency; Wilk's $\Lambda = 0.91$; $F(2, 94) = 4.40$, $p = 0.02$, $\eta_p^2 = 0.09$. Follow up ANOVAs were conducted in order to get deeper insights into the significant main effect. A significant effect was found for retention efficiency; $F(1, 95) = 7.53$, $p = 0.01$, $\eta_p^2 = 0.07$. Students in the computerized condition had a higher efficiency than students in the condition with the handwritten font. No effect was found for transfer efficiency; $F(1, 95) = 0.08$, $p = 0.78$, $\eta_p^2 = 0.001$.

Social Presence. An ANOVA was conducted with social presence as dependent variable. A significant effect with a large effect size was found for disfluency; $F(1, 101) = 29.12$, $p < 0.001$, $\eta_p^2 = 0.22$. Students in the handwritten font condition reported higher presence scores than students in the computerized condition.

Mediation Models. Mediation models were conducted to get deeper insights into how cognitive, metacognitive, and social

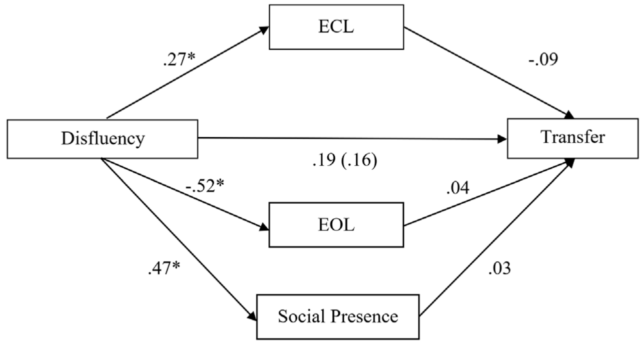


FIGURE 5 | Indirect influence of disfluency on transfer (β values are displayed; *$p < 0.05$); Mediators: ECL (extraneous cognitive load), EOL (ease of learning), social presence.

variables influence learning with disfluent material. Concerning the previous findings, ECL, EOL, and social presence were used as mediators and learning outcomes (retention and transfer) were used as dependent variables. All variables were z-standardized.

For retention as dependent variable (see **Figure 4**), the mediator analysis showed no significant direct effect of disfluency on retention (β = –0.06; *SE* = 0.10; $p = 0.54$). When ECL, EOL and social presence were considered as mediator, this effect remained non-significant (β = 0.13; *SE* = 0.13; $p = 0.32$). As already outlined, using a handwritten font instead of a computerized font led to a higher ECL (β = 0.27; *SE* = 0.10; $p = 0.01$), a lower EOL (β = –0.51; *SE* = 0.09; $p < 0.001$) and a higher social presence (β = 0.48; *SE* = 0.09; $p < 0.001$). ECL had a negative impact on retention (β = –0.26; *SE* = 0.11; $p = 0.02$). Social presence (β = –0.14; *SE* = 0.12; $p = 0.23$) and EOL (β = 0.11; *SE* = 0.12; $p = 0.39$) had no impact on retention performance.

For transfer as dependent variable (see **Figure 5**), the mediator analysis showed no significant direct effect of disfluency on retention (β = 0.16; *SE* = 0.10; $p = 0.11$). When ECL, EOL and social presence were considered as mediator, this effect remained non-significant (β = 0.19; *SE* = 0.14; $p = 0.16$). As already outlined, using a handwritten font instead of a computerized font led to a higher ECL (β = 0.27; *SE* = 0.10; $p = 0.01$), a lower EOL (β = –0.52; *SE* = 0.09; $p < 0.001$) and a higher social presence (β = 0.47; *SE* = 0.09; $p < 0.001$). ECL (β = –0.09; *SE* = 0.12; $p = 0.43$), social presence (β = 0.03; *SE* = 0.12; $p = 0.22$), and EOL (β = 0.04; *SE* = 0.13; $p = 0.77$) had no impact on transfer performance.

Discussion

Again, the results are rather ambiguous. In contrast to the previous experiments but in line with the hypotheses, a handwritten font increased ECL. Nevertheless, in Experiment 3, no main effect on learning could be observed but related to the learning time, students in the disfluent condition had a lower retention efficiency (but not transfer efficiency) than students in the fluent condition. Furthermore, in contrast to Experiment 2, participants in the disfluent condition overestimated their learning skills at the beginning and during learning. Even if learners in the disfluent condition had a higher EOL they did not metacognitively adapt their learning strategy to the increased demand through the illegible font. Furthermore, the experienced ECL might have such negative effects that the adaptation was insufficient. An additional hint for this explanation can be derived from the mediation analyses. Even if the mediation analyses detected no direct effect, these effects can be interpreted because the missing direct effect is not a gatekeeper for interpretation (Hayes, 2009). The only significant mediation could be observed concerning ECL and retention. Disfluency enhanced ECL which in consequence reduced retention outcomes. This indicated that disfluency had negative impacts on retention and retention efficiency because of cognitive factors and not because of metacognitive or social factors. Disfluency was, indeed, capable of increasing the perception of social presence but social presence did not influence learning outcomes. Nevertheless, overall, the implications of Experiment 3 are restricted since only mediation effects concerning retention but not transfer could be observed.

GENERAL DISCUSSION

Overall, serval differences between the three experiments could be observed. In hypothesis 1, it was assumed that a disfluent font should prevent learners from overestimating their learning performance and foster monitoring processes (Alter et al., 2007; Xie et al., 2018). The results of the current experiments were mixed. Learners in the disfluent condition underestimated their performance in contrast to participants in the fluent condition (Experiment 2). This effect is reversed in Experiment 3. The metacognitive benefits which are postulated to arise from learning with disfluent material cannot be supported in general. In consequence, hypothesis 1 has to be rejected. In hypothesis 2, it was assumed that a disfluent font negatively enhances ECL since additional cognitive resources are required to read and decipher the information (Seufert et al., 2017; Beege et al., 2021). This effect could only be observed in Experiment 3. In Experiment 1 and 2, no effects on ECL occurred. In consequence, hypothesis 2 can only partially be supported. Hypothesis 3 took the social perspective into account. Disfluency operationalized through a handwritten font can trigger social processes and act as a cue for perceived social presence (embodiment principle; Mayer, 2014). Concerning the results of Experiment 3, learners in the handwritten font condition reported higher social presence scores than participants in the computerized font condition. Thus, hypothesis 3 can be supported. Nevertheless, activating a social reaction should also increase cognitive processing and foster learning outcomes (e.g., Mayer et al., 2004; Mayer, 2014). This could not be supported by the data of Experiment 3, since mediation analyses pointed out that social presence had no effects on learning outcomes. Hypothesis 4 dealt with the influence of disfluency on learning outcomes in dependence of the element interactivity of the learning material. It was assumed that either an effect of desirable difficulty (e.g., Diemand-Yauman et al., 2011; Geller et al., 2018), no general effect (e.g., Faber et al., 2017), or a learning inhibiting effect, based on arguments of the CLT (e.g., Lehmann et al., 2016; Xie et al., 2018), could be found in the dependence or the element interactivity. Indeed, the results of the current studies indicate that boundary conditions determine the effectiveness or harmfulness of disfluent learning material. When learning with materials with low element interactivity (Experiment 1), beneficial effects of disfluency on learning outcomes and germane processing could be shown. Nevertheless, further process variables were not investigated in Experiment 1 and thus, further explanations cannot be taken from the data. If the element interactivity increases (Experiment 3), no general effects on learning could be observed. Nevertheless, investigating efficiency revealed that disfluency had detrimental effects on efficiency regarding retention. Overall, inducing ECL through disfluency might have rather suppressing effects on learning when the element interactivity increases. When the element interactivity is high (Experiment 2), disfluency had clearly negative effects on learning and learning efficiency. Thus, implications from the cognitive load perspective might be especially relevant for learning with complex material. Thus, hypothesis 4 could be supported. Nevertheless, it has to be discussed that these explanations have to be viewed with caution. At first, element interactivity was not investigated as a separate experimental factor. In consequence, not only element interactivity but also the learning material as a whole differed between all experiments. This approach was chosen to ensure content equivalence within the single experiments. Nevertheless, this led to the problem, that element interactivity cannot be clearly separated from the effects of the use of different learning materials. Different fields of knowledge might have a crucial influence on processing superficial aspects of the material like the font and in consequence, the written information. Results can thus, give first insights in the effect of element interactivity on learning, but results are rather exploratory and implications can only be drawn with caution. Furthermore, results are ambiguous, even within single experiments. For example, in Experiment 2, disfluency hindered learning performance indicating that disfluent material induced an unproductive load. Nevertheless, no effect on ECL could be observed. Furthermore, in Experiment 3, effects only occurred for retention processes. Transfer and transfer efficiency were not affected through disfluency. In consequence, the complexity of the learning process has to be considered. Rather basal memorization processes seemed to be stronger influenced by superficial structural changes of the learning material. More complex knowledge application processes were not or rather weakly influenced by changes in the legibility of the material.

Implications

On the theoretical side, there is a long and ongoing discussion on the emergence of the disfluency effect (e.g., Rummer et al., 2016; Faber et al., 2017; Geller et al., 2018; İliç and Akbulut, 2019). Because of the ambiguous results, researchers need to identify boundary conditions of the emergence of the disfluency effect, for example, the degree of disfluency (Seufert et al., 2017). The current experiments contribute to this discussion by considering element interactivity as moderator. Further, the current investigation operationalized disfluency as a handwritten font to investigate the potential social benefits of illegible fonts. The results of the experiments indicate that the learning fostering as well as learning inhibiting effects are rather based on cognitive factors than on metacognitive or social processes.

On the practical side, designers should be aware that the complexity of the learning material can influence how handwritten fonts are processed. This is especially important in situations where handwritten instructions are heavily used, for example in the classroom or university lecturers when the lecturer draws or writes on the board while teaching. Furthermore, element interactivity is usually medium to high in instructional situations since learners are constantly being thought new information based on previous instructions. Thus, in general, implications from the cognitive load theory should be considered to reduce additional ECL while learning.

Limitations and Future Directions

At first, the handwritten font has to be discussed. For the current study, standard school writing was used to ensure that the font is slightly disfluent but not illegible. Nevertheless, the perception of handwriting can differ in many variables like aesthetics and legibility. Even legibility can arise from many factors like serifs, tilt, or thickness of letters. Thus, it is hardly possible to provide generalized implications for the use of handwritten instructional material. Future studies could specify the effects of different characteristics of handwritten fonts by explicitly manipulate them in experimental studies.

Second, the current studies investigated learning of different materials dealing with different learning domains. In consequence, implications across multiple learning materials can be stated but element interactivity was not investigated with the same learning material restricting comparability. Future studies could explicitly manipulate element interactivity by using one learning material and increase complexity across experimental conditions to further investigate element interactivity as a moderator of the disfluency effect.

Third, the study assessed global metacognitive judgements in order to strengthen economics of the study. Nevertheless, further studies should consider measuring item-by-item judgements, because item-by-item judgements might be more accurate and rely more on metacognitive beliefs (e.g., Bjork et al., 2013).

Finally, the study was carried out with two university students and one young secondary student sample. Yet, handwritten learning materials are heavily used in nearly all educational stages. Thus, investigating primary school students and older secondary school students is important to further specify the role of handwritten materials on learning processes.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

MB: Conceptualization; Methodology; Investigation; Data Curation; Formal Analysis; Validation; Project Administration; Writing - Original Draft FK: Writing - Original Draft; Data Curation; Writing - Review & Editing SS: Writing - Review & Editing SN: Writing - Review & Editing GR: Writing - Review & Editing; Supervision.

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Reading Comprehension in Both Spanish and English as a Foreign Language by High School Spanish Students

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Several studies have highlighted that reading comprehension is determined by different linguistic skills: semantics, syntax, and morphology, in addition to one's own competence in reading fluency (accuracy, speed, and prosody). On the other hand, according to the Linguistic Interdependence Hypothesis, linguistic skills developed in one's own native language (L1) facilitate the development of these skills in a second one (L2). In this study, we wanted to explore the linguistic abilities that determine reading comprehension in Spanish (L1) and in English (L2) in Secondary Education students. To do this, 73 Secondary Education Students (1st and 3rd year) participated in this study. The students carried out a battery of tasks in English and Spanish, all of them related to reading comprehension (expository text) and different linguistic skills, which included syntactic awareness tasks, synonymy judgment tasks (vocabulary), and morphological awareness tasks. The results indicated a positive correlation between linguistic competencies in both languages (indicating a transfer effect between languages), which were determined by school year, with a lower performance in the 1st year than in the 3rd year. Moreover, we found more skills with correlations in English reading comprehension than in Spanish. Finally, reading comprehension in L1 was mainly explained English reading comprehension, while English reading comprehension was predicted by grade, and syntactic awareness, as well as Spanish reading comprehension. This could be explained by the different levels of exposure to L1 and L2 of sample subjects, as the linguistic variables have different influences on the reading comprehension of both languages.

Keywords: Spanish, secondary students, EFL, reading comprehension, morphology, syntax, vocabulary

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INTRODUCTION

Reading comprehension skills are a requirement to be successful in the academic, as well as professional realms of life (García and Cain, 2014). Furthermore, in our contemporary and global society, it is not sufficient to understand native language (L1) texts, it is also necessary to achieve reading proficiency in other languages. Specifically, English is the most used language in both work and study environments, therefore being taught as a second language (L2) in many countries where numerous children also follow bilingual programs in schools. In this context, studies about reading comprehension in L1 and L2 are of considerable relevance, as reading comprehension sometimes supposes an academic difficulty for L2 students, with lower language levels than monolingual peers (Low and Siegel, 2005). Some students learning in English (L2) might be at a disadvantage due to the lack of language development.

In Spain, children start to learn English in schools at a very early age and many of them follow bilingual or semi-bilingual programs from their 1st grade (6 years). They study some subjects in English and have English textbooks. Given that Spanish and English don't share an origin, English being a Germanic opaque language, while Spanish is a Romance transparent one, having to read and learn in English could pose an additional challenge for Spanish children. Furthermore, although there is a great semantic correspondence between the concepts in Spanish and English (Vivas et al., 2020), there are many other differences between the languages on a morphological level (e.g., absence of gender in nouns or few conjugations of verbs in English) and syntax (e.g., in English there exists a mandatory use of the subject in sentences, unalterable order of words, use of simple negation versus double Spanish negation) (Valenzuela, 2002). This is an additional difficulty when it comes to the acquisition of this new language for Spanish children.

In addition, it is necessary to underline the low exposure to English, compared to Spanish, that children receive before the formal reading instruction begins. Most frequently, if they are in school, from the age of 3 (in Spain, schooling is not compulsory until the age of 6) exposure to English begins, averaging around 2 h a week. With the commencement of primary education (+6 years of age), the teaching of English is carried out in a more formal and academic manner. Students receive approximately 4 weekly hours of English classes. Moreover, there are certain bilingual schools where approximately half of the subjects are taught in English (e.g., science, music, and arts). When students complete their secondary education (two final years in addition to mandatory secondary school, 18 years old) it is assumed that they have reached an A2 level of Common European Framework of Reference (CERF) in the different competencies (comprehension and expression, both oral and written) of English. In the case of secondary students with a bilingual itinerary, the level would be B1or B1+ (CERF). Spanish children suffer the highly demanding situation of learning in the English language while simultaneously developing oral and reading proficiency. This condition could be affecting the development of linguistic competencies, and therefore, different language skills might be contributing to reading comprehension in Spanish and/or English.

On the other hand, regarding language proficiency, previous studies showed that language skills transfer across languages (Cummins, 1979; August and Shanahan, 2006). In other words, reading abilities in L1 might be transferred to L2 reading (D'Angelo and Chen, 2017; Tong et al., 2018). D'Angelo and Chen (2017) explored reading comprehension in English (native language) and French (L2). Three groups of comprehenders were identified (poor, average, and good) based on English reading performance. They found that poor comprehenders showed similar language characteristics both in L1 and L2. Similarly, Tong et al. (2018) reported the co-occurrence of reading comprehension difficulty in L1 Chinese and L2 English. Chinese–English L2 learners (10 years old) that manifested problems in L1 Chinese reading comprehension are likely to show low performance in L2 English reading comprehension. These results suggest that the comprehension skills developed in one language will facilitate reading comprehension in another language and reading comprehension profiles will be similar in both L1 and L2 languages.

In this field of study, over the last few years, research about reading comprehension in monolingual and bilingual populations has increased considerably (Choi et al., 2017; D'Angelo and Chen, 2017; Mackay et al., 2017; Spencer and Wagner, 2017; D'Angelo et al., 2020; Zhang et al., 2020; Zhao et al., 2021).

Reading Comprehension

Reading comprehension is a universal process that consists of eliciting and conjuring meaning through interaction and involvement with written language (McNamara and Magliano, 2009). Reading comprehension is considered a very complex process, involving several abilities for the acquisition of significance from a written text (Kirby, 2007). However, the Simple View of Reading (SVR) states that reading comprehension depends on decoding skills and language comprehension (Hoover and Gough, 1990; Gottardo and Mueller, 2009), so some processes are not specific for reading comprehension. Furthermore, decoding skills improve with age and the influence on reading comprehension diminishes, while the effects of other skills such as vocabulary, syntax, and morphology remain, apart from inference skills, working memory, and monitoring (Hannon and Daneman, 2001; Perfetti and Hart, 2001; Perfetti et al., 2013; Landi and Ryherd, 2017). Although in recent years there have been quite a few studies on the components of language that contribute to reading comprehension in monolingual and bilingual children, little is known about whether reading comprehension skills are manifested similarly in L1 and L2 (and the components contributing to successful reading comprehension in English) for Spanish adolescents in a bilingual school context, where they study 50% of subjects in English, whilst the language of the community is Spanish.

Vocabulary

The term vocabulary refers to the set of words that a person knows or uses, as well as to the words of a specific language (Hornby, 2006). It is presumed to be one of the most crucial language skills contributing to reading competence (National Reading Panel and National Institute of Child Health and Human Development (US), 2000; Fernandes et al., 2017; Sparapani et al., 2018; Quinn et al., 2020). It constitutes a pillar essential to reading success and progress (Lonigan, 2006; Dickinson et al., 2010). Likewise, it has been reported that children with poor comprehension around 9 years of age exhibit low levels of vocabulary (Nation et al., 2007; Ricketts et al., 2007; Hock et al., 2009). These deficits, not always evident, would limit the ability to understand a text with unfamiliar words. However, the impact of vocabulary on reading comprehension appears to depend on age (Protopapas et al., 2007). Protopapas et al. (2007) supported the idea that vocabulary becomes more important around 7–10 years of age, once word decoding is automated, results that coincide with those found in other studies (Hock et al., 2009). What's more, it seems that in skilled readers there is a bidirectional relationship between vocabulary and reading comprehension (Quinn et al., 2020), signaling that vocabulary is a leading indicator of change in reading comprehension, and reading comprehension is a leading indicator of change in vocabulary.

Regarding L2 reading comprehension, several studies suggested that vocabulary, among other skills, determines its development in L2 (Lesaux and Kieffer, 2010; Li and Kirby, 2014; D'Angelo et al., 2017; Tong et al., 2018). However, Burgoyne et al. (2011) found that vocabulary was a predictor of English reading comprehension for 4th-grade bilingual children whose first language was of South-Asian origin, but not for those of their monolingual peers. It suggests that the contributions of language skills to reading comprehension could also depend, to a certain extent, on language exposure.

Morphological Awareness

Morphological awareness is defined as the ability to manipulate morphemes and the structure of words (Kuo and Anderson, 2006). This metalinguistic consciousness, especially considering derivational morphology, continues to develop throughout schooling (Casalis and Louis-Alexandre, 2000), and it is important to achieve word meanings, in turn then favoring reading comprehension (McBride-Chang et al., 2003; Deacon and Kirby, 2004; Cain and Oakhill, 2006; Guo et al., 2011; Jeon and Yamashita, 2014; Tong et al., 2014; D'Alessio et al., 2019; Zhang et al., 2020; Kotzer et al., 2021; Li et al., 2021).

Regarding monolinguals, Carlisle (2000) reported that morphological awareness tasks contributed to text comprehension at both 3rd and 5th grades, but with a stronger effect for older children than for younger ones. Similarly, morphological awareness also appears to benefit reading comprehension, independent from word decoding, in 4th-grade Spanish-speaking children (D'Alessio et al., 2019). In addition, native English speakers seem to rely on morphology to infer the meaning of the new words encountered while reading (Crosson and McKeown, 2016), hence supposing an advantage to reading comprehension.

Concerning children who received education in L2, Lipka and Siegel (2012) found that English L2 poor comprehenders (7th grade) had lower scores in morphological awareness than good comprehenders. Similarly, in a study about children with English L1 and French L2 (10-to-11-year-old), French morphological awareness differentiated bilingual poor from good comprehenders, supporting the proposal that morphological awareness impacts reading comprehension when some language levels are achieved (D'Angelo and Chen, 2017). Recently, an interesting study addressed the role of (English) language proficiency (native, fluent, and limited proficiency) and morphological competence as beneficial for reading comprehension (Zhang et al., 2020). However, the contribution of morphological awareness to reading comprehension seems to be dependent on English proficiency, as participants with a higher English proficiency (native speakers and fluent levels) were better at taking advantage of morphological information to infer word meanings than participants with lower English levels (Zhang et al., 2020).

Syntax Awareness

Syntactic awareness is the ability to reflect on grammar rules and to manipulate the grammatical structure of sentences in a language (Gombert, 1992). This ability to manipulate the syntactic structure of spoken language is generally considered related to reading development via its contribution to reading comprehension (Paris and Landauer, 1982; Bowey, 1986) and to word recognition (Tunmer et al., 1987; Tunmer and Hoover, 1992). Several reading models considered syntactic awareness as an important skill to achieve reading comprehension include: Simple View of Reading (Gough and Tunmer, 1986; Hoover and Gough, 1990), the Triangle Model (Seidenberg and McClelland, 1989; Bishop and Snowling, 2004) or the Reading Systems Framework (Perfetti, 1999; Perfetti et al., 2008; Perfetti and Stafura, 2014). Syntactic awareness is important for reading success, as it allows the anticipation of syntactic categories and the inference of which word class will follow (Tunmer and Bowey, 1984; Bishop and Snowling, 2004).

Some studies carried out with monolinguals found that poor comprehenders also have syntactic weaknesses. In a study with English fourth graders, Adlof and Catts (2015) found that poor comprehenders also had problems in some syntactic constructions as be-do questions in an orally grammatical judgment task. These findings are in agreement with other studies that relate poor comprehension to grammatical difficulties (Tong et al., 2018; Guo et al., 2020; Li et al., 2021).

Focusing on bilingual studies, the most thoroughly investigated issue is whether there exists a transfer skill between languages. In this sense, it has been shown that the syntax of Chinese–English elementary school children had an influence and predicted reading comprehension (Chik et al., 2012; Yeung et al., 2012; Siu and Ho, 2015). Moreover, in Chinese–English children, syntactic awareness improved from first to second grade in both L1 and L2; and L1 syntactic awareness predicted L2 reading comprehension 1 year later (Siu and Ho, 2020). Similar results were found in studies with Spanish-French children where L2 text comprehension was explained by L1 text comprehension and L1 syntactic awareness (Lefrançois and Armand, 2003). On top of that, for Spanish primary school students with English as a second language, findings showed that both syntax and morphology in oral language predicted levels of reading comprehension (Gottardo et al., 2018).

In conclusion, studies about comprehension in monolinguals and bilinguals reported that several linguistic skills contribute to reading comprehension. However, the contribution of different skills appears to vary depending on age or exposure to the language.

The Current Study

The present study aims to explore the development of Spanish and English competence (vocabulary, morphology, syntaxis, and reading comprehension) of Spanish secondary school children (1st and 3rd grade) and the contribution of said abilities to reading comprehension in both languages, in absence of poor reading decoding. We are interested in students with adequate word-reading skills, so comprehension differences could not be attributed to decoding performance. In addition, it should be highlighted that these participants were native Spanish speakers receiving a Spanish–English bilingual education, so participants differed from immigrant children in English monolingual schools.

According to the language skills transference across languages theory, we hypothesized relationships between languages in different tasks; however, considering language-specific factors (such as exposure or practice) and the age of the participants, we expected differences in the contribution of linguistic skills to reading comprehension in Spanish and English.

METHODOLOGY

Participants

Seventy-three students participated in this study from the 1st (24 girls and 20 boys; M_{age} = 12.93, SD = 0.25), and 3rd grades of secondary school, equivalent to seventh and ninth grade, respectively, in the American and British education systems (20 girls and 9 boys; M_{age} = 14.81, SD = 0.25). The difference in the number of participants in each course may be due to greater involvement and interest in carrying out voluntary tasks in younger ages. Participants were recruited from two Spanish–English bilingual secondary schools in Asturias (Spain). Participants have been exposed to English from the beginning of preschool, around 3 years old. At the end of first grade, they have reached an A2 English level, although some may reach a B1; while at the end of third grade they are expected to have got a B1 level, although some students may have reached a B2. To teach English reading, instructors primarily employed a global method – introducing meaning, pronunciation, and spelling at the same time. At this point in time, children received 4 h of English language lessons per week, and they follow (from 1st grade of primary school) a Content and Language Integrated Learning methodology (CLIL; de Martínez Agudo, 2019), with 50% of subjects being taught in the English language.

All participants had Spanish as their first language and belonged to a middle-class socioeconomic status. None of them had developmental, behavioral, or cognitive issues, as 12 students with learning and academic difficulties were excluded from the study. Teachers confirmed that the schooling of all participants had been developed without suffering remarkable incidents and they had not retaken a year of studies. In addition, 5 participants were also removed for not completing the tasks and 3 were considered outliers because of their performance.

Tasks

The present study consisted of four linguistic tasks in both Spanish and English languages:

(a) *Synonym judgment task* (Spanish and English versions). Thirty-two pairs of words were constructed, for which participants had to decide whether the two items of the pair had a similar meaning (e.g., courage-bravery [valor-valentía] and historieta-cuento [tale-story]). Although other semantic tasks could have been used, this task was selected granted its effectiveness, as seen in previous studies (D'Angelo and Chen, 2017). The English stimuli were selected according to their lexical frequency (Kuperman et al., 2012), and Spanish words were selected following their lexical frequency from B-pal (Davis and Perea, 2005). Considering the thirty-two pairs of words, the Cronbach's alpha coefficient was 0.50 for the Spanish task and 0.71 for the English task, so we dropped some items to increase reliability. After dropping 8 items for each language, the Cronbach's alpha coefficient was 0.62 for the Spanish task and 0.75 for the English task. The final Spanish task had a total of 10 pairs of not similar words and 14 pairs of similar words [$M_{similarlist}$ = 30.27, SD = 33.65; $M_{differentlist}$ = 23.05, SD = 41.58; $t(46)$ = 0.664, p = 0.51]. Besides, syllable count was similar in both lists [$M_{similarlist}$ = 3.25, SD = 1.04; $M_{differentlist}$ = 3.2, SD = 0.69; $t(46)$ = 0.815, p = 0.425]. Moreover, English task had 14 pairs of similar words and 10 pairs of not similar words, also with a similar lexical frequency [$M_{similarlist}$ = 23.76, SD = 24.14; $M_{differentlist}$ = 22.87, SD = 23.07; $t(46)$ = 0.129, p = 0.89] and syllabic length [$M_{similarlist}$ = 2.25, SD = 1.02; $M_{differentlist}$ = 1.71, SD = 0.54; $t(46)$ = 1.76, p = 0.09]. Therefore, the maximum score in each language task was 24, one point for each of the items (pair of words) correctly answered.

(b) *Syntactic judgment task*. This consisted of thirty-two sentences, in Spanish and English. Participants had to decide whether those sentences were syntactically correct or incorrect (e.g., *Much* soldiers came to the battlefield ['*Muchos*' *soldados acudieron al campo de batalla*]; *Al* perro es perseguido por el gato [*To the* dog is chased by the cat]). Taking in consideration the thirty-two sentences, the Cronbach's alpha coefficient was 0.50 for the Spanish task and 0.64 for the English task. After dropping 8 items for each language, the Cronbach's alpha coefficient was 0.61 for the Spanish task and 0.73 for the English task. The final Spanish task consisted of a total of 11 correct and 13 incorrect sentences, while the final English task included 13 correct and 11 incorrect sentences. So, the possible maximum score was 24 in each language, one point for each of the items (pair of sentences) correctly answered.

(c) *Morphological task*. This included eight prefixes and four suffixes, of which students were asked to provide an example of a word with that morpheme (e.g., tri- [meaning: three]; semi- [meaning: half]). Morphemes were different for each language, not the translation of them. The maximum score was 12 in each language, given a point for each correct answer. The Cronbach's alpha coefficient was 0.60 for the Spanish task and 0.75 for the English task.

(d) *Reading comprehension task*. The Spanish text used ("El ornitorrinco" ["*The platypus*"]) was part of PROLEC-SE-R test (Cuetos et al., 2016). For the English task, we adapted an existing text ("Discovered species"), like the Spanish one in terms of length (English text: 381 words, 16 sentences; Spanish text: 387 words, 15 sentences) and complexity considering the Automated Readability Index (ARI; Senter and Smith, 1967) (English text: 12.17, Spanish text: 11.8). Besides, the English text's vocabulary used corresponds with a B2 CEFR level in English, according to the Global Scale of English text analyzer of Pearson[1]. After the reading component, participants had to answer 10 multiple-choice questions, both literal (six questions) and inferential (four questions). Participants could score a maximum of ten in each language, one point for each comprehension question correctly answered. The Cronbach's alpha coefficient was 0.61 for the Spanish task (0.55 reported in the PROLEC-SE-R test) and 0.81 for the English task.

Procedure

The tasks were presented in a booklet, one for the Spanish and one for the English language. Participants had to complete the booklets on two different days during the month of April. Instructions and one example were presented at the beginning of each task. The completion of each booklet took about an hour. When correcting each task, the number of items with a correct answer was counted, obtaining an overall score for each of the tasks (sum of all the correct items). The research design and procedure were approved by the Ethics Committee for Research of the Principality of Asturias, Spain. It was performed in accordance with the Declaration of Helsinki and the Spanish Law of Personal Data Protection (15/1999 and 3/2018) principles. Before conducting the experimental tasks, parents received information about the study and its objectives and authorized the data collection through signed consent.

Analysis

Different analyses were conducted with SPSS.24 software package. First, preliminary analyses were performed to assess the normality of the score's distribution. From the Kolmogorov–Smirnov statistic, we found that five tasks were not normally distributed, so we decided to use non-parametric statistics (even when considering the number of participants some authors approved the use of parametric statistics).

After that, we carried out several Mann–Whitney *U* Tests to check for differences between grades on the tasks. Then, the relationship between tasks' performance in each language (and between languages) was examined using the Spearmen correlation coefficient. Finally, linear regression analyses were completed to determine if variations in comprehension outcomes could be attributed to variations in the other linguistic tasks.

RESULTS

Mann–Whitney *U* Tests

The analysis revealed significant differences between grades in all tasks except the Spanish synonym task, where the difference was close to significance, with better performance in 3rd than in 1st grade. See **Table 1**.

Spearman Correlations

Spearman correlations were used to explore the strength of relationships between variables. As portrayed in **Table 2**, a considerable number of interesting correlations were observed. According to questions raised in the study, it is worth noting the positive relationship between the different variables (vocabulary, syntax, and morphology) and English reading comprehension, while in Spanish we solely found a relationship between morphology and reading comprehension. See **Table 2**.

When the data were split by grade, the fact that no relationship between Spanish reading comprehension and other linguistic tasks was found resulted striking. Meanwhile, in English, correlations were found between reading comprehension and vocabulary, syntax, and morphology in 1st grade, although only with syntax in 3rd grade. See **Table 3**.

Additionally, taking into account all participants, the relationship between the same tasks in different language (Spanish vocabulary task with English vocabulary task; Spanish syntactic task with English syntactic task; Spanish morphological task with English morphological task; and Spanish reading comprehension task with English reading comprehension task) was also of interest. See **Table 2**. Finally, considering the different tasks (vocabulary, syntax, and morphology in both languages), in 1st grade a relationship was found between languages for syntax, morphology, and reading comprehension, but only for syntax task in 3rd grade. See **Table 3**.

Regression Analysis

Two hierarchical multiple regressions (one for Spanish and one for English languages) were performed to assess the ability of grade and the linguistic measures (vocabulary, morphology, and syntax) to predict reading comprehension outcomes.

With regards to the Spanish reading comprehension, predictors were entered in the following order: grade, Spanish vocabulary, Spanish morphology, Spanish syntax, and English comprehension. The analyses revealed that at Step one, grade contribute significantly to the regression model and accounted for 18.4% of the variance in Spanish reading comprehension, $F(1,71) = 16.019$, $p = 0.000$. At steps 2–4, the independent variables (vocabulary, morphology, and syntax) did not contribute significantly to the regression model, none of the variables was a significant predictor of Spanish reading comprehension. However, step five accounted for an additional 16.2% of variation in Spanish reading comprehension and this change in R^2 was significant, $F(1,67) = 17.842$, $p = 0.000$. However, only the English reading comprehension was a significant predictor of Spanish reading comprehension. See **Table 4**.

TABLE 1 | Linguistic competence in both languages by 1st and 3rd graders.

	Md 1st	Md 3rd	*U*	*z*	*p*-value	*r*
Spanish comprehension	8.00	9.00	293.50	−4.032	0.000	0.48
Spanish vocabulary	19.00	20.00	467.00	−1.941	0.052	0.23
Spanish syntax	21.00	22.00	452.50	−2.125	0.034	0.25
Spanish morphology	9.00	10.00	352.00	−3.271	0.001	0.39
English comprehension	6.00	9.00	157.50	−5.487	0.000	0.65
English vocabulary	17.00	20.00	367.50	−3.066	0.002	0.36
English syntax	16.00	20.00	267.50	−4.195	0.000	0.49
English morphology	6.00	9.00	391.00	−2.802	0.005	0.33

[1] https://www.pearson.com/english/about-us/global-scale-of-english.html

TABLE 2 | Correlation matrix among all the tasks for the whole group.

	Spanish vocabulary	Spanish syntax	Spanish morphology	Spanish comprehen	English vocabulary	English syntax	English morphology	English comprehen
Spanish vocabulary		0.130	0.214	0.134	0.237*	0.198	0.118	0.065
		0.275	0.068	0.260	0.043	0.094	0.322	0.585
Spanish syntax			0.376**	0.111	0.195	0.507**	0.243*	0.453**
			0.001	0.352	0.098	0.000	0.039	0.000
Spanish morphology				0.276*	0.347**	0.532**	0.433**	0.462**
				0.018	0.003	0.000	0.000	0.000
Spanish comprehen					0.185	0.282*	0.143	0.538**
					0.117	0.016	0.228	0.000
English vocabulary						0.530**	0.477**	0.398**
						0.000	0.000	0.000
English syntax							0.508**	0.682**
							0.000	0.000
English morphology								0.421**
								0.000

Correlations for 1st and 3rd grades together.
$^{*}p < 0.05$, $^{**}p < 0.001$.

TABLE 3 | Correlation matrix among all the tasks for each grade.

	Spanish vocabulary	Spanish syntax	Spanish morphology	Spanish comprehen	English vocabulary	English syntax	English morphology	English comprehen
Spanish vocabulary		0.067	0.011	0.094	0.014	−0.043	0.024	−0.186
		0.666	0.942	0.544	0.927	0.781	0.875	0.226
Spanish syntax	0.066		0.345*	0.051	0.132	0.418**	0.379*	0.364*
	0.732		0.022	0.744	0.394	0.005	0.011	0.015
Spanish morphology	0.388*	0.038		0.101	0.251	0.363*	0.476**	0.337*
	0.037	0.846		0.513	0.100	0.016	0.001	0.025
Spanish comprehen	−0.040	−0.069	0.128		0.192	0.171	0.086	0.602**
	0.836	0.721	0.509		0.212	0.266	0.579	0.000
English vocabulary	0.313	0.089	0.078	−0.227		0.418**	0.368*	0.313*
	0.099	0.647	0.688	0.237		0.005	0.014	0.039
English syntax	0.293	0.405*	0.406*	−0.036	0.401*		0.503**	0.601**
	0.123	0.029	0.029	0.853	0.031		0.000	0.000
English morphology	0.105	−0.194	0.201	−0.169	0.548**	0.180		0.325*
	0.587	0.314	0.297	0.382	0.002	0.350		0.031
English comprehen	−0.032	0.368*	0.043	−0.118	0.156	0.450*	0.149	
	0.871	0.050	0.824	0.543	0.420	0.014	0.441	

Above diagonal for 1st-grade children and under diagonal for 3rd-grade children.
$^{*}p < 0.05$, $^{**}p < 0.001$.

As for the English reading comprehension, predictors were entered in this order: grade, English vocabulary, English morphology, English syntax, and Spanish comprehension. Results indicated that at step one, grade contributed significantly to the regression model, accounting for 36% of the variance in English reading comprehension $F(1,71) = 40.007$, $p = 0.000$. After entry of vocabulary at step 2, the contribution (2.7% of variance) to the regression model of this contribution was not significant. The contribution of morphology at step 3 was significant and explained a 3.7% of variance, $F(1,69) = 4.410$, $p = 0.039$. At Step 4 syntax added a 13.7% of explanation of variance, $F(1,68) = 21.236$, $p = 0.000$; and at step 5, final model Spanish comprehension accounted for 8.9% of the variance in English reading comprehension, $F(1,67) = 17.083$, $p = 0.000$. See **Table 5**.

DISCUSSION

The aim of our study was to explore the Spanish and English reading comprehension in Spanish secondary students attending a bilingual school, as well as their relationship with other linguistic skills. Besides, we wanted to know the contribution of these linguistic skills to reading comprehension. To do this, we carried out several tasks about vocabulary, syntactic and morphological awareness, and reading comprehension in both

TABLE 4 | Summary of hierarchical multiple regression analysis for variables predicting the outcome Spanish reading comprehension.

Variable	B	SE	Beta	t	p	*R*	R^2	ΔR^2
Step 1						0.429	0.184	0.184
Grade	0.698	0.174	0.429	4.002	0.000			
Step 2						0.430	0.185	0.001
Grade	0.709	0.180	0.430	3.939	0.000			
Sp. vocabulary	−0.016	0.059	−0.030	−0.275	0.784			
Step 3						0.477	0.228	0.043
Grade	0.577	0.189	0.355	3.057	0.003			
Sp. vocabulary	−0.023	0.058	−0.043	−0.394	0.695			
Sp. morphology	0.193	0.099	0.224	1.960	0.054			
Step 4						0.478	0.228	0.000
Grade	0.578	0.190	0.355	3.038	0.003			
Sp. vocabulary	−0.022	0.059	−0.040	−0.366	0.716			
Sp. morphology	0.197	0.102	0.228	1.925	0.058			
Sp. syntax	−0.013	0.084	−0.017	−0.152	0.880			
Step 5						0.625	0.391	0.162
Grade	0.084	0.207	0.052	0.409	0.684			
Sp. vocabulary	0.037	0.055	0.068	0.664	0.509			
Sp. morphology	0.118	0.093	0.137	1.263	0.211			
Sp. syntax	−0.118	0.079	−0.157	−1.481	0.143			
Eng. comprehension	0.329	0.078	0.559	4.224	0.000			

TABLE 5 | Summary of hierarchical regression analysis for variables predicting the outcome English reading comprehension.

Variable	B	SE	Beta	t	p	*R*	R^2	ΔR^2
Step 1						0.600	0.360	0.360
Grade	1.659	0.262	0.600	6.325	0.000			
Step 2						0.622	0.387	0.027
Grade	1.489	0.276	0.539	5.391	0.000			
Eng. vocabulary	0.128	0.073	0.176	1.757	0.083			
Step 3						0.651	0.424	0.037
Grade	1.376	0.275	0.498	5.004	0.000			
Eng. vocabulary	0.050	0.080	0.068	0.620	0.537			
Eng. morphology	0.218	0.104	0.230	2.100	0.039			
Step 4						0.749	0.561	0.137
Grade	0.971	0.257	0.351	3.776	0.000			
Eng. vocabulary	−0.017	0.072	−0.023	−0.231	0.818			
Eng. morphology	0.089	0.095	0.094	0.934	0.353			
Eng. syntax	0.338	0.073	0.470	4.608	0.000			
Step 5						0.806	0.650	0.089
Grade	0.640	0.245	0.232	2.615	0.011			
Eng. vocabulary	−0.005	0.065	−0.007	−0.075	0.941			
Eng. morphology	0.115	0.086	0.122	1.341	0.185			
Eng. syntax	0.277	0.068	0.385	4.097	0.000			
Sp. comprehension	0.576	0.139	0.339	4.133	0.000			

languages. Our results showed that 3rd graders obtained better results than 1st graders, especially in English. This allowed us to confirm that secondary school students continue developing reading and linguistic skills after primary education, as other authors have already shown (Watson et al., 2012; Álvarez-Cañizo et al., 2020). However, no significant differences between grades were found in Spanish vocabulary (the difference was close to significance). A potential explanation would be that the growth in vocabulary knowledge slows after a certain level (although never ceasing to increase), such as secondary education, and for this reason, we did not find differences between the grades.

Regarding the correlations between reading comprehension and linguistic skills in both languages, and considering both groups together, our results showed that reading comprehension in L1 correlated with morphological awareness. The contribution of morphological awareness to reading comprehension has already been proven, being greater in more advanced grades (Carlisle, 2000). Similarly, 4th-grade Spanish students showed an effect of morphology in reading comprehension (D'Alessio et al., 2019). However, it was reported that morphology helps to infer the significance of words, seemingly indicating that the effect of morphology relates to vocabulary (Crosson and McKeown, 2016). On the other hand, when considering grades separately, there was an absence of relationships between reading comprehension and linguistic abilities in L1. This may seem striking but may be given to the fact that the task's characteristics do not allow us to catch the influence of these skills in reading comprehension, or perhaps, at certain levels of linguistic proficiency, other skills could be influencing reading comprehension, such as inference making, working memory, previous knowledge, or the ability to monitor the reading activity (Landi and Ryherd, 2017).

As for reading comprehension in L2, when considering 1st and 3rd grades together, reading comprehension correlated with all linguistic tasks (i.e., vocabulary, morphological awareness, and syntactic awareness). However, when grades were considered separately the relationship between reading comprehension and vocabulary and morphological awareness disappeared for 3rd graders. Once again, the relationship between linguistic skills and reading comprehension seems to be determined by age or language proficiency. Vocabulary has been identified as a strong predictor of reading comprehension in English L2 learners (Pasquarella et al., 2012; Farnia and Geva, 2013; van den Bosch et al., 2020), but for native speakers' vocabulary is decisive for reading comprehension at younger ages (Nation et al., 2007; Ricketts et al., 2007; Hock et al., 2009). As mentioned, we only found a relationship between vocabulary and English reading comprehension for 1st graders, not in 3rd graders in Spanish either. However, the influence of vocabulary on reading comprehension may depend on the text. With regards to morphology, we have already observed that the relationship with reading comprehension varies with age and proficiency level (Carlisle, 2000; Zhang et al., 2020). This way, we could conceive that in the Spanish language as L1, where secondary students demonstrated proficient competencies, the contribution of different skills to reading comprehension differs than in English as L2.

The correlation analysis between languages showed a significant positive relationship in all tasks: reading comprehension, vocabulary, morphological and syntactic awareness when both groups were taken together. This might confirm the linguistic interdependence hypothesis (Verhoeven, 1994). Following this hypothesis, in bilingual learning, language and literacy skills can be transferred from one language (L1) to another (L2), or languages skills have a common basis irrespective of language. It has been seen that this transfer effect also occurs in developing skills, as it is observed in the study of Cisero and Royer (1995). The regression analysis results confirmed the different contributions of linguistic skills to reading comprehension in L1 and L2, a very interesting result. The reading comprehension in Spanish (L1) is explained by English reading comprehension. Morphology correlated with reading comprehension, but the regression analysis indicated that the main predictor of Spanish reading comprehension was English reading comprehension, after controlling the effect of the grade. As previously stated, morphological awareness is a skill that continues to develop throughout the school years (Casalis and Louis-Alexandre, 2000), along with reading expertise (Rastle, 2019). In addition, several studies demonstrated its relationship with reading comprehension, since it contributes significantly to knowing the meaning of words, thus favoring the understanding of the text (e.g., Deacon and Kirby, 2004; Cain and Oakhill, 2006; D'Alessio et al., 2019; Zhang et al., 2020; Li et al., 2021). However, the study of Zhang et al. (2020) supports that the contribution of morphological awareness depends on language proficiency. It is possible that L1 students have reached a sufficient level of vocabulary, syntactic and morphological awareness, so that they no longer influence reading comprehension, although these skills continue to develop at these ages, as we have seen in our results and in previous studies (Casalis and Louis-Alexandre, 2000; Hock et al., 2009).

Regarding English (L2), reading comprehension was explained by grade, syntax, and Spanish reading comprehension. According to this, it should be highlighted the importance of language exposure and competence, as variance of English reading comprehension is determined by grade. As far as syntax awareness is concerned, it was supposed to be an important predictor of reading, helping to anticipate words and make inferences (Bishop and Snowling, 2004), but the role of syntax was different for L1 and L2. The differences between English and Spanish syntax (Klavans, 1985) could make it a determining variable in L2 reading comprehension. In addition, Spanish reading comprehension also appeared to be a good predictor of English reading comprehension, supporting the interdependence hypothesis between languages (Verhoeven, 1994). In addition, it could be hypothesized that other variables, related to reading comprehension, could be influencing reading comprehension in both Spanish and English; as Cummins (1979) considered, there could be some underlying cognitive or academic proficiency common across languages, which eases the transfer of cognitive, academic, and literacy-related skills.

In closing, this study is a pioneer in the examination of reading comprehension in Spanish L1 as in English L2. It can be concluded that reading comprehension along with other linguistic skills continue developing well into secondary school, both in L1 and L2, with a better performance in L1. Besides, we can support a transfer or interdependence effect between languages as previously proved by different authors, such as the Linguistic Interdependence Hypothesis (Verhoeven, 1994). Finally, it seems that the language proficiency in Spanish (L1) and English (L2), given the differences in exposure to them, determines the linguistics skills related to reading comprehension, as previously proven by other authors (Jiang, 2011; Edele and Stanat, 2016).

IMPLICATIONS

The findings in our study allow us to highlight the importance of certain abilities for reading comprehension, as well as the need to increase exposure to a second language to facilitate the development of different language skills, which ultimately have an impact on reading comprehension. Regarding English reading comprehension, specific attention should be given to syntactic awareness, bearing in mind its important contribution to reading comprehension.

LIMITATIONS

Despite the considerable results of this study, we would like to mention some limitations or noteworthy aspects to be included in future studies. Results seem to help us understand the contribution of certain linguistic skills to reading comprehension in L1 and L2, but results should be interpreted with caution due to the relatively small groups, limited range of grades, and the near ceiling effect in some tasks. It could be interesting to include or explore the contribution to reading comprehension of some abilities such as working memory, previous knowledge, or the ability to make inferences while reading. Furthermore, it could be interesting to expand the sample with students from other high school grades, in order to comprehend the development of reading comprehension in L2 students, taking into account that our sample was not very sizeable. The use of larger sample sizes could also allow the performance of mediation analysis, to study indirect effects of certain skills. Besides, the tasks used to assess the different linguistics skills could be complemented, as making decisions based on a single score is generally a poor practice. However, it is necessary to find a balance between cost-benefit, especially when it comes to working with children. For example, in the vocabulary tasks, it could be interesting to include an expressive vocabulary task (e.g., picture naming), rather than just a comprehensive task such as semantic judgment.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee for Research of the Principality of Asturias, Spain. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

PS-C, MÁ-C, and EC carried out the research design and preparation of the materials. EC performed the data collection and analysis. All authors contributed to the preparation of the manuscript.

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Text Reading Fluency and Text Reading Comprehension Do Not Rely on the Same Abilities in University Students With and Without Dyslexia

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Developmental dyslexia is a specific learning condition characterized by severe and persistent difficulties in written word recognition, decoding and spelling that may impair both text reading fluency and text reading comprehension. Despite this, some adults with dyslexia successfully complete their university studies even though graduating from university involves intensive exposure to long and complex texts. This study examined the cognitive skills underlying both text reading comprehension and text reading fluency (TRF) in a sample of 54 university students with dyslexia and 63 university students without dyslexia, based on a set of tests adapted for an adult population, including listening comprehension, word reading, pseudoword reading (i.e., decoding), phonemic awareness, spelling, visual span, reading span, vocabulary, non-verbal reasoning, and general knowledge. The contribution of these skills to text reading fluency and text reading comprehension was examined using stepwise multiplicative linear regression analyses. As far as TRF is concerned, a regression model including word reading, pseudoword reading and spelling best fits the data, while a regression model including listening comprehension, general knowledge and vocabulary best fits the data obtained for text reading comprehension. Overall, these results are discussed in the light of the current literature on adults with dyslexia and both text reading fluency and text reading comprehension.

Keywords: adults with dyslexia, reading comprehension, text reading fluency, compensation, reading

INTRODUCTION

Developmental dyslexia (hereafter dyslexia), a specific learning disorder which affects 10% of the population is primarily characterized by significant difficulties in written word recognition, slow and inaccurate decoding that may impair reading comprehension, and poor spelling performance (American Psychiatric Association, 2013). Because most symptoms of dyslexia persist in adulthood, it is considered to be a non-transient developmental deficit and its prevalence in adults can therefore be considered to be stable. However, an increasing number of students with dyslexia are entering and graduating from higher education[1]. Some studies have reported that these readers can exhibit text reading comprehension performance comparable to that of adult skilled readers of the same chronological age (Parrila et al., 2007; Deacon et al., 2012; Hebert et al., 2018; Cavalli et al., 2019), despite impairments in decoding and written word recognition (Bruck, 1990, 1992; Pennington et al., 1990; Kemp et al., 2009; Martin et al., 2010; Cavalli et al., 2018). However, according, for example, to the *verbal efficiency hypothesis* (Perfetti, 1985), fluent and efficient written word recognition is a fundamental pre-requisite for achieving good text comprehension (Gough and Tunmer, 1986; Perfetti and Hart, 2002). Consequently, inefficient written word recognition (i.e., slow and inaccurate) is likely to impair reading comprehension (Perfetti, 1985). This does not always appear to be the case for university students with dyslexia and studies (mentioned above) have reported a dissociation between performance on visual word recognition and/or decoding skills and reading comprehension skills (see, for example, Cavalli et al., 2019). Because it is possible that reading comprehension in this population cannot be reliably predicted on the basis of both visual word recognition and decoding skills, it is possible to hypothesize that these readers have probably developed compensatory and/or adaptive mechanisms induced by continued exposure to written texts (Lefly and Pennington, 2000) that allow them to understand a text at the same level as typical readers. Interestingly, it can also be argued that skills associated with the recognition of written words may not provide an adequate basis for estimating reading skills when compared to text reading fluency (Fuchs et al., 2001).

According to the "Simple View of Reading" (SVR) model (Gough and Tunmer, 1986; Hoover and Gough, 1990; Tunmer and Chapman, 2012), reading comprehension involves decoding skills (hereafter named "word reading skills" as in Hoover and Gough's (1990) model), listening comprehension skills and the interaction between these two skills (Keenan et al., 2008). This model has mainly been tested with typical readers (children and adults; see the metanalysis by García and Cain, 2014) and more rarely with readers with dyslexia, especially adults. It is nevertheless an interesting starting point for understanding the processes involved in text reading comprehension in adults with dyslexia, who are exposed to clearly established severe and persistent difficulties at the level of the word reading processes. In this context, some studies have attempted to identify some of the factors explaining text reading comprehension performance (for example in terms of visual word recognition, decoding, general knowledge and working memory) in adults with dyslexia (see, for instance, Ransby and Swanson, 2003). However, such studies are very rare and provide only scattered, disparate data which do not allow us to come to a clear and satisfactory picture or interpretation of the processes involved.

The overall aim of this study is therefore to gain a better understanding of the text reading comprehension processes in university students with dyslexia compared to those mobilized by adult skilled readers. More specifically, since graduating at university involves intensive exposure to long and complex texts, this study also aims to investigate the relationship between text reading fluency processes (a more appropriate measure of adult reading ability) and those involved in text reading comprehension.

Text Reading Fluency in Adults With Dyslexia

A recent study pointed out that text reading fluency provides a more natural and ecological way of assessing reading than word reading fluency (see Rouweler et al., 2020) because words are almost never read in isolation. Despite this, researchers in English-speaking countries do not prefer to measure text reading fluency when assessing dyslexia, because they feel that the text contents may obscure the measurement of word decoding skills. Words in context are indeed read faster than words out of context, because the context can be used as a top-down predictor (Jenkins et al., 2003). This means that readers with poor word reading skills can use contextual cues as a compensatory mechanism to mask their difficulties. Measurements of text reading fluency may therefore appear to be an interesting indicator of the efficiency of adult dyslexic reading skills. Text reading fluency (hereafter TRF) is a complex skill that likely depends on the simultaneous integration of multiple cognitive and linguistic processes (Fuchs et al., 2001). The current conception of TRF takes account of and integrates the ability to group words into syntactic and semantic units as well as the ability to use punctuation to modulate phrasing and intonation while reading (Veenendaal et al., 2014; Paige et al., 2017; Godde et al., 2021). Efficient TRF is behaviorally defined as "*accurate, rapid, effortless reading with appropriate prosody*" (Wolf and Katzir-Cohen, 2001). Its most widely used and accepted measure consists of a time-limited text reading aloud task (Fuchs et al., 2001).

Very recently, a comprehensive meta-analysis conducted by Reis et al. (2020) including 178 studies compared the reading performance of adult readers with and without dyslexia and reported that deficits in TRF are persistent in adults with dyslexia and are expressed by a very large (and significant) effect size ($d = 1.76$). Although the TRF deficit is well established in adults with dyslexia (see also, for example, Callens et al., 2012), only very few studies have looked at the predictors of TRF in adults with dyslexia. To our knowledge, the study by Ransby and Swanson (2003) is one rare work that has directly addressed this issue. In this study, TRF performance was assessed with a composite score from both the Gray Oral Reading Test (GORT-3; Wiederholt and Bryant, 1992), in which a text reading aloud task was followed by a comprehension questionnaire, and the Fast Reading Subtest of the Stanford Diagnostic Reading Test (SDRT, Karlsen et al., 1984). In this subtest, participants were given 3 min (180 s) to silently read one-page stories. Interspersed throughout the stories were 30 highlighted lines, each containing three words. Participants had to choose (in a multiple-choice context) the word that made the most sense. The composite score

[1] Approximately 1.4% of the student population in France (unpublished data from University Disability services); between 4% and 6.3% in the United Kingdom (*UK Higher Education Statistic Agency*); between 1.6% and 6.4% in Spain (López-Escribano et al., 2018); and between 1.5% and 4% in Sweden (Wolff and Lundberg, 2002).

calculated on the basis of performance on the GORT Reading Aloud Subtest and the SDRT Fast Reading Subtest was called the Reading Comprehension Fluency score. In this study, a wide range of tasks were administered assessing phonological skills (pseudoword reading, phoneme deletion and counting), word recognition, naming speed, vocabulary, listening comprehension (oral versions of the passages from Form B of the *GORT*), verbal working memory (VWM) [assessed with a listening span task derived from Daneman and Carpenter (1980) and a semantic association task], general knowledge and non-verbal intelligence (Raven Progressive Matrices, Raven and Summers, 1986). In all the administered tasks, the performances of the adults in the dyslexia group were significantly lower than those of the control group (except for the non-verbal intelligence test and one phoneme task, namely the phoneme deletion task). Using hierarchical regression modeling, the authors reported that three scores predicted independent variance in text reading fluency (in this case, for comprehension), namely verbal working memory/non-verbal intelligence, phonological processing (a composite score including pseudoword reading, phonemic awareness) and listening comprehension. Interestingly, higher-order factors (such as listening comprehension) explained significantly more additional variance than lower-order factors (such as phonological factors) and there was no indication of any interaction with the group factor. These results suggest that when adults with dyslexia read texts aloud for comprehension, the explanatory factors are the same as those at work in control readers and, as might be expected, higher-order skills have a greater explanatory power than lower-order skills. Using the Gray Oral Reading Test (GORT-3; Wiederholt and Bryant, 1992) to assess TRF in adolescents with dyslexia, Rose and Rouhani (2012) reported that word recognition, verbal working memory and expressive vocabulary (vocabulary subtest of the WISC, Wechsler, 1997) were significant predictors of their scores. A significant interaction between verbal working memory and expressive vocabulary also predicted the TRF scores, with verbal working memory being more involved when adolescents exhibited poor vocabulary, suggesting a compensatory effect of vocabulary skills (higher-order factor).

Although interesting, these two studies do not provide a "pure" measure of TRF, i.e., text reading fluency independently of the reading comprehension process (involving semantic/interpretation processes). Such a measure might unambiguously explain, for example, the influence of higher-order skills such as listening comprehension, which has conventionally been used to explain text reading comprehension scores (Keenan et al., 2008). Thus, one of the objectives of this study is to clarify this point because, based on the SVR framework (Gough and Tunmer, 1986), it has long been considered that both decoding and word recognition skills [assessed by a pseudoword reading fluency (PWF) task and a word reading fluency (WRF) task, respectively] are sufficient to explain TRF performances without any need for recourse to higher-order factors (LaBerge and Samuels, 1974; Allington, 1983; Torgesen et al., 1999; Fuchs et al., 2001; Adolf et al., 2006; Hudson et al., 2008).

Even though they used many different measures, Ransby and Swanson (2003) did not study the role of spelling skills when explaining TRF scores, although research on children and adolescent with dyslexia has shown a reciprocal relationship between decoding and visual word recognition skills, on the one hand, and spelling skills on the other (Berninger et al., 2008; Bazen et al., 2020). Furthermore, the involvement of spelling skills in the reading of adults with dyslexia has been little studied, probably because research on this point has shown a persistent deficit in these skills. For example, the meta-analysis by Reis et al. (2020) reported an impairment among these readers, with the spelling tasks used to assess the ability to spell in this population, such as writing words or pseudowords from dictation (deficit assessed with a Cohen's *d* of 1.7), making use of the conventions of letter-sound relationships. This result is not surprising since spelling tasks require participants to use orthographic knowledge, the acquisition of which depends partially on phonological factors widely impaired among readers with dyslexia (in children, Manis et al., 1993; Vellutino et al., 2004; but also in adults, Bruck, 1990).

However, some studies suggest that orthographic knowledge/skills in adults with dyslexia might be less impaired than in children. For example, Miller-Shaul (2005) used a variety of orthographic tasks (for example, the orthographic decision task in which participants have to decide whether two orally presented words are written with the same letters or not) and reported some particularly informative results. In this study, the orthographic skills of dyslexics were compared to those of typical readers in two groups of participants, i.e., children in their fourth year of primary school and adult university students. Overall, the performances of dyslexic readers were significantly better in adults than in children, suggesting an improvement in orthographic skills during development, and no difference was observed between the dyslexic and the typical readers in adulthood.

In one of the very few studies to have examined the role of spelling skills and TRF in compensated and non-compensated dyslexic adults, Lefly and Pennington (1991) reported that compensated dyslexic adults performed better than non-compensated dyslexic adults on TRF (as assessed with the GORT test) and spelling tasks. Interestingly, Leinonen et al. (2001) used a text reading aloud task followed by comprehension questions and concluded that advanced spelling skills might help some adult dyslexic readers to compensate for their phonological deficits. This hypothesis is consistent with the results of the study by Siegel et al. (1995), which made use of an orthographic awareness task (designed to measure awareness of the properties of English words and the probable sequence and positions of letters) and revealed that the scores of dyslexic readers from first to eighth grade were significantly higher than those of control readers. The authors suggest that "the difficulties with phonological processing and the increased orthographic knowledge of the dyslexic readers may indicate a reading strategy that relies more on the visual than the phonological features of words." Overall, these studies indirectly suggest that spelling skills may in some way be used in the TRF skills of adults with dyslexia through one of their components, namely orthographic knowledge, given that these participants' visuo-spatial memory skills, on which the orthographic coding of words partly relies, seem to be preserved (see the meta-analysis by Swanson and Hsieh, 2009). To summarize, the main predictive factors of a "pure" measure of TRF which would not require extensive semantic processing (contrary to that proposed by Ransby and Swanson, 2003) would primarily consist of lower-order skills, including visual word recognition, decoding and spelling skills, whereas higher-order factors would exert less influence in skilled readers (who may rely on automatized word reading processes) than in individuals with dyslexia.

Text Reading Comprehension in Adults With Dyslexia

Reading comprehension is a complex cognitive activity that involves "*performing in a very short time a set of operations ranging from the recognition of written words to the construction of a coherent representation of the situation described, through syntactic analysis and the linking of referents and ideas stated in successive sentences*" (Bianco, 2015). Word recognition skills, language and general knowledge activation, working memory and reasoning skills as well as inference-making abilities are involved and often interact during reading comprehension in order to construct a coherent mental representation of the text (i.e., a model of the situation) that integrates the information contained in the text, the reader's knowledge and the inferences that he or she has made during the reading of the text (van Dijk and Kintsch, 1983; Kintsch, 1988). In line with this proposal, findings from a meta-analysis by Quinn and Wagner (2018) investigating the relationships among components of reading comprehension in a large sample of children and adolescents (N = 1,205,581; 155 studies included) have shown that three cognitive factors best predict reading comprehension performance, especially for adolescent readers. These factors include (1) a "decoding" factor corresponding to WRF, TRF and word reading accuracy, (2) a "linguistic comprehension" factor corresponding to general knowledge, semantic and morphological knowledge and listening comprehension, and (3) a "cognitive" factor corresponding to working memory, reasoning and inference-making.

According to this general framework, each of the postulated skills/knowledge involved in reading comprehension may represent potential sources of difficulty for individuals with dyslexia in understanding written text. Interestingly, it seems possible that some of these components may also act as compensatory factors, thereby explaining that whereas some meta-analyses report significantly poorer performance in reading comprehension (Reis et al., 2020), the amplitude of the deficits appears to be much less than that observed for low levels of reading (effect size for visual word recognition is d = 1.81; for decoding skills d = 2.03 and for text reading comprehension d = 0.729). Thus, as mentioned earlier, a number of studies report similar text reading comprehension performance in adults with dyslexia and in skilled control readers when no time constraints are imposed (Lesaux et al., 2006; Parrila et al., 2007; Deacon et al., 2012).

Few studies have systematically investigated the factors (from reading skills to executive functions, general knowledge and listening comprehension skills) that explain text reading comprehension in adult readers with and without dyslexia. The study by Ransby and Swanson (2003) is one of the most comprehensive in this respect. Using hierarchical regression modeling in both adults with and without dyslexia, the authors reported that phonological processing, naming speed, vocabulary, general knowledge, and listening comprehension are good predictors of text reading comprehension. However, one interesting finding was that the predictive power of higher-order factors was much greater than that of lower-order factors, with the respective contributions being similar in both groups of readers. These results are in line with those of the meta-analysis by García and Cain (2014), which reported that the relationship between reading comprehension and oral language comprehension becomes stronger as the reader's decoding skills become more automatized (see also Verhoeven and van Leeuwe, 2012; Foorman et al., 2015). Consequently, the primary demand faced by most skilled adult readers is not word decoding but instead comes from the nature of the text itself, for example in terms of content and vocabulary complexity (Braze et al., 2007). Therefore, skilled adult readers would be more likely to place greater reliance on listening comprehension and semantics (i.e., vocabulary skills) in support of reading comprehension (Lervåg et al., 2018).

In the study by Ransby and Swanson (2003), VWM and non-verbal intelligence were no longer reported as predictors of text reading comprehension scores once naming speed was included in the analysis. Using Structural Equation Modeling in skilled adult readers, Georgiou and Das (2016, 2018) also reported no influence of VWM capacity (i.e., as assessed with listening span and digit memory) on text reading comprehension scores. However, it can be hypothesized that the tasks used to assess VWM might not have been sensitive enough for the effects to be clearly demonstrated. Working Memory is a limited-capacity memory system that is involved in the temporary storage and processing of information by maintaining, integrating and manipulating information from a variety of sources (Smith-Spark and Fisk, 2007). A number of different span tasks have been developed and one of those to have attracted the most attention from researchers is the reading span task developed by Daneman and Carpenter (1980), which has been argued to provide a good overall measure of the WM capacity involved in reading (that is, the capacity which mobilizes the processes involved in reading comprehension, Daneman and Carpenter, 1980; Friedman and Miyake, 2004; Conway et al., 2005; Smith-Spark and Fisk, 2007). A recent meta-analysis by Reis et al. (2020) reported a VWM deficit for adults with dyslexia, with an effect size of d = 0.9, and Ransby and Swanson (2003) found a similar involvement of VWM when explaining text reading comprehension in adults with dyslexia compared to control readers.

Text Reading Fluency and Reading Comprehension

As mentioned earlier, university students with dyslexia have to read large numbers of long and complex texts. TRF would therefore be a more ecological and appropriate measure of their basic reading competence and may be considered to underlie their text reading comprehension processing, which involves word access and a word-to-text integration process (Perfetti and Stafura, 2014).

Within the general information processing framework, Georgiou and Das (2014) used two indicators of reading fluency, namely fluency at word level and fluency at passage level, to address the question of how reading fluency and text reading comprehension may be related. In their formal framework (Georgiou and Das, 2014), TRF first makes it necessary to identify the isolated words in the text (based on orthographic and phonological processes) and to memorize the sequence of words they belong to. Both these steps are mainly performed under the control of sequential (or) successive processes. Simultaneous processes then come into play as it becomes necessary to process the relationship between words and integrate them into complete units of information (sentences, for example), for example when it is necessary to analyze and synthesize grammatical relationships during reading comprehension. In their revised framework (Georgiou and Das, 2014), simultaneous processing is assumed to predict reading comprehension through the effects of TRF and successive processing is assumed to predict reading comprehension through the effects of word-reading fluency. In addition, simultaneous processing is expected to have a direct effect on reading comprehension because the full, integrated comprehension of the main and subsidiary ideas is required only for a fraction of the text in any given passage. The authors used structural equation modeling (i.e., path analysis) for a sample of 128 university students and showed that successive processing predicted reading comprehension indirectly via text- and word-reading fluency, whereas simultaneous processing predicted reading comprehension both directly and indirectly via text-reading fluency. In a second study, they compared a sample of university students with (n = 20) and without (n = 23) reading difficulties and showed that the cognitive difficulties experienced by the group of university students with reading difficulties related primarily to successive processing (25% of the sample), and also found that 30% had a dual simultaneous/successive deficit and that only 5% exhibited a simultaneous deficit. The path analysis was not tested because of sample size issues.

In the light of the results of the study by Ransby and Swanson (2003), Georgiou and Das (2014) did not include the TRF measures in their analysis of reading comprehension measures and the TRF measure itself was not a "pure" one, unlike that used by Georgiou and Das (2014), it can be assumed that, in skilled readers, written word recognition (or word reading fluency) and TRF abilities are sufficiently developed to support text reading comprehension. As far as individuals with dyslexia are concerned, two alternative hypotheses can be considered. The first assumes that both word reading and TRF skills are qualitatively too poorly developed to significantly assist text reading comprehension. This hypothesis is supported by the results of Gelbar et al. (2016) reporting that TRF was not a significant predictor of text reading comprehension in secondary students with dyslexia. These results are in line with those showing a dissociation between TRF and text reading comprehension skills in university students with dyslexia (Murray and Wren, 2003; Corkett et al., 2006; Deacon et al., 2006; Cavalli et al., 2019). According to Tunmer and Greaney (2010) and Gelbar et al. (2016), readers with dyslexia would have developed some reading comprehension compensation strategies above the "word" level, thus explaining why some individuals with dyslexia demonstrate age-appropriate reading comprehension abilities that are not explained by their word reading skills and decoding abilities. An alternative interpretation, proposed by Pedersen et al. (2016), suggests that many dyslexics in higher education tend to focus their attention on one subcomponent of the reading process, for example, decoding or comprehension, because engaging in both simultaneously may be too demanding for them. The second hypothesis is that the skills involved in written word recognition and the successive processing of information are too deficient to influence comprehension. However, because TRF is thought to rely on both relatively preserved simultaneous processing (integrating words into whole units of information) and compensatory processes (higher-order factors such as general knowledge, listening comprehension, for example), it may be involved in text reading comprehension.

The Current Study

The objective of our research is twofold. Firstly, we will compare the text reading fluency and text reading comprehension skills of French dyslexic university students reading in a more transparent orthographic system than English (which is over-represented in the studies cited) on the basis of tests specifically created or adapted for an adult population (listening comprehension, text reading comprehension, TRF, word reading, decoding, phoneme awareness, spelling, visual span, reading span) and on the basis of more general tests that are already available (vocabulary, non-verbal reasoning, general knowledge tests). In line with the literature, we predicted lower scores in the dyslexic group on all the lower-order skills, including word reading fluency, decoding, phoneme awareness, as well as spelling and TRF. Moreover, based on persistent deficits in decoding and visual word recognition skills as well as in VWM (Reis et al., 2020) in adults with dyslexia, we expected reading span to be impaired in this population. In contrast, we expected text reading comprehension performance to be preserved (as it is assessed with no time pressure) in the same way as higher-order skills such as general knowledge, vocabulary and non-verbal intelligence. Finally, based on the meta-analysis by Swanson and Hsieh (2009), we also expected visuo-spatial skills to be preserved in adults with dyslexia.

Secondly, using multiplicative linear regression analysis we will identify the best predictors of both TRF and text reading comprehension in these two populations. To this end, we will test the hypothesis that TRF and text reading comprehension in adults with dyslexia are mediated not only by low-level skills, but also by higher-level skills. We also formulated two alternative hypotheses which contrast the involvement of TRF in text reading comprehension in adults with dyslexia with the case of skilled readers, for whom TRF is expected to be a significant predictor of text reading comprehension.

MATERIALS AND METHODS

Participants

The experiment was conducted in accordance with the Declaration of Helsinki and with the understanding and written consent of all the participants. The project was approved by the local ethics committee (Aix-Marseille University, Marseille, France). One hundred and seventeen participants were recruited (54 adults with dyslexia, DYS; 63 skilled adult readers, SR). All were university students, French native speakers, and had normal or corrected-to-normal vision. The 65% of the participants were enrolled in social science programs (e.g., psychology, law, economics, or archaeology) and 35% were enrolled in science programs (e.g., neurosciences, pharmacy, medicine, chemical physics, or mathematics). The data of four participants (one participant with dyslexia and three skilled readers) were removed from the data set because they performed under the 75th percentile in non-verbal intellectual quotient (IQ) (Raven's Matrices; Raven et al., 1998). The remaining 113 participants (53 DYS and 60 SR) had a non-verbal IQ within the normal range (above the 75th percentile). None of them reported any neurological or psychiatric disorders. All participants with dyslexia reported major difficulties in learning to read during childhood and had received a formal diagnosis of dyslexia (mean age of diagnosis = 9.17, sd = 3.3) established by a physician in a reference center for learning disabilities. They were recruited at Aix-Marseille University and Lyon University, primarily through the University Disability Service.

As reported in **Table 1**, the two groups were matched on chronological age, educational level, vocabulary knowledge (the EVIP scale; Dunn et al., 1993), and non-verbal IQ (Raven's matrices; Raven et al., 1995).

TABLE 1 | Cognitive profiles of readers with and without dyslexia.

	Readers with dyslexia	Skilled readers	*t*-values		Cohen's *d*
Chronological age	20.4 (1.9)	20.2 (1.7)	0.09	ns	0.09
Years of higher education	2.43 (1.56)	2.37 (1.69)	0.33	ns	0.04
Non-verbal IQ (raw scores)	43.57 (6.88)	44.84 (5.55)	−1.06	ns	0.20
Visuo-spatial span	6.64 (1.52)	5.96 (1.73)	2.17	*	0.42
Reading and spelling skills					
Alouette (efficiency)	119.19 (24.42)	171.73 (24.61)	−11.37	***	2.14
Word reading	76.94 (21.84)	105.5 (22.33)	−6.86	***	1.29
Pseudoword reading	75.71 (28.21)	137.26 (29.89)	−11.25	***	2.11
Text reading fluency	142.67 (29.51)	197.83 (30.54)	−9.70	***	1.83
Reading span	38.3 (8)	44.19 (7.29)	−4.04	***	0.77
Spelling	68.87 (6.02)	75.15 (2.85)	−6.94	***	1.36
Phonological skills					
Phonemic awareness (efficiency)	1.18 (0.42)	2.01 (0.45)	−9.81	***	1.89
Phonological short-term memory	4.36 (0.88)	4.93 (0.8)	−3.61	***	0.69
Comprehension skills					
Listening comprehension	10.3 (4.25)	10.48 (3.6)	−0.24	ns	0.05
Text reading comprehension	23.23 (5.5)	20.75 (5.8)	2.32	*	0.44
General knowledge	11.43 (3.6)	12.37 (4.1)	−1.28	ns	0.24
Vocabulary knowledge	38.44 (6.23)	40.18 (4.59)	−1.62	ns	0.32

*Standard deviations are reported in parentheses. T-values were obtained from unpaired Student t-tests comparing the two groups of participants (***$p < 0.001$; *$p < 0.05$; $^{ns}p > 0.10$).*

Material

We administered a battery of 14 tasks to each participant. Administration of the tasks took about 2 to 2.5 h and the tasks were presented in the same order for each participant.

One-Minute Word Reading (Word Reading Fluency)

Participants were instructed to read written words aloud as fast and accurately as possible for 1 min. Words were presented on a printed sheet containing six words per line. The 120 disyllabic French words with a length between 4 and 9 letters (mean = 6.4; sd = 1.29) and a frequency varying from low to high (mean = 28.6; sd = 43.4) were selected using the *lexique.org* database (New et al., 2001). An efficiency score which took account of both accuracy (A) and reading time (RT) was then computed for each participant: (A/RT)*60.

Two-Minute Pseudoword Reading (Decoding)

Participants were instructed to read 116 written pseudowords aloud as fast and accurately as possible for 2 min. Pseudowords were presented on a printed sheet containing six pseudowords per line. They were one or two syllables in length and had an average letter length of 5.5 (sd = 0.5). Efficiency scores were again calculated for each participant: (A/RT)*120.

Text Reading Fluency

Participants were instructed to read a text aloud as fast and accurately as possible in 1 min and to respect the punctuation marks while doing so. The text was taken from *"The red silk scarf"* (Leblanc, 1913), a short narrative literary French text consisting of 434 words and 24 sentences. For the purposes of our task, we reduced the text length by presenting only the first 337 words (17 sentences). The main linguistic characteristics of the text were determined using the *Cordial Neo* software (Synapse Développement, 2019). The sentences in the text were of normal length (mean: 19.8 words/sentence) and had a simple grammatical structure (few adjectives and pronouns, 11.2% and 5.9%, respectively). Moreover, the text included a high proportion of very frequent words [85.8% according to Gougenheim's Fundamental French (Gougenheim, 1977) and 78.9% according to Dubois–Buyse's scale (Dubois and Buyse, 1940/1952)], and a limited number of low-frequency words (1.2%). Thus, the readability index of the passage (Flesch score) was equal to 49 on a scale ranging from 1 (very difficult) to 100 (easy), situating it as a text of average complexity (secondary education level). Gougenheim's Fundamental French (Gougenheim, 1958, revised in 1977) is a list of the 3,500 most common words and of the most usual grammatical concepts in French. The Dubois–Buyse scale (Dubois and Buyse, 1940, revised in 1988) is a corpus of 3,787 commonly used words that are assumed to be known by any French-speaking adult (80% after 6 years of schooling).

Alouette

The Alouette test (Lefavrais, 1967) requires participants to read a 265-word text aloud as rapidly and as accurately as possible within a maximum of 3 min. The specificity of this test is that the text consists of real words contained in meaningless but grammatically and syntactically correct sentences, thus preventing dyslexic readers and poor readers from compensating for their written word recognition difficulties by using contextual information. The test yields measures of accuracy (A, number of words correctly read), reading time (RT, time taken to read the text), and reading efficiency [called CTL, computed using the following formula: CTL = (A/RT)*180, where A = accuracy (self-corrections included), and RT = reading time (maximum = 180 s); see Bruyer and Brysbaert (2011), Cavalli et al. (2018), for a detailed presentation of efficiency scores]. Interestingly, the test is standardized for children aged 5 to 14 and provides a score expressed in terms of reading age. The test has now also been standardized for adults with and without dyslexia (Cavalli et al., 2018). The psychometric qualities of this test have been demonstrated in a number of previous studies in both children (Bertrand et al., 2010) and adults (Cavalli et al., 2018).

Spelling

In this computerized timed-test, participants were instructed to write down the words they heard as accurately as possible on a sheet of paper (see Tops et al., 2012 for more details). They had 3 s to write down a given word before hearing the next one and were instructed to go on to the next if they could not write the word. They were also warned that they could not go back to a word to correct its spelling. Eighty words were selected from the *lexique.org* database (New et al., 2001). Words varied in spelling consistency (half consistent words, half inconsistent words), written frequency (mean = 47; sd = 100), were from 3 to 8 letters long (mean = 6; sd = 1,35) and were composed of 1 to 2 syllables. Words had been recorded in a soundproof room by a French native speaker prior to the test. Word order was randomized. The final score corresponded to the number of correctly written words (maximum 80).

Phonemic Awareness

In this computerized test, participants were instructed to repeat, as fast and accurately as possible, the pseudowords they heard after deleting the first phoneme (e.g., they heard/blɔ/and had to say/lɔ/). The 30 monosyllabic pseudowords with a Consonant-Consonant-Vowel (CCV) structure were selected. Pseudowords were used in order to avoid the activation of lexical knowledge. Reliability (Cronbach's α) was 0.88 (95% confidence interval [0.83; −0.90]). As in the previous tasks, the final scores were efficiency scores which took account of both accuracy and response times: (A/RT)*100.

Phonological Short-Term Memory

This computerized task was selected from the EVALEC battery (Sprenger-Charolles et al., 2005). Participants heard 24 pseudowords which they had to repeat. The length of the pseudowords increased progressively (from 3 to 6 syllables, six items per condition). The task started with a practice session of three items (not included in the final scores). The final scores were efficiency scores: (A/RT)*100.

Non-verbal Intellectual Quotient

Non-verbal reasoning abilities were determined using the Standard Progressive Matrices (Raven et al., 1998). The final score corresponded to the number of correctly completed patterns (maximum = 60).

Vocabulary Knowledge

We used a short computerized presentation of the French adaptation of the *Peabody Picture Vocabulary Test* (EVIP; Dunn et al., 1993). This task assesses the participants' receptive vocabulary. The task started with a practice session of four items (not included in the final scores). Only accuracy was recorded (the number of correctly identified words; maximum = 51).

General Knowledge

This task corresponds to the subtest of the Wechsler Adult Intelligence Scale (WAIS, Wechsler, 1981). The task was untimed and consisted of 24 questions assessing non-specific general knowledge. The final score corresponded to the correct number of responses (max = 24).

Text Reading Comprehension

We created a text comprehension task to evaluate literal comprehension and two types of inferential comprehension skills. We assessed, on the one hand, "text-connecting" inference skills, which require participants to integrate text information in order to establish local cohesiveness and, on the other, "knowledge-based" inference skills, which make it possible to establish links between the text content and the reader's personal knowledge. Participants had to read three short texts to themselves without time constraints. All three texts were newspaper articles from *Le Monde* concerning the Great Barrier Reef. This topic was chosen to avoid any advantage due to knowledge of the field of study on the part of participants. After reading the texts, participants had to answer eight questions evaluating their comprehension: four questions about explicit literal comprehension and four inferential questions about the comprehension of the implicit information in the texts (two examining text-connecting inferences and two examining knowledge-based inferences). One half of the questions were multiple choice questions, the other half were open questions. Participants were not allowed to refer to the text when answering the questions. The main characteristics of each text are presented in the **Appendix Table A1**. Reliability (Cronbach's α) was 0.78 (95% confidence interval [0.74; 0.83]).

Listening Comprehension

In this task, participants had to listen to a short story while trying to remember it in order to answer questions. The selected story was a passage taken from the French version of Planet of The Apes (Boulle, 1963). It consisted of 278 words and 22 sentences (mean length: 12.6 words/sentence). The linguistic characteristics of the text were determined using the *Cordial Neo* software (Synapse Développement, 2019). A high proportion of common words were used, thus making the text easy to understand: 84.9% of words belonged to Gougenheim's core French corpus (Gougenheim, 1977), and 79.5% to Dubois–Buyse's scale (Dubois and Buyse, 1940; Ters et al., 1988). The story was about a man captured and made prisoner by apes, making the situation incongruous. The understanding of this text requires both precise literal understanding and good inferential reasoning. The story was recorded in a soundproof room by a French-native female speaker. At the end of the story, participants had to answer 20 open questions (10 questions examining literal comprehension, 10 questions examining inferential comprehension). The final score corresponded to a global comprehension score (/20). Reliability (Cronbach's α) was 0.69 (95% confidence interval [0.56; 0.76]).

Reading Span Test

This (computerized) test was created by Daneman and Carpenter (1980) and uses 60 sentences (out of 100) selected from the French version of Desmette et al. (1995). Participants were instructed to read sentences while memorizing the last word of each and indicating if the sentence was meaningless or not. Sentences were presented in blocks containing 2 to 6 sentences. After each block, participants had to recall all the last words of the sentences in the previous block. The task started with a practice session containing one block of two sentences (not included in the final score). The final score corresponded to the number of correctly recalled words (maximum = 60), regardless of the order in which they were recalled (Friedman and Miyake, 2005).

Visuo-Spatial Span

This task corresponded to the Visual Pattern Test (Della Sala et al., 1997) and allowed us to examine the ability to remember static visual patterns. Square matrices were presented to participants for 3 s. The participants were then asked to recall the pattern by shading the appropriate squares on a blank matrix. Matrices of increasing difficulty were presented (from 2 to 15 filled squares, three matrices for each difficulty level). The test stopped when the participants could not correctly recall a pattern. The final score corresponds to the mean difficulty level of the last three correctly recalled patterns, with a maximum score of 15.

RESULTS

As can be seen in **Table 1**, the t-tests revealed that readers with and without dyslexia did not differ on non-verbal IQ, listening comprehension, general knowledge, or the vocabulary knowledge tasks (all t values between −0.2 and 1.2; Cohen's $d \leq 0.32$). Interestingly, readers with dyslexia had a greater visuo-spatial span than skilled readers ($p < 0.05$), even if the associated effect size was relatively low (Cohen's $d = 0.42$). The group with dyslexia also achieved better text reading comprehension scores than skilled readers ($p < 0.05$), and this was associated with a moderate effect size (Cohen's $d = 0.44$). However, and as expected, they exhibited poorer performance than skilled readers on the phonological tasks (i.e., phonemic awareness, and phonological short-term memory; all ps < 0.001), and this was associated with moderate to large effect sizes (all Cohen's $d \geq 0.69$). They also achieved poorer reading and spelling performances than skilled readers on all measures, including the Alouette, word and pseudoword reading, the TRF, reading span, and spelling (all ps < 0.001), again with moderate to large associated effect sizes (all Cohen's $d \geq 0.77$).

Text Reading Fluency Among University Students With and Without Dyslexia

In a first step, a correlation analysis was performed between TRF performance and performance on low-level skills (decoding, reading words, spelling) and high-level skills (listening comprehension, vocabulary, general knowledge and reading span). This was done for both groups together, and separately. For reasons of clarity, **Figure 1** shows only significant correlations between TRF and each of the covariates we selected in the model of subsequent stepwise regression analysis- for the two populations together (i.e., the red line) and for each group separately (i.e., the black lines). As can be seen, TRF was highly positively correlated with word (DYS: $r = 0.51$, $p < 0.001$; SR: $r = 0.67$, $p < 0.001$; both: $r = 0.74$, $p < 0.001$) and pseudoword (DYS: $r = 0.42$, $p < 0.01$; SR: $r = 0.55$, $p < 0.001$; both: $r = 0.74$, $p < 0.001$) reading skills, both for the two groups separately and when taken together. Spelling skills were positively correlated with TRF when both populations were considered ($r = 0.59$, $p < 0.001$). This correlation was also observed for readers with dyslexia ($r = 0.48$, $p < 0.001$), but not for skilled readers ($r = 0.18$). In contrast, oral comprehension was positively correlated with TRF in skilled readers ($r = 0.38$, $p < 0.01$), but not in readers with dyslexia ($r = −0.10$) or in the two populations taken together ($r = 0.11$). Finally, reading span was also positively correlated with TRF when both populations were considered ($r = 0.26$, $p < 0.01$), but not in each population separately (DYS: $r = −0.03$; SR: $r = 0.10$).

We then applied a multiplicative linear regression model. The selected covariates result from the significant correlations that were observed. Their interactions with the group covariate were also tested (as well as the group covariate itself). A summary of the model is available in **Table 2** and the regression coefficients are presented in **Table 3**. As shown in **Table 2**, the fifth model fitted the data well (adjusted $R^2 = 0.686$; RMSE = 22.695) and explained 69.7% of changes in TRF ($R^2 = 0.697$, $R = 0.835$) based on the combination of pseudoword reading, word reading, and spelling skills, as well as the pseudoword reading * group interaction.

As can be seen in **Table 3**, reading span and listening comprehension skills do not appear to significantly explain any variability in TRF scores. However, the presence of positive relations in the final model (i.e., model 5) between TRF and pseudoword reading (β = 0.295, $p < 0.001$), word reading (β = 0.391, $p < 0.001$), and spelling skills (β = 0.148, $p = 0.03$) suggests that individuals who had better word and pseudoword reading abilities and spelling skills were also those with better TRF scores. Moreover, the presence of a negative relation

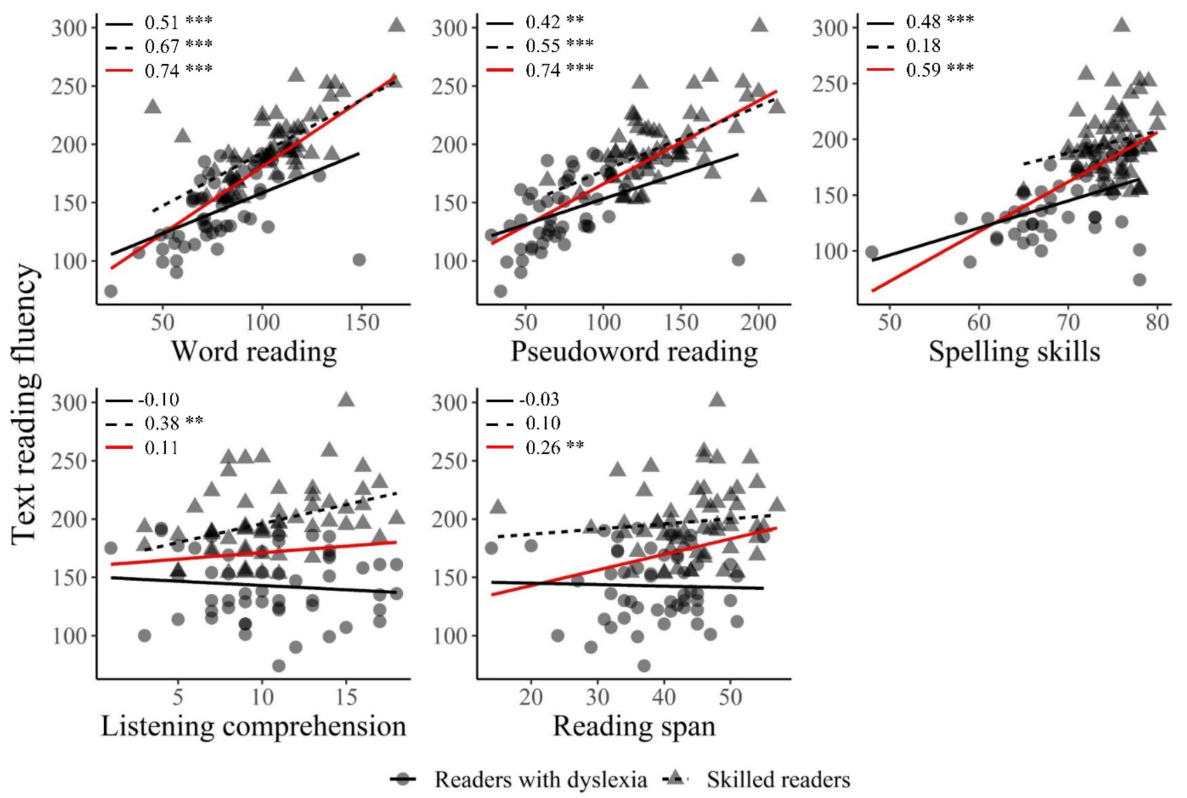

FIGURE 1 | Correlations between TRF and each of the covariates (i.e., word reading, pseudoword reading, spelling skills, listening comprehension, and reading span). Skilled readers are represented by dots, and the corresponding correlation slope is represented by the solid black line. Readers with dyslexia are represented by triangles, and the corresponding correlation slope is represented by the dashed black line. The solid red line represents the correlation slope for the two populations combined. Pearson's correlations for each slope are indicated in the top left corner of each plot and asterisks represent the significance level of the *p*-value (**$p < 0.01$, ***$p < 0.001$).

between TRF and the pseudoword reading * group interaction ($\beta = -0.208$, $p < 0.001$) suggests that pseudoword reading explained TRF to a lesser extent in readers with dyslexia than in skilled readers (see **Figure 1**).

Text Reading Comprehension Among University Students With and Without Dyslexia

A correlation analysis was first performed between Text reading comprehension performance and performance on low-level skills (decoding, reading words, spelling) and high-level skills (listening comprehension, vocabulary, general knowledge and reading span). This was done for both groups together, and separately. For reasons of clarity, **Figure 2** shows only significant correlations between Text reading comprehension and each of the covariates we selected in the model of subsequent stepwise regression analysis- for the two populations together (i.e., the red line) and for each group separately (i.e., the black lines). As can be seen, text reading comprehension was highly positively correlated with general knowledge (DYS: $r = 0.52$, $p < 0.001$; SR: $r = 0.35$, $p < 0.01$; both: $r = 0.38$, $p < 0.001$), vocabulary knowledge (DYS: $r = 0.44$, $p < 0.001$; SR: $r = 0.40$, $p < 0.01$; both: $r = 0.41$, $p < 0.001$), and listening comprehension (DYS: $r = 0.61$, $p < 0.001$; SR: $r = 0.36$, $p < 0.01$; both: $r = 0.46$, $p < 0.001$), both when the two populations were taken separately and when they were considered together. TRF was positively correlated with text reading comprehension in skilled readers ($r = 0.33$, $p < 0.05$), but not in readers with dyslexia ($r = 0.07$) or when the two populations were taken together ($r = 0.004$). Non-verbal IQ was positively correlated with text reading comprehension in skilled readers ($r = 0.47$, $p < 0.001$) and when both populations were taken into account ($r = 0.27$, $p < 0.01$), but not in readers with dyslexia considered on their own ($r = 0.17$). Finally, reading span was slightly positively correlated with text reading comprehension in each population separately (DYS: $r = 0.28$,

TABLE 2 | Regression model summary of TRF.

Model	*R*	R^2	Adjusted R^2	RMSE
1	0.000	0.000	0.000	40.877
2	0.740	0.548	0.544	27.612
3	0.801	0.641	0.634	24.725
4	0.827	0.683	0.674	23.333
5	0.835	0.697	0.686	22.922

TABLE 3 | Regression coefficients of the model.

Model		Unstandardized	Standard error	Standardized	t	p
1	(Intercept)	171.673	3.898		44.047	<0.001
2	(Intercept)	94.617	7.231		13.084	<0.001
	Pseudoword reading	0.71	0.062	0.74	11.441	<0.001
3	(Intercept)	64.06	8.697		7.366	<0.001
	Pseudoword reading	0.431	0.077	0.449	5.611	<0.001
	Word reading	0.66	0.125	0.421	5.263	<0.001
4	(Intercept)	82.105	9.508		8.636	<0.001
	Pseudoword reading	0.332	0.077	0.346	4.299	<0.001
	Word reading	0.667	0.118	0.426	5.63	<0.001
	Pseudoword reading * Group	−0.219	0.058	−0.229	−3.76	<0.001
5	(Intercept)	11.153	33.596		0.332	0.741
	Pseudoword reading	0.283	0.079	0.295	3.588	<0.001
	Word reading	0.613	0.119	0.391	5.158	<0.001
	Pseudoword reading * Group	−0.199	0.058	−0.208	−3.434	<0.001
	Spelling skills	1.113	0.506	0.148	2.199	0.03

T-values and p-values were obtained from a stepwise regression linear model.

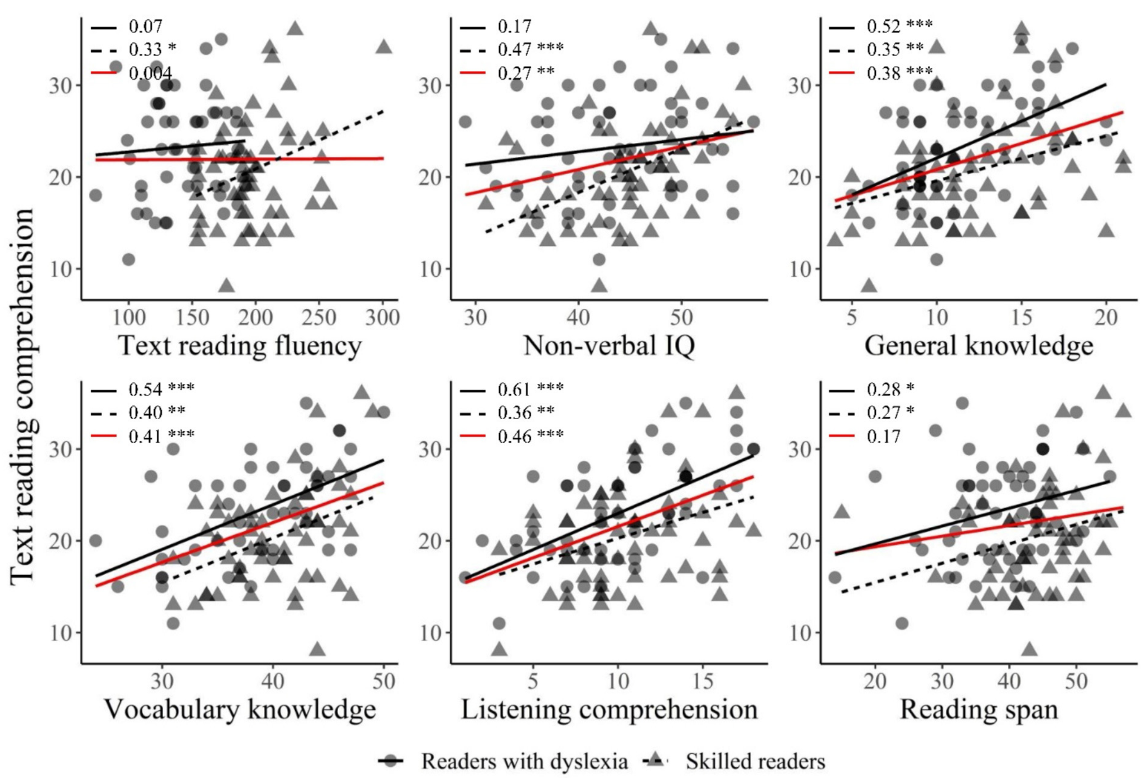

FIGURE 2 | Correlations between text reading comprehension and each of the covariates (i.e., TRF, non-verbal IQ, general knowledge, vocabulary knowledge, listening comprehension, and reading span). Skilled readers are represented by dots, and the corresponding correlation slope is represented by the solid black line. Readers with dyslexia are represented by triangles, and the corresponding correlation slope is represented by the dashed black line. The solid red line represents the correlation slope for the two populations combined. Pearson's *r* for each correlation slope is indicated in the top left corner of each plot and asterisks represent the significance level of the *p*-value (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

$p < 0.05$; SR: $r = 0.27$, $p < 0.05$), but not when both populations were considered ($r = 0.17$).

We then applied a multiplicative linear regression model. The selected covariates result from the significant correlations that were observed. Their interactions with the group covariate were also tested (as well as the group covariate itself). A summary of the model is available in **Table 4** and the regression coefficients are presented in **Table 5**. As shown in **Table 4**, the fourth

TABLE 4 | Model summary of text reading comprehension.

Model	R	R^2	Adjusted R^2	RMSE
1	0.000	0.000	0.000	5.766
2	0.488	0.239	0.231	5.056
3	0.578	0.334	0.320	4.754
4	0.642	0.413	0.395	4.485

model chosen for the analysis fitted the data well (adjusted R^2 = 0.395; RMSE = 4.485) and explained 41.3% of changes in written comprehension (R^2 = 0.413, R = 0.642) based on the combination of listening comprehension, vocabulary knowledge, and the general knowledge * group interaction.

As can be seen in **Table 5**, the presence of positive relations in the fourth model between text reading comprehension and listening comprehension (β = 0.349, $p < 0.001$) and vocabulary knowledge (β = 0.301, $p < 0.001$) suggests that individuals who had better oral comprehension and vocabulary knowledge also had better text reading comprehension abilities. In addition, the presence of a positive relation between text reading comprehension and the general knowledge * group interaction (β = 0.314, $p < 0.001$) suggests that general knowledge better explained text reading comprehension performances in readers with dyslexia than in skilled readers (see **Figure 2**). However, variability in text reading comprehension did not seem to be explained at a significant level by word reading, pseudoword reading, TRF, non-verbal IQ, or reading span.

DISCUSSION

The overall objective of this study was to gain a better understanding of the text reading comprehension processes in university students with dyslexia compared to those observed in skilled adult readers. To do so, we first compared the text reading fluency and text reading comprehension skills of French dyslexic university students and used a large set of tests to identify their components. We predicted lower scores in the dyslexic group on all the lower-order skills (including word reading fluency, decoding, phonemic awareness, spelling and TRF and reading span) but expected visuo-spatial skills and text reading comprehension scores to be preserved and no different from those of skilled adult readers. We then used stepwise linear regressions to examine the contribution of these skills to, first, TRF skills and, second, to text reading comprehension skills. Our hypotheses were, first, that the main predictive factors of a "pure" measure of TRF would essentially consist of lower-order skills including visual word recognition, decoding and spelling skills, while higher-order factors would have less influence in skilled readers (who may rely on automatized word reading processes) than in individuals with dyslexia. Second, we tested whether low-level skills and higher-level skills would have different impacts on text reading comprehension in adults with or without dyslexia and predicted that the involvement of higher-level skills would play a greater role in dyslexics, due primarily to the difficulties experienced by these participants. We formulated two alternative hypotheses concerning the involvement of TRF in text reading comprehension in adults with dyslexia. The first assumed that (underdeveloped) TRF would not act as a significant predictor of text reading comprehension, whereas the second considered that because TRF appears to rely on both relatively preserved and compensatory processes (higher-order factors such as general knowledge, listening comprehension, for example), it may be involved in text reading comprehension. As far as the skilled readers were concerned, we predicted that TRF skills would provide efficient support for text reading comprehension.

The Cognitive Profile of Dyslexic University Students

Unsurprisingly, we found that dyslexic university students achieved significant lower performances than skilled readers in phonological tasks (phonemic awareness and phonological short-term memory), reading fluency tasks (Alouette, isolated word and pseudoword reading fluency, TRF) and spelling (word dictation). The largest effect sizes were observed for the Alouette test, pseudoword reading, TRF and phonemic awareness. These results are consistent with studies targeting literacy and phonological skills in adults with dyslexia that have documented persistent deficits in isolated word and pseudoword reading (Ransby and Swanson, 2003; Wolff, 2009; Callens et al., 2012;

TABLE 5 | Regression coefficients of the model.

Model		Unstandardized	Standard error	Standardized	t	p
1	(Intercept)	21.82	0.56		38.41	<0.001
2	(Intercept)	14.34	1.42		10.10	<0.001
	Listening comprehension	0.71	0.12	0.48	5.62	<0.001
3	(Intercept)	13.29	1.36		9.74	<0.001
	Listening comprehension	0.66	0.12	0.45	5.55	<0.001
	General knowledge * Group	0.28	0.07	0.31	3.77	<0.001
4	(Intercept)	1.99	3.35		0.59	0.553
	Listening comprehension	0.51	0.12	0.34	4.21	<0.001
	General knowledge * Group	0.28	0.07	0.31	4.06	<0.001
	Vocabulary knowledge	0.32	0.08	0.30	3.65	<0.001

T-values and p-values were obtained from a stepwise regression linear model.

Swanson, 2012), spelling (Erskine and Seymour, 2005; Parrila et al., 2007; Swanson and Hsieh, 2009; Nergård-Nilssen and Hulme, 2014), TRF (Nergård-Nilssen and Hulme, 2014; Suárez-Coalla and Cuetos, 2015; Reis et al., 2020), phonological skills including phonemic awareness and phonological short-term memory tasks (Ramus et al., 2003; Miller-Shaul, 2005; Lindgrén and Laine, 2011; Swanson, 2012), and reading span (for which a reading task has been used to confirm the results observed with oral tasks, see Reis et al., 2020). The Cohen's *d* values confirmed those reported in the meta-analysis by Reis et al. (2020), which observed larger effect sizes in reading and spelling tasks as well as in phonological tasks.

We also showed that scores on the listening comprehension, vocabulary, general knowledge (WAIS information), and non-verbal reasoning (Raven's Matrices) tasks were similar to those of skilled readers. However, Reis et al. (2020) reported very low but significant Cohen's *d* values on these tasks (vocabulary, d = 0.59 and non-verbal IQ = 0.18). Furthermore, Ransby and Swanson (2003) found that adults with dyslexia scored significantly lower than skilled adult readers on vocabulary (receptive and productive) and listening comprehension tasks as well as on general knowledge. The discrepancies between results may be due, at least in part, to the wide variability in the cognitive profiles of dyslexic students. For example, the students in Ransby and Swanson's study all had special education backgrounds due to their reading disorder, whereas the students in our study all came to university after a conventional school career, which in most cases had also involved support from physiotherapists.

Our results also showed the visual-spatial span of students with dyslexia to be significantly larger than that of skilled readers. These results are in line with those of the meta-analysis by Swanson and Hsieh (2009), which found a trend (also non-significant) in favor of dyslexics. These results may explain why students with dyslexia appear to use significantly more visual-spatial cues than skilled adult readers when they read texts for comprehension (Cavalli et al., 2017). Dyslexic participants were also found to achieve higher scores in the text reading comprehension test (under unconstrained time reading). These surprising findings must be interpretated in the light of those obtained in research showing that dyslexic adults' text reading comprehension is equivalent to that of their skilled reading peers when they are allowed to read with no time constraints (Miller-Shaul, 2005; Parrila et al., 2007; Tops et al., 2012; Cavalli et al., 2019) as well as of data from the meta-analysis conducted by Reis et al. (2020), which showed that the effect sizes characterizing reading comprehension in dyslexic and skilled adults readers are small in languages with opaque orthographies such as French, and that the differences are reduced when the tests are not performed under time pressure. The absence of time constraints in our text reading comprehension test was undoubtedly beneficial for adults with dyslexia, who are less fluent in reading text and make more errors than their normal reading peers (Pedersen et al., 2016). The ability to read at their own pace for comprehension, reread if needed, and correct errors are all reading strategies that may participate in the comprehension performance of adults with dyslexia (Moojen et al., 2020). Furthermore, the fact that TRF was assessed independently of text reading comprehension likely meant that the cognitive resources involved in text comprehension were less impacted by a low fluency level.

Another reason is the length of the text and its complexity. For example, Ransby and Swanson (2003) used the GORT test in their study. This presents narrative and expository texts which are of average length (between 80 and 150 words) and have a lexical, syntactic and semantic complexity that is considered to be less than that of the texts we used, which were particularly suitable for adults (news articles from the daily newspaper *Le Monde*, intended for adults). One of the consequences of using these texts is that readers may have to draw heavily on their general knowledge to be able to understand precisely what they are currently reading. In line with this interpretation, the results of the regression analyses we conducted show that dyslexic readers made extensive use of this knowledge (see the next section on text reading comprehension) when reading for understanding. Indeed, Keenan et al. (2008) showed that the involvement of high-level factors, such as listening comprehension skills, in reading increases with increasing text length, to the benefit of lower-level factors (e.g., decoding skills).

Text Reading Fluency in University Students With and Without Dyslexia

The regression model that best fits our data is a three-factor model including word reading, pseudoword reading, and spelling. Explaining 69.7% of the variance in the two populations, it enabled us to identify low-level literacy skills as the best predictors of TRF in both samples. We also reported that decoding skills (as assessed by a pseudoword reading task) explained TRF to a lesser extent in dyslexic readers than in skilled readers. This result is consistent with data from dyslexic adolescents (Rose and Rouhani, 2012) showing that word reading is a stronger predictor of TRF than pseudoword reading in this population. This is no surprise since pseudoword reading scores in our sample were clearly deficient (d = 2.11) when compared to word reading scores (d = 1.29), a result which is consistent with many other studies (Reis et al., 2020) and which confirms that TRF in dyslexic students probably relies mainly on visual/orthographic word codes due to their phonological deficits, whereas phonological codes would also be involved in skilled readers. This interpretation is in line with that proposed by Siegel et al. (1995), Leinonen et al. (2001) and Miller-Shaul (2005), who suggest that individuals with dyslexia may compensate for their phonological deficiencies when reading by mobilizing less impaired spelling skills (d = 1.36). Visual-spatial abilities could in some way support the visual/orthographic abilities activated during word reading (and spelling). However, they would operate indirectly, as shown by our results, since visual-spatial abilities were not clearly identified as a predictor of TRF. Recent findings by Franzen et al. (2021) using eye movement recordings showed that dyslexic adults may use a different visual sampling strategy during text reading. Contrary to our expectations, higher-order factors, such as listening comprehension, vocabulary or general knowledge, did not emerge as significant predictors of TRF in French university students. These results are contradictory to those of Ransby and Swanson (2003) who reported that higher-order factors explain more variance than lower-order factors (see also Rose and Rouhani (2012) with adolescent dyslexics). This difference can be explained by the demands of the tasks in the two studies. While the participants in Ransby and Swanson's (2003) study were asked to read the text aloud and then answer questions, a task requiring extensive semantic processing that may demand the activation of general knowledge, vocabulary and processing skills involved in listening comprehension, the participants in the TRF task we proposed were not. Finally, using a "pure" TRF task, verbal working memory (in our case measured with the reading span task) does not appear to be a predictor of TRF for either dyslexic readers or skilled readers. These results echo the data from the literature showing that the verbal working memory of dyslexic adults is poorer than that of skilled readers (Hatcher et al., 2002; Ransby and Swanson, 2003; Miller-Shaul, 2005; Swanson et al., 2009; Martinez Perez et al., 2013; Nielsen et al., 2016; Eloranta et al., 2018) and that its relationship to TRF is weak (Peng et al., 2018) and decreases over development (Pham and Hasson, 2014). When concerned with skilled readers, it is possible that the direct link between Working Memory and TRF is not identifiable in our study with the tests we used, but also that this link may not direct but indirect, i.e., mediated by another skill (e.g., processing speed, attentional resources, or general knowledge), as Hannon (2012) suggests.

Text Reading Comprehension in University Students With and Without Dyslexia

Our best-fitting model of reading comprehension, explaining 41.3% of the variance, is a three-factor model involving listening comprehension, general knowledge and vocabulary. It is consistent with the results reported by Ransby and Swanson (2003) who showed that higher-order factors explained significant variance in both adult dyslexics and skilled readers, thus suggesting that text reading comprehension in this population relies primarily on top-down processes. One difference between this study and our own is that we found that general knowledge explained text reading comprehension scores in dyslexic readers better than in skilled readers, thus suggesting that the former group relies heavily on semantic information (possibly as a compensatory mechanism) when understanding written texts. Surprisingly, and contrary to our expectations, neither word reading, pseudoword reading, TRF nor reading span explained text reading comprehension scores at a significant level. Even more surprisingly, this was also true of skilled readers, for whom Georgiou and Das (2014) found significant effects of these factors. However, in an experiment which was more similar to our own, Ransby and Swanson (2003) found very little additional contribution of lower-level factors such as word reading and decoding (about 5% but significant) to explained variance. With skilled adult readers, Gonçalves et al. (2021) also reported the influence of both high-level factors such as vocabulary and listening comprehension and low-level factors (such as word reading) on explaining text reading comprehension performance although the authors observed a greater explanatory power of the former. In our study, the questions used in the text reading comprehension test are implicit and explicit questions. It is then possible that performance on explicit questions depends on decoding and word reading skills, whereas performance on implicit questions relies on interpretative processes involving high-level knowledge (e.g., general knowledge). We did not perform an analysis taking this parameter into account but this hypothesis should be tested in future work. However, as far as the dyslexic students are concerned, these results are in line with those of Gelbar et al. (2016), who found no significant contribution of TRF in the text reading comprehension scores of adults with dyslexia. The authors suggested that readers with dyslexia might have developed some reading comprehension compensation strategies above the "word" level, thus explaining why some individuals with dyslexia demonstrate age-appropriate reading comprehension abilities that are not explained by their word reading skills and decoding abilities. It is possible to hypothesize that lower levels of the reading process have a much smaller influence on skilled readers reading in a more transparent orthographic system than English. This would be due to the semantic demands of reading long texts, on the one hand, and automatized visual word recognition processes, on the other. Another possibility is to follow the lead given by Duke and Cartwright (2021) and consider that the overlap between the word recognition and listening comprehension components of the SVR model may not be entirely separate processes. In line with this proposal, Perfetti and Stafura (2014) suggest that the lexicon might play a central role in linking the word identification and comprehension systems. This would explain why the involvement of vocabulary knowledge and semantic systems in high-functioning dyslexics appears to compensate for an impaired written word recognition process. In skilled readers faced with long texts adapted to their cognitive level, comprehension processes would be central to successful reading and would take over from lower-order processes.

To conclude, among the important results of this study, we have shown that Text reading fluency and text reading comprehension do not rely on the same abilities in university students with and without dyslexia. While TRF skills in adults with dyslexia are based on the activation of visual/orthographic codes of words (phonological codes are difficult to be activated), skilled readers use orthographic and phonological codes of the words they read in a flexible way. The corollary of these results is that when participants are asked to read aloud a text and are warned that it is not a comprehension task, high-level knowledge is not strongly mobilized. An TRF task therefore appears to be an interesting ecological task for testing the ability to read (and decode) written material at the university that consists of long texts. This is in contrast to research with adults with dyslexia which uses mainly single word or pseudoword reading tasks.

This study also shows that when university students with dyslexia have to understand a text precisely, their answers do not depend on their ability to decode and read words but, and more importantly than for skilled readers, on their general knowledge, This enables them to achieve a level of reading comprehension that will allow them to pursue higher education. This is one compensatory mechanism that needs to be further elucidated in future research providing a better understanding of dyslexic compensated reading.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

All authors contributed to the experimental, data analysis, and writing parts of the manuscript.

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APPENDIX

APPENDIX TABLE A1 | Main metric characteristics of the selected articles.

	Text 1	Text 2	Text 3
Number of paragraphs	8	7	6
Number of sentences	35	35	45
Number of words	531	465	477
Number of sentences/paragraph	4.4 (3.3)	5 (5.1)	7.5 (2.8)
Number of words/sentence	15.2 (11.5)	13.3 (11.3)	10.6 (8.6)

Standard deviations are reported in parentheses.

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Promoting Handwriting Fluency for Preschool and Elementary-Age Students: Meta-Analysis and Meta-Synthesis of Research From 2000 to 2020

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Handwriting is a complex activity that involves continuous interaction between lower-level handwriting and motor skills and higher-order cognitive processes. It is important to allocate mental resources to these high-order processes since these processes place a great demand on cognitive capacity. This is possible when lower-level skills such as transcription are effortlessness and fluent. Given that fluency is a value in virtually all areas of academic learning, schools should provide instructional activities to promote writing fluency from the first stages of learning to write. In an effort to determine if teaching handwriting enhances writing fluency, we conducted a systematic and meta-analytic review of the writing fluency intervention literature. We selected 31 studies: 21 true and quasi-experimental studies, 4 single-group design, 3 single-subject design, and 3 non-experimental studies, conducted with K-6 students in a regular school setting. A total of 2,030 students participated in these studies. When compared to no instruction or non-handwriting instructional conditions, teaching different handwriting intervention programs resulted in statistically significant greater writing fluency (ES = 0.64). Moreover, three specific handwriting interventions yielded statistically significant results in improving writing fluency, when compared to other handwriting interventions or to typical handwriting instruction conditions: handwriting focused on training timed transcription skills (ES = 0.49), multicomponent handwriting treatments (ES = 0.40), and performance feedback (ES = 0.36). There were not enough data to calculate the impact of sensory-motor and self-regulated strategy handwriting interventions on writing fluency. The significance of these findings for implementing and differentiating handwriting fluency instruction and guiding future research will be discussed.

Keywords: handwriting, intervention, fluency, early writing, meta-analysis, systematic review

INTRODUCTION

Fluent and proficient writing communication abilities are crucial in our increasingly technical and literate society. While digital tools have become common, writing with paper and pen (or pencil) is the preferred tool for learning to write at schools, especially in the early grades (Santangelo and Graham, 2016), and is still considered a cultural technique not only for fulfilling academic requirements, but also in everyday life when writing a note or writing a shopping list (Wicki et al., 2014). In order to develop handwriting skills, children must begin building their foundation in kindergarten and elementary grades (Puranik et al., 2018).

Writing comprises several sequential and simultaneous language, cognitive, and motor processes, all of which demand some of the writer's limited cognitive resources. Low level processes of handwriting involve an integration and coordination of spelling knowledge, allographic representations, and the execution of fine motor movements, while higher-level processes include planning, ideation, consideration of audience, and revising (Hurschler Lichtsteiner et al., 2018). Translating ideas into written language is not a significant problem for expert writers. Nonetheless, writing can be especially demanding for young children because their handwriting is not automated, and their motor processes are more capacity consuming than for adults (Peverly, 2006). Developing writers usually spend more time on lower-order processes than higher-order processes and may have limited knowledge of writing (Finlayson and McCrudden, 2019). Moreover, all the cognitive low- and high-level processes related to writing contribute to skilled writing, are interdependent and operate recursively with one another, they can interrupt each other and are embedded in each other (Berninger et al., 1996).

The most influential model of the cognitive processes on writing was proposed by Hayes and Flower (1980) and included three cognitive processes in skilled writing—planning, translating, and reviewing. In a subsequent revised version Hayes (2012) added other elements to the model like the task environment, the cognitive process of transcription, apart from planning, translation, evaluation, and motivation. Berninger et al. (1992) found that beginning writers had difficulty generating language to express ideas and lacked the knowledge of how to represent oral language orthographically. Thus, they added two components to the Hayes and Flower's (1980) model: *text generation* and *transcription*. Accordingly, Berninger et al. (2002) presented the *Simple View of Writing* model that consists of three components: *transcription* (handwriting and spelling), *text generation* (translating generated ideas into written language), and *executive functions operations* (e.g., attention, planning, revising, and self-regulation) (Berninger et al., 2002, 2006). Berninger et al. (2002) stressed the key role of handwriting automation in their *Simple View of Writing* model, highlighting the importance of efficient and fluent execution of lower level processes in order to execute higher level metacognitive processes in composing a text. From a developmental point of view transcription and text generation dominate early writing, as the executive functions do not become prominent until students achieve self-regulation (Berninger et al., 2006). A subsequent study by Berninger et al. (2012) focused on the *transcription* component of writing and pointed out that in most instances the outcomes of this component could be text quality or production measures such as fluency or text length.

From the point of view of low- and high-level writing processes, the present study is focused on handwriting intervention to improve the automatization of allographic representations which is considered a low-level writing process. Considering, the above writing models this study is centered on the transcription component, specifically on how to teach handwriting to became fluent and automatic. In spite of the fact that the present research is centered in one element of writing, we understand that handwriting education needs to address all the elements of writing, be built on meaning-making and effective communication, and recognize social, linguistic, cognitive, affective, sensorimotor, motivational, and technological dimensions of writing development (Bazerman et al., 2017).

Berninger et al. (2006) emphasized fluency as an important aspect of writing development in the early grades to develop advanced text-generation skills. Fluency refers to automaticity and effortlessness in information processing (LaBerge and Samuels, 1974). According to information processing theory (LaBerge and Samuels, 1974), fluency is a developmental phenomenon, encompassing various grain sizes including sub-lexical, lexical, and text or discourse levels, and fluency at lower level is necessary for achieving fluency at a higher level (Wolf and Katzir-Cohen, 2001). Kim et al. (2018, p. 5) proposed "a developmental and componential definition of writing fluency as efficient and automatic writing connected texts, with accuracy, speed, and ease. In the beginning, text writing fluency is a function of transcription skills. With further development text writing fluency is efficiency and automaticity in writing text. When transcription is accurate, rapid, and effortless, cognitive resources such as attention and working memory can be allocated to meaning related processes, facilitating text generation."

It takes students a long time to develop handwriting fluency at the expert level. In fact, the development of handwriting fluency continues to increase well beyond primary grades, at least until Grade 9 (Wicki et al., 2014; Alves and Limpo, 2015). Handwriting fluency and spelling significantly contribute to both writing quality and productivity (Kim et al., 2011). Moreover, automatic letter writing correlates with quantity and quality of written composition for both children (Graham et al., 1997; Jones and Christensen, 1999) and adult writers (Peverly, 2006). In addition, handwriting fluency continues to make a unique contribution beyond the primary grades in accounting for variability in how much and how well students write (Graham et al., 1997; Jones and Christensen, 2012). Unless automatic, the transcription processes can place so many demands on working memory that they interfere with other higher-order processes required for writing, such as planning and reviewing (Olive and Kellogg, 2002).

Findings of studies from different countries suggest that a very large percentage of students are experiencing difficulties with their writing skills (National Center for Education Statistics, 2012; Alves and Limpo, 2015; Koster et al., 2015). However, as Graham and Perin (2007) highlighted, not all the children that experience writing difficulties are identified as having a learning disability; low-achieving writers are included in this percentage of students with writing difficulties as a silent majority who lack writing proficiency but do not receive additional help. Moreover, a study by Puranik et al. (2018) reported that kindergarten teachers did not use any specific writing curriculum to teach writing, and most of the time consumed on writing instruction was spent on students writing independently. In a similar way, Vander Hart et al. (2010) study suggested that even though kindergarten teachers employ several effective intervention strategies for writing, there is room for improvement on implementing good handwriting practices based on research. In addition, studies by Gilbert and Graham (2010) and Koster et al. (2015) pointed out that the time devoted to writing in elementary schools is limited, and only a minority of schools and teachers used evidenced-based instructional practices.

Vander Hart et al. (2010) research on the in-depth analysis of handwriting curriculum in kindergarten classrooms found that writing fluency was a moderate priority in handwriting instruction. During the interviews, the teachers mentioned that their goal for their students was to learn how to form letters. They were not concerned about fluency and timed writing or writing from memory as these practices were never observed in kindergarten classrooms. Traditional handwriting lessons used to focus on legibility of handwriting and the importance and the knowhow of teaching handwriting fluency is not yet well known (Hurschler Lichtsteiner et al., 2018). A lack of opportunity to set up writing fluency skills in the elementary grades is particularly problematic because formal writing instruction is typically not offered to students after elementary school (Hier and Eckert, 2014). It seems likely that, without tailored supplementary support, these slow writers will be harshly constrained in their ability to enact high-level processes during text production (Limpo et al., 2018). Fluency-building interventions are conceptualized as time-efficient practices that can supplement instruction or intervention already occurring in the classroom (Martens et al., 2011).

Promoting writing fluency with evidence-based materials is particularly important in the initial years of learning to write. Nevertheless, previous reviews and meta-analyses on evidence-based writing interventions have focused mainly on children and youngsters in first grade and beyond; therefore, studies involving kindergartens were excluded and writing fluency-based outcomes were missing in most of the writing intervention reviews and meta-analyses done to date (Rogers and Graham, 2008; Graham and Sandmel, 2011; Graham et al., 2012, 2015; Koster et al., 2015; Graham and Harris, 2018). In this sense, it is worth mentioning Graham and Harris's (2018) review, in which the authors conducted an extensive synthesis on writing instruction in elementary grades. Their research included 20 meta-analyses of true and quasi-experiments testing the effectiveness of one or more writing practices with children in grades from 1 to 12. The primary outcomes assessed by this study were writing quality, content learning, or reading comprehension. No writing fluency outcomes were included and none of the reviewed studies integrated instructional methods on how to teach handwriting skills to kindergarten children.

Nevertheless, Edwards (2003) review examined the literature on how to teach writing to kindergarten children. Writing and their instructional components related to handwriting, letter writing accuracy, spelling, fluency, and simple compositions are discussed in Edwards' review, along with several handwriting instructional approaches, such as Alphabet Practice emphasizing letter formation and Alphabet Rockets targeting handwriting fluency. Besides, two meta-analyses provided findings on kindergarten children and on writing-based fluency interventions. Santangelo and Graham's (2016) meta-analysis was conducted with students from kindergarten to 12th grade, they found that handwriting compared to no instruction or non-handwriting instructional conditions resulted in significantly greater legibility and fluency. Similarly, a previous work from the same authors (Santangelo and Graham, 2013) showed that handwriting instruction improved legibility and fluency in 18 studies including children from kindergarten to grade 7th.

Taking into consideration the Simple View of Writing model (Berninger et al., 2002), which emphasizes the idea that efficient or fluent execution of lower-level processes in writing development, and accounting for the scant research on handwriting fluency in the initial years of learning to write, the purpose of the present review is to identify instructional practices to increase writing fluency from kindergarten to 6th grade. In this line, a useful approach for identifying instructional practices that enhance the power to increase writing fluency is to conduct systematic reviews of writing fluency intervention research. Therefore, we intend to identify effective writing fluency instructional practices in kindergarten and elementary grade students by conducting a review of the writing fluency intervention literature.

It is important to identify writing fluency treatments with evidence of effectiveness, in order to provide teachers with instructional practices that potentially could improve the quality of their instruction and their students' writing fluency. Moreover, applying evidence-based writing practices with students in earlier grades should reduce the number of youths who reach middle school not writing well enough to meet grade-level demands (Graham et al., 2012).

Although several meta-analyses and reviews targeting handwriting and strategy use have been published (Rogers and Graham, 2008; Graham and Sandmel, 2011; Hoy et al., 2011; Graham et al., 2012, 2015; Santangelo and Graham, 2013, 2016; Koster et al., 2015; Graham and Harris, 2018), there has not been a comprehensive systematic review targeting writing fluency interventions that was conducted focused on kindergarten and elementary grade students.

The present paper reports a meta-analysis of handwriting fluency intervention research involving true and quasi-experimental and single-group design studies. It also includes a review of single subject design and non-experimental studies to draw a broad set of recommendations for teaching handwriting fluency-based interventions, applying the principle to make the best of the available data, not simply experimental effect sizes (Pressley et al., 2006). It focused broadly on teaching handwriting fluency to K-6 students in regular school settings (i.e., not schools exclusively for students with special needs). Therefore,

TABLE 1 | Summary of reviewed studies categorized by intervention type.

Study first author (year)	Type of study	Description of conditions and (n) in each condition	Grade	Student type	Sessions	Quality score	Flu. ES[a]
Handwriting-Transcription/True-QES studies							
Alves et al., 2016[b,c]	True-QES	1. Handwriting (*n* = 18) 2. Spelling (*n* = 17) 3. Keyboarding (*n* = 20)	Second grade	Full range	10 weeks units	9	0.82
Graham et al., 2000[b,c]	True-QES	1. Handwriting (*n* = 15) 2. Phonological awareness (*n* = 15)	First grade	Struggling writers and learning disabilities	27 sessions	9	0.77
Howe et al., 2013[c]	True-QES	1. Intensive Practice from the handwriting curriculum (*n* = 34) 2. Visual-Perceptual-Motor skills (*n* = 38)	First and second grades	Full range and struggling writers	12 weeks	6	-0.05
Handwriting-Transcription/Single group design study							
Mackay et al., 2010	Single group design	1.Log Handwriting Program (LHP) (*N* = 16)	First and second grades	Struggling writers	8 weeks	7	-0.49
Handwriting-Transcription/Single subject design study							
Limpo et al., 2018	Single subject design	1. Handwriting intervention (N = 3)	Fifth grade	Struggling writers	5 weeks	6	2.14
Combined Handwriting Instruction/True-QES studies							
Graham et al., 2018[b]	True-QES	1. Handwriting + spelling (*n* = 15) 2. Phonological awareness (*n* = 15)	First grade	Learning disabilities	8 sessions	9	0.95
Hurschler Lichtsteiner et al., 2018	True - QES	1. Handwriting + spelling (*n* = 78) 2. Spelling (*n* = 36)y 3. Handwriting (*n* = 34) 4. Reading (*n* = 27)	Third grade	Full range	5 weeks	6.5	–
Limpo and Alves, 2018[b]	True - QES	1. Transcription + self-regulation (*n* = 43) 2. Self-regulation (*n* = 37) 3. Typical handwriting instruction (*n* = 39)	Second grade	Full range	10 sessions	7	0.58
Multicomponent programs/True-QES studies							
Case-Smith et al., 2014b[b,c]	True-QES	1. Write Star Program (*n* = 37) 2. Typical handwriting instruction (*n* = 30)	First grade	Full range	12 weeks	9	0.46
Case-Smith et al., 2014b[b,c]	True-QES	1. Write Star Program (*n* = 77) 2. Typical handwriting instruction (*n* = 55)	First grade	Full range	12 weeks	9	0.06
Puranik et al., 2017[b,c]	True-QES	1. Peer Assisted Writing Instruction (PAWS) (*n* = 22) 2. Typical handwriting instruction (*n* = 62)	KG	Full range	35 sessions	9	0.55
Puranik et al., 2018[b,c]	True-QES	1. PAWS (*n* = 78) 2. Typical handwriting instruction (*n* = 71)	KG	Full range	26 weeks	10	0.69
Van Waelvelde et al., 2017[b,c]	True-QES	1. I can! Program (*n* = 18) 2. Delayed instruction (*n* = 13)	7 and 8 years old	Struggling writers	7 weeks	8	0.27
Multicomponent programs/Single group design studies							
Case-Smith et al., 2011	Single group design	1. Write Star Program (*N* = 17)	First grade	Full range	12 weeks	7.5	1.61
Case-Smith et al., 2012	Single group design	1. Write Star Program (*N* = 36)	First grade	Full range	12 weeks	7	0.87
Multicomponent programs/Single subject design studies							
Hansen and Wills, 2014	Single subject design	1. Handwriting + goal setting + contingent reward (*N* = 1)	Ten-year-old student	Struggling writers	20 sessions	4.5	–
Sensory-motor handwriting/True-QES studies							
Bara and Bonneton-Botté, 2017	True-QES	1. Whole body visuo-motor (*n* = 36) 2. Visual teaching (*n* = 36)	KG	Full range	6 weeks	6	–
Salls et al., 2013	True-QES	1. Handwriting Without Tears (*n* = 14) 2. Peterson directed program (*n* = 17)	First grade	Full range	One school year	7	0.16
Study first author (year)	Type of study	Description of conditions and (n) in each condition	Grade	Student type	Sessions	Quality score	Effect size

(Continued)

TABLE 1 | (Continued)

Study first author (year)	Type of study	Description of conditions and (n) in each condition	Grade	Student type	Sessions	Quality score	Flu. ES[a]
Sensory-motor handwriting/True-QES studies (cont.)							
Weintraub et al., 2009[b]	True-QES	1. Sensorio-motor (*n* = 19) 2.Task oriented interventions (*n* = 13) 3. Typical handwriting instruction (*n* = 17)	Second, third, and fourth grades	Struggling writers	8 sessions	7	0.07
Sensory-motor handwriting/Single group design study							
Roberts et al., 2010	Single group design	1. Kinesthetic cursive handwriting program (*n* = 28)	Fourth, fifth and sixth grades	Struggling writers	7 weeks	6	0.86
Self-regulated strategy/True-QES study							
Jongmans et al., 2003	True-QES	1. Handwriting self-instruction (*n* = 7) 2. Typical handwriting instruction (*n* = 7)	7.92 years old	Struggling writers	18 sessions	6	-0.28
Self-regulated strategy/Single subject design study							
Geisler et al., 2009	Single subject design	1. Self-counting + A synonym list (*N* = 5)	First grade	High ability	25 sessions	5	–
Self-regulated strategy/Single subject Non experimental studies							
Kasper-Ferguson and Moxley, 2002	Non-exp.	1. Students counting and graphing words + sample writing (*N* = 20)	Fourth grade	Full range	One school year	4	–
Zumbrunn and Bruning, 2012	Non-exp.	1. Self-regulated strategy development (*N* = 6)	First grade	Full range	Spring term	6	–
Performance feedback/True-QES studies							
Alitto et al., 2016[c]	True-QES	CBM-WE 1. Performance feedback and goal setting (*n* = 57) 2. Practice only (*n* = 57)	Fourth and fifth grades	Full range and learning disabilities	10 weeks	10	0.26
Hier and Eckert, 2014[c]	True-QES	CBM-WE 1. Performance feedback (*n* = 51) 2. Practice only (*n* = 52)	Third grade	Full range	12 weeks	9	0.54
Hier and Eckert, 2016[c]	True-QES	CBM-WE 1. Performance feedback (*n* = 34) 2. Practice only (*n* = 33) 3. Multiexemplar training (*n* = 41)	Third grade	Full range	9 weeks	8	0.05
Study first author (year)	Type of study	Description of conditions and (n) in each condition	Grade	Student type	Sessions	Quality score	Effect size
Koenig et al., 2016[b,c]	True-QES	CBM-WE 1. Performance feedback + goal setting (*n* = 39) 2. Performance feedback (*n* = 39) 3. Typical handwriting instruction (*n* = 39)	Third grade	Full range	8 weeks	10	-0.18
Roth and Guinee, 2011[b,c]	True-QES	1. Interactive writing + teacher feedback (*n* = 49) 2. Typical handwriting instruction (*n* = 52)	First grade	Full range	One school year	8	0.81
Truckenmiller et al., 2014[b,c]	True-QES	CBM-WE 1. Performance feedback (*n* = 46) 2. Typical handwriting instruction (*n* = 48) 3. Practice only (*n* = 39)	Third grade	Full range and learning disabilities	8 weeks	9	0.66
Performance feedback/Non-exp. study							
Heskial and Wamba, 2013	Non-exp.	1. Collaborative inquiry/action with teacher feedback (*N* = 120)	KG	3 full range classes and 1 learning disabilities	Daily 50 min writing work-shops	3.5	–

[a]*When ES could be calculated between conditions 1 and 2, the result is shown; otherwise, the studies that did not allow the calculation of the effect size are marked with a line.*

[b]*Study included in the analysis of the first objective.*[c]*Studies include in the analysis of the second objective.*

True-QES, True quasiexperimental; KG, kindergarten; Non-Exp, non-experimental. Studies are organized by intervention category and alphabetical order; fluency effect sizes were calculated between condition 1 and condition 2.

**Studies marked with this symbol were selected for calculating the effectiveness of handwriting instruction compared to conditions involving no instruction or instruction unrelated to handwriting.*

the final goal was to systematically review the effectiveness of the impact on writing fluency of handwriting interventions to both update and better quantify the conclusions from a narrative review and meta-analysis perspective. Concretely, the objectives of this review were: (1) to perform a systematic review and meta-analysis about the effectiveness of handwriting instruction compared to conditions involving either no instruction or instruction unrelated to handwriting and (2) to determine the effectiveness of specific handwriting programs (e.g., handwriting based on transcription skills, combined handwriting treatments, multicomponent handwriting interventions, sensory-motor handwriting treatment, self-regulated strategy, and performance feedback) used to improve writing fluency in the pretest and posttest outcomes compared to other handwriting conditions. If an intervention category had at least three studies that reported outcomes for a congruent measure of writing fluency, we performed a meta-analysis; otherwise, we reviewed the studies and presented a conclusion.

METHOD

Inclusion and Exclusion Criteria

The selection of the articles was made taking into consideration the following inclusion criteria: (a) interventions and theoretical approaches to improve writing fluency; (b) students aged between 5 and 12 years; (c) students enrolled in general education classrooms; (d) not experiencing severe motor and/or perceptual deficits that precluded students from handwriting; (e) not experiencing significant cognitive and/or developmental deficits; (f) not second language acquisition (SLA) students; (g) articles published in scientific journals between 2000 and 2020; (h) writing intervention done on paper. Research with the main focus on the assessment of writing fluency was rejected.

Location and Selection of Studies

A pairwise search of articles published in English between 2000 and 2020 was carried out in the following databases: WoS, ERIC, Scopus, PROQUEST, Medline, and PubMed. To search papers related to the present study topic, we inserted a combination of the following keywords: *writing OR handwriting AND fluency OR automaticity OR speed AND intervention OR instruction OR training OR treatment OR teaching,* considering only the category of journal articles.

A total of 1,120 publications were found, 318 from WoS database, 210 from Scopus, 235 from PROQUEST, 211 from Medline and 146 from PubMed. Additionally, eight records were identified through other sources. All of them were exported to the Mendeley program for further sorting and selection. Subsequently, duplicate articles were eliminated and a total of 747 publications were obtained to be analyzed. Next, the three authors made the independent selection of each study and resolved disagreements. Once the inclusion and exclusion criteria had been analyzed and applied, a total of 31 articles were obtained. All of them were coded and included in **Table 1**.

This study followed guidelines proposed by Preferred Reporting Method for Systematic Reviews (PRISMA Declaration), according to the flowchart of four phases (**Figure 1**) in addition to its checklist and report items (Page et al., 2021).

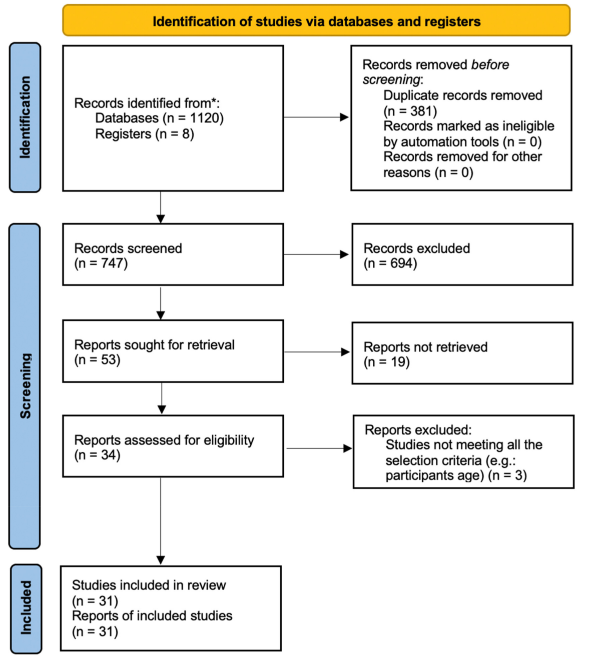

FIGURE 1 | PRISMA flow diagram (Page et al., 2021).

Categorizing Interventions

For the analysis, the first author examined each study and grouped them according to their main focus of intervention. Next, a list of handwriting intervention categories was developed collaboratively by the authors. Once the list was created it was reread again by the authors and the categories were refined and each study placed in its respective category. Studies with a comparable focus of intervention were grouped into categories, based on those used in previous meta-analyses (e.g., Graham and Perin, 2007; Santangelo and Graham, 2016; Koster et al., 2015).

At least one or more studies examined the effectiveness of the following categories (1) handwriting/transcription, (2) sensory-motor handwriting, (3) spelling, (4) peer-assisted learning, (5) self-regulated strategy, (6) performance feedback, (7) goal setting, and (8) contingent reward. **Table 2** presents a definition of the eight treatment categories found in the reviewed studies.

The goal of this categorization process was to create groups of studies that isolated specific teaching methods. There were three exceptions to this basic approach (per the previously described questions of this review). We created one category that compared any handwriting intervention to a control condition that did not involve a handwriting treatment. In addition, two more categories were added for studies that fit in more than one category previously described: combined handwriting instruction and multicomponent programs. Studies in the combined handwriting instruction included investigations where handwriting was combined

TABLE 2 | Identification of writing fluency treatments.

Treatments	Description	Authors
Handwriting/ transcription	Handwriting treatment consists of explicit instruction and intensive practice in writing letters, words, and sentences to promote legibility, handwriting speed, writing fluency, and writing expression. The most common handwriting instruction tasks are writing and modeling letter formation, fostering automatic letter production and copying exercises	Graham et al., 2000; Howe et al., 2013; Alves et al., 2016
Sensory-motor handwriting	Sensory-motor handwriting practices include visual, auditory, tactile, rhythm, and movement techniques to reinforce letter formation, size, and alignment. Usually in sensory-motor handwriting practices, letters are taught in groups that share movement patterns	Weintraub et al., 2009; Salls et al., 2013; Hansen and Wills, 2014; Bara and Bonneton-Botté, 2017
Spelling	In spelling treatments, students (depending on the characteristics of the language) receive explicit instruction and practice in the alphabetic principle and its alternations, vowel sounds, onset and rime, and morphemic structures of words, as well as spelling patterns. Spelling lessons usually follow a sequence of increasing complexity from consistent or rule-based spelling patterns to inconsistent alternations and complex spelling patterns	Graham et al., 2018; Hurschler Lichtsteiner et al., 2018
Peer-assisted learning strategy	Peer-assisted learning strategies involve peers helping one another to write, to practice, and to learn themselves by teaching others on how to write. Commenting on a peer's work can make students aware of their own writing and help children build metacognitive/metalinguistic skills	Puranik et al., 2017; Puranik et al., 2018
Self-regulated strategy	Self-regulated writing consists of teaching children specific strategies for planning and writing a complete story: to set goals, to monitor their understanding of the writing process, and to evaluate the written text. Consequently, some self-regulated strategies regulate performance (e.g., self-instruction), the observation of one's progress (e.g., self-monitoring), and the evaluation of the written task (e.g., self-evaluation)	Jongmans et al., 2003; Limpo and Alves, 2018
Performance feedback	Performance feedback is a means by which students receive objective information on their task mastery. Performance feedback could be presented in both visual and oral formats. The visual presentation could be, for example, in the form of a page that includes numeric feedback and a graphic or an arrow pointing up or down, indicating whether performance increased or decreased. The oral presentation could be completed by the teacher who reviewed the information presented on the feedback page	Hier and Eckert, 2014; Truckenmiller et al., 2014; Alitto et al., 2016; Hier and Eckert, 2016; Koenig et al., 2016
Goal setting	Goal setting involves the design of an action plan aimed to motivate and guide a student toward a defined goal or a set of goals. Goals must be provided in a clear, objective way that is easily understood by the individual receiving the intervention	Alitto et al., 2016; Koenig et al., 2016
Contingent reward	Contingent rewards consist of a motivational-based system that is used to reward students that meet their identified goals by providing reinforcement for a job well done	Hansen and Wills, 2014

with other practices, such as handwriting and spelling (e.g., Graham et al., 2018). Multicomponent interventions included skill-based combined with performance-based writing treatments (e.g., Case-Smith et al., 2011; Puranik et al., 2017).

In addition, it should be noted that a study could be placed in more than one category, as some studies included more than one intervention. For example, Koenig et al. (2016) included performance feedback and goal setting as well as a non-intervention group. Since performance feedback was the experimental category, it was included in the performance feedback category.

Coding and Data Analysis

First, two independent investigators coded all the studies considering main different aspects: Grade, Participants, Type of Study, Writing intervention, and Measurements. Percentage of agreement was: 90.3, 93.5, 80.6, 90.3, 93.5, and 71.0%, respectively. Subsequently, several meetings were held to debate and share the information included in the finally selected articles. The coding sheet collected information on the following aspects (see **Table 1**):

- Study first author (year).
- Type of study: Indicates the category of the research. true or quasi-experimental; single-group design; single-subject design; non-experimental or qualitative studies.
- Description of conditions and (n): Presents a list of the study conditions and the participants in each condition. Studies are categorized by types of intervention and alphabetical order.
- Grade: Applies to participants' grade level; when the study did not mention age, this was reported.
- Student type: As Santangelo and Graham. (2016) stated, there were three categories for the type of participant: (1) full range for students with typical handwriting skills; (2) high for those with above-average handwriting skills; (3) struggling for students with significant handwriting difficulties. When none of the previous conditions was specified, full range was reported. We added the category of learning disabilities when the authors explicitly mentioned it.
- Sessions: The length of the intervention in weeks or sessions, as defined by the authors. In a few cases, the only data available was the number of semesters or the academic year.
- Quality score: This was calculated considering the quality indicators of Gersten et al. (2005). These indicators refer to:

(a) adequate information about participants; (b) methods to guarantee participants had been randomly assigned; (c) appropriate explanation regarding interventionists or teachers running the intervention; (d) sufficient details of the intervention, its description and assessment; (e) treatment fidelity; (f) report of the characteristics and evaluation of comparison conditions; (g) variety of measures to assess all the variables; (h) results that prove the impact of the intervention; (i) adequate data analysis techniques; and (j) presence of inferential statistics and effect size estimations. When the indicator was met 1 point was assigned, and when it was not, no points were assigned; therefore, the maximum score was 10. Nevertheless, and since some of the indicators specified two criteria, 0.5 points were given, for example in the indicator (d) some researchers might describe the intervention but not its evaluation.

- Flu. ES: This calculation is explained below (section "Results").

Table 3 presents the findings from analysis of 10 quality indicators (described in **Table 4**). Across all the selected studies the mean quality score was 8.5 (SD = 1.13), for the *Handwriting interventions studies* 8.3 (SD = 1.15), for *Handwriting instruction studies* 8.8 (1.10), for *Multicomponent handwriting treatments studies*, and 9.0 (1.14) for *Performance feedback studies*. Therefore, most of the chosen studies included in the performed meta-analyses according to the two objectives of the study were of significant quality. Considering the type of studies, *Handwriting instruction studies* got the highest adherence (100%) to most of the quality indicators, even though none of them report information regarding the interventionists or teachers conducting the program. On the contrary, *Handwriting instruction studies* were found as the lowest adherence research scoring the lowest value for 0% in the Interventionists or teachers' information indicator. Taking all type of studies, the quality indicators with most adherence (75.1%) were Participant's description, Intervention description, Comparison conditions reported, and Multiple measures.

Second, when data were available for true and quasi-experimental studies (True-QES) and for single-group design studies, Cohen's d values with pooled 95% CIs were used to

TABLE 4 | Definitions for quality indicators.

Quality Indicator	Definition
Participant's description	Provides sufficient information about participants to be informed about whether they present learning difficulties
Methods randomization	Follows adequate procedures for randomly assigning participants across conditions
Interventionists or teachers' information	Properly describes information related to those who conduct the interventions (either professionals or teachers) such as years of experience
Intervention description	Reports the type of intervention/programs used in the research, specifying instructions, materials, sessions, etc.
Treatment fidelity	Explains the extent to which the intervention has been implemented as planned
Comparison conditions reported	Includes the description and document the treatment implementation in the comparison group along with its assessment
Multiple measures	Incorporates a variety of valid and consistent measurements that line up with the objectives of the intervention
Results proving intervention's impact	Reports all the results showing the impact of the intervention at the appropriate times (immediately, long-term effects, etc.)
Data analysis techniques	The selected analysis of the data fits the research questions and hypotheses established by the authors
Presence of inferential statistics	Reports inferential statistics and effect sizes estimations

TABLE 3 | Total quality score and percentage of studies in which a quality indicator by types of study.

	Total score*	Quality Indicators									
Type of Study	***M (SD)***	***PT* (%)**	***MR* (%)**	***ITI* (%)**	***ID* (%)**	***TF* (%)**	***CCR* (%)**	***MM* (%)**	***RPII* (%)**	***DAT* (%)**	***PIS* (%)**
Handwriting interventions compared to conditions with no instruction or unrelated to handwriting studies (*k* = 13)	8.5 (1.13)	92.3	69.2	38.5	92.3	76.9	92.3	92.3	84.6	69.2	69.2
Handwriting instruction studies (*k* = 3)	8.3 (1.15)	100.0	100.0	0.0	100.0	66.7	100.0	100.0	100.0	100.0	66.7
Multicomponent handwriting treatments studies (*k* = 5)	8.8 (1.10)	100.0	60.0	80.0	100.0	80.0	100.0	100.0	100.0	80.0	80.0
Performance feedback studies (*k* = 6)	9.0 (1.14)	100.0	83.3	66.7	100.0	100.0	100.0	100.0	83.3	83.3	83.3
TOTAL (*k* = 17)	8.6 (1.06)	75.1	59.2	33.7	75.1	61.4	75.1	75.1	73.6	63.2	59.8

*k number of studies; M mean; SD. *Total quality score is the sum of all quality indicators (scale 0–10).*
PT, participant's description; MR, methods randomization; ITI, interventionists or teachers' information; ID, intervention description; TF, treatment fidelity; CCR, comparison.

estimate the effect size (ES) of each study (see **Table 1**). Before calculating ES, for True-QES, an adjustment was made to the scores of the comparison groups. Means for each pretest and posttest group were subtracted separately, then the ES was calculated by subtracting the adjusted posttest scores of one group from the adjusted posttest score of the other comparison group and dividing it by the pooled standard deviation. Positive Cohen's d values indicated a greater gain in the intervention group versus the control group or versus other intervention groups, while a negative value indicated the opposite, i.e., a greater gain in the control group or in groups with other types of intervention.

Then, in the case of the single-group design studies, the positive values of Cohen's d indicated an increase between pre-treatment and post-treatment in the variable under study. When the Cohen's d value was negative, the value of the pre-treatment measure was greater than the value of the post-treatment measure and therefore there had been no gain associated with the application of the program over time.

After calculating each intervention ES of True-QES, following our first research goal, we ran a meta-analysis considering the studies where the experimental group or intervention under study was compared to control groups or to other groups with an intervention not related to writing. Studies under consideration to calculate this meta-analysis are marked with a (*b*) in **Table 1**. Fifteen studies were finally included. The results of the meta-analysis are shown in **Table 5**.

Another meta-analysis was conducted in accordance with our second study goal. Following a previous meta-analysis (Santangelo and Graham, 2016), if an intervention category had at least three studies that reported outcomes for a congruent measure of fluency, we computed an average weighted ES; otherwise, we reviewed the studies and presented a conclusion. Only three handwriting intervention categories met this condition: handwriting/transcription instruction, multicomponent handwriting treatments, and performance feedback (see **Table 5**).

Meta-Essential software was used to perform four meta-analyses (Suurmond et al., 2017). We followed the Hedges (1981) procedure in order to correct bias due to the small sample sizes. As Cohen (1988) proposed, the magnitude of the ES was interpreted from small to large (d = 0.2 small, d = 0.5 medium, d = 0.8 large). Statistical heterogeneity of ES values was analyzed by applying several methods: The Q statistic and the I^2 index (Cooper et al., 2019), by visually inspecting funnel plots (Borenstein et al., 2009) and the linear regression test proposed by Egger et al. (1997). Using the guidelines proposed by Higgins and Green (2011), we interpreted heterogeneity, i.e., 0–40% might not be important, 30–60% may represent moderate heterogeneity, 50–90% may represent substantial heterogeneity, and 75–100% may imply considerable heterogeneity.

To carry out both meta-analyses with regard to the similarity of outcome measures, ES were only calculated when the research measured the same construct: writing fluency. It should be noted that we considered all those measures related to writing fluency, even though researchers assessed the same construct in different ways. The outcomes measures used were based on comparable assessments (e.g., number of words and sentences spelled correctly in 3 min based on a curriculum-based measurement in written expression (CBM-WE) probes, a copying task in 5 min, letters per minute, and other measures and test of writing fluency such as the rate scale of the Minnesota Handwriting Assessment by Reisman (1999). When a study had several measures that could be considered as writing fluency or several studies, a single measure was obtained by averaging the individual effects.

Finally, due to the small number of participants, we did not include the analysis of single-subject design from **Table 1**. Nevertheless, we considered including single-subject design studies and qualitative or non-experimental studies in order to identify the greatest amount of relevant evidence on the subject under analysis. The aim was to classify, compare, translate, display, and analyze the information included in these studies in order to make further interpretations (Jensen and Allen, 1996). We read, identified, and coded the practices on writing fluency for each single-subject and non-experimental study.

RESULTS

The results of our meta-analysis are summarized in **Table 1**, reporting the ES for each study, and **Table 5** reporting the number of studies used in the analysis, combined and simple ES, levels of statistical significance, CIs, and measures of homogeneity, i.e., Q and I^2.

First Study Objective: Effectiveness of Any Type of Handwriting Intervention Compared to Conditions Involving Either No Instruction or Instruction Unrelated to Handwriting

We aimed to search whether or not the effects of any type of handwriting instruction produce greater gains in writing fluency than non-handwriting instruction or instruction non-related to handwriting. A total of 13 True-QES investigations were analyzed to examine whether any type of handwriting-based interventions improves writing fluency versus non-intervention or non-handwriting-related instruction. From the total of studies analyzed all showed positive results. In total, these studies comprised a total of 1,111 students and a range of sessions between five weeks and the whole school year.

The results show a combined ES of 0.66 [95% CI (0.51, 0.81)]. Regarding the heterogeneity statistic, the Q statistic was not significant and the I^2 statistic indicated that 0% of the variance was produced by variations between the studies. The fail-safe N showed that 148 studies would be necessary to make the combined ES statistically insignificant. With the trim and fill method, no studies were imputed in the funnel plot to alleviate difficulties with missing studies showing negative effects. **Figure 2** shows the effectiveness of the different programs used with respect to no instruction or instruction unrelated to handwriting.

TABLE 5 | Summary of results for each research question.

	k	ES	95% CI	Q	I^2
Objective 1. Handwriting interventions compared to conditions involving either no instruction or instruction unrelated to handwriting?	13 True-QES	0.66	0.51 to 0.81	10.83	0
Objective 2: Effectiveness of specific methods and strategies used to improve handwriting fluency[a]					
Handwriting instruction	3 True-QES	0.49	–0.10 to 0.99	4.64	56.87
Multicomponent handwriting treatments	5 True-QES	0.51	0.38 to 0.63	1.60	0
Performance feedback	6 True-QES	0.36	0.06 to 0.66	16.86**	70.34

[a] *Combined handwriting treatments, sensory-motor handwriting treatment and self-regulated strategies did not meet the criteria of a minimum of three investigations to perform a meta-analysis calculation.*
True-QES, true quasiexperiments on writing fluency; k, number of studies; ES, effect size; CI, confidence interval.
**p < 0.05.*
***p < 0.01.*

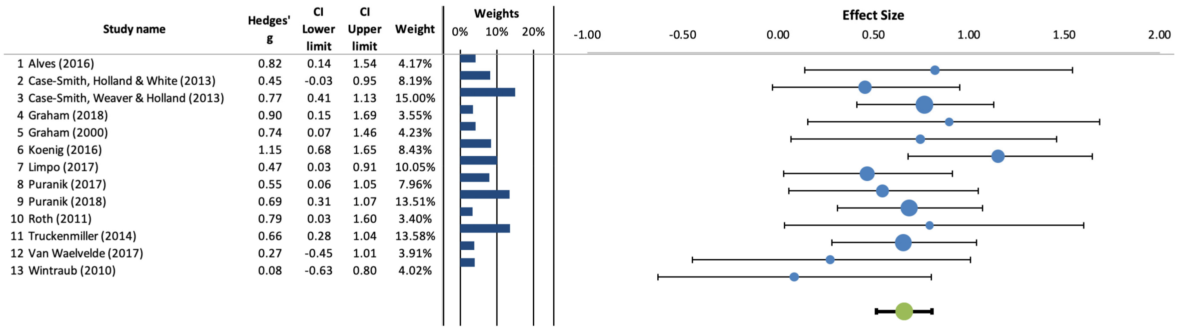

FIGURE 2 | Effectiveness of handwriting interventions compared to conditions involving either no instruction or instruction unrelated to handwriting.

Second Study Objective: Effectiveness of Specific HandWriting Methods and Strategies to Improve Writing Fluency Compared to Other Handwriting Conditions

The main aim was to analyze whether any type of handwriting intervention improves handwriting compared to other conditions involving handwriting fluency interventions or no instruction. In any case, the calculated ES to perform these meta-analyses for a specific handwriting method was the result of comparing condition 1 to condition 2 (see **Table 1**).

Handwriting/Transcription

We found five studies that used handwriting instruction, and included the participation of 176 students. The interventions in these handwriting investigations ranged from short 5-week treatments to longer interventions with 27 sessions. Although the intervention conditions all involved handwriting instruction, the specific tasks of focus varied across studies (e.g., writing letters, words and sentences fluently and accurately, copying exercises, writing letters with correct alignment, size and spacing). Three of the studies used a true or quasi-experimental design; the first two of them showed a gain in the treatment group or condition 1 compared to condition 2 (Graham et al., 2000; Alves et al., 2016). However, the third study did not show effectiveness of treatment (Howe et al., 2013). Together, they showed a combined ES of 0.49 [95% CI (–0.10, 0.99)]. The Q statistic was not significant and the I^2 statistic indicated that 56.87% of the variance was explained by variability between the studies, indicating moderate heterogeneity. The Fail-safe N indicated that 793 missing studies would be needed to reverse this finding. The control conditions of these two studies were quite diverse (see **Table 1**). Two studies used a single group design. The first (Mackay et al., 2010) indicated a decrease in writing fluency (ES = –0.49) and the second study (Limpo et al., 2018) was excluded from the overall ES analysis of this question due to the small sample size. Despite this, the last study revealed that handwriting intervention through fast-paced alphabet and copying activities was highly effective in increasing students' handwriting fluency, as the calculated ES shows (see **Table 1**).

Combined Handwriting

In the following question, it was analyzed whether combined treatments on handwriting were effective. These studies analyzed a total of 324 students and comprised between 5 and 10 treatment sessions. Of the studies analyzed, only three showed combined treatments (Graham et al., 2018; Hurschler Lichtsteiner et al., 2018; Limpo and Alves, 2018). Two of them had a true or quasi-experimental design showing positive results (**Table 1**). The study carried out by Hurschler Lichtsteiner et al. (2018), did not allow for a calculation of ES; however, the study results reported that as handwriting automaticity was high at the beginning of the study, the intervention was not able to improve it further.

Multicomponent Handwriting

A total of eight studies analyzed whether students who received multicomponent treatment in writing fluency showed improvements in the mentioned variables compared to those students who did not receive it. These studies comprised the participation of 464 students and the duration of treatment varied between 12 and 35 sessions. From the eight studies, five were true or quasi-experimental (Case-Smith et al., 2014a,b; Puranik et al., 2017, 2018; Van Waelvelde et al., 2017) and showed a combined ES of 0.51 [95% CI (0.38, 0.63)]. The Q statistic was not significant and the I^2 statistic with a value of 0 indicated that the effects were homogeneous. Two other studies, Case-Smith et al. (2011) and Case-Smith et al. (2012), had a single group design and indicated a positive gain in the treatment group with an ES of 1.61 and 0.87, respectively. In addition, the study by Hansen and Wills (2014) described in a case study a male student in elementary school who, after the performance-based intervention (goal setting and contingent reward) and skill-based intervention (handwriting instruction based on writing complete sentences), increased the number of complete sentences written.

Sensory-Motor Handwriting

We found four studies, all comparing the impact of sensory-motor handwriting treatment on writing fluency. In total, 225 students participated in these studies and the amount of instruction provided ranged from six weeks to one year. Two of the studies had a true or quasi-experimental design and they showed no effect of intervention or it was very low (Weintraub et al., 2009; Salls et al., 2013). A third study, conducted by Bara and Bonneton-Botté (2017), assessed the impact of a teacher-implemented visuomotor intervention program. They compared a visuomotor program in which letters were explored with the arm and whole body, with a typical visual training program. This study was not included in the analysis because results on writing fluency were not clearly stated and were somehow contradictory. Finally, the study by Roberts et al. (2010) with a single group design investigated whether students participating in a kinesthetic writing program intervention improved speed. Although the calculations showed a positive effect of the program, the authors claimed that the increase in handwriting speed was not clinically significant.

Self-Regulated Strategies

Regarding this category, four studies were analyzed to test whether or not students who received self-regulation strategies showed gains in writing fluency compared to those students who did not receive this kind of technique or compared to other types of strategies. In total, 45 students participated in these studies. The results are mixed. The first study, with a quasi-experimental design carried out by Jongmans et al. (2003), did not show gains in writing fluency in the intervention group (condition 1 in **Table 1**) in relation to the control group (condition 2 in **Table 1**). On the other hand, it was found in the study by Zumbrunn and Bruning (2012), implementing a self-regulated strategy combined with self-regulation procedures such as monitoring and goal setting, showed that participants wrote stories that contained more essential components, were longer, and had better quality after the treatment. However, the information provided did not allow for the calculation of the ES. A third study, by Kasper-Ferguson and Moxley (2002), reported the results of student graphing of writing fluency (monitoring their writing fluency) after brief freewriting periods. The primary goal was to increase writing fluency. The writing rates from all students improved over the course of the school year. These improvements in writing rate occurred without evidence of ceiling effects over a year's time. Finally, Geisler et al.'s (2009) study examined the effects of self-counting and study use of synonym lists on the number of total words written by high-achieving students. All five students increased the amount of writing they produced in the intervention phase compared to baseline results.

Performance Feedback

In order to determine if performance feedback showed improvement in writing fluency, a total of seven studies were analyzed; 796 students participated in these studies. The amount of instruction varied from eight weeks to one academic year. Of these studies, six had a True-QES design (Roth and Guinee, 2011; Hier and Eckert, 2014, 2016; Truckenmiller et al., 2014; Alitto et al., 2016; Koenig et al., 2016) and showed a combined ES of 0.36 [95% CI (0.06, 0.66)]. The significant Q and I^2 value of 70.34 indicated that the effects may imply considerable heterogeneity. The Fail-safe N indicated that 58 missing studies would be needed to reverse this finding. One non-experimental study reported gains in writing fluency associated with the use of performance feedback (Heskial and Wamba, 2013), highlighting that kindergarten students benefit from engagement in dialogue with the teacher, who read the feedback to them in order to support their development of a sense of story.

DISCUSSION

In comparison with other academic areas such as reading, little attention has been directed to preventing writing difficulties. The findings from the previous reviewed studies, however, indicate that handwriting treatments early in kindergarten and the primary grades may be a critical factor to improve and to prevent writing fluency difficulties, for full range students as well as for students with handwriting difficulties in producing letters fluently and automatically.

Similar to treatments for improving reading fluency, different theoretical and empirical frameworks have been found in the reviewed studies to enhance writing fluency; these can be grouped into two broad categories: skill-based and performance-based interventions (Chafouleas et al., 2004). Skill-based strategies involve the use of antecedent teaching procedures such as handwriting, teaching transcription skills, spelling, and sensory-motor handwriting interventions. In contrast, performance-based strategies implicate the manipulation of consequences for fluent writing. These strategies typically incorporate an element of reinforcement in the form of programmed contingencies, self-regulated strategies, goal setting, and performance feedback. In some cases, skill-based as well as performance-based interventions to improve writing fluency incorporate peer-assisted strategies (Puranik et al., 2017, 2018). Skill- and performance-based instructional strategies can be used in isolation or combined both within and across categories (Chafouleas et al., 2004).

As expected, we found that skill-based as well as performance-based writing interventions enhance writing fluency. The findings from this meta-analysis and systematic review have important theoretical implications for writing fluency development among initial writers (kindergarten to 6th grade). These findings apply to students with and without handwriting difficulties in kindergarten through 6th grade. While different types of handwriting instruction improved fluency, there was considerable variability in the magnitude of the effects.

In the first place, we analyzed whether any type of handwriting instruction produced greater effects in writing fluency than no instruction or instruction unrelated to handwriting, such as phonological awareness or keyboarding. We located 13 studies including students representing a full range of handwriting skills. They included students in kindergarten to through 5th grade. Although all the intervention conditions involved a type of handwriting instruction, the specific type of intervention and tasks of focus varied greatly across the 13 studies. Three of them focused on performance-based interventions (e.g., performance feedback or goal setting). Five of them focusing on skill-based interventions (e.g., writing letters, words, and sentences fluently and accurately; one of the studies used sensory-motor handwriting practices). Finally, five of them were multicomponent programs using combined skill- and performance-based interventions. The result show that handwriting instruction had a statistically significant impact on improving writing fluency.

Secondly, we categorized studies by the intervention type tested in their experimental conditions: handwriting/transcription skills, handwriting combined treatments, multi-component programs, sensory-motor handwriting interventions, self-regulated strategy, and performance feedback (see **Table 1**). The handwriting instruction presented ranged from relatively short and focused interventions (e.g., copying letters during a few sessions) to longer and more comprehensive handwriting programs (e.g., multi-component instruction spanning several months). As noted earlier, we calculated only a summary statistic (ES) for treatments that included at least three studies. We recognize, however, that small sample sizes are less reliable and must be interpreted more cautiously than a summary statistic based on a larger number of studies.

One skill-based strategy that was shown to be effective in isolation or combined is handwriting/transcription intervention, especially when it is aimed at writing automatically and fluently (Graham et al., 2000, 2018; Alves et al., 2016; Limpo and Alves, 2018; Limpo et al., 2018). The reviewed research indicated robust significant differences in writing fluency for primary grade students assigned to a handwriting treatment alone (see **Tables 1**, **3**) or combined (see **Table 1**). However, in the handwriting/transcription intervention group, two out of five studies (Mackay et al., 2010; Howe et al., 2013) did find negative effects in handwriting fluency after treatment. Nonetheless, Howe et al. (2013) reported limitations in the test used to score writing fluency. The authors claimed that the test used did not accurately assess differences in speed between students. Moreover, the study by Mackay et al. (2010) did not explicitly train handwriting fluency and although students gained in writing legibility, but they obtained lower scores in writing speed after treatment. In the case of the combined handwriting intervention, Hurschler Lichtsteiner et al. (2018) reported that, as handwriting automaticity was already high at the beginning of the study, the intervention was not able to improve it further.

Due to the important role of transcription skills, handwriting must be trained not only to be as legible as possible, but also to become more and more fluent (Hurschler Lichtsteiner et al., 2018). The results of the present review show that when handwriting programs solely teach the components of legibility (Mackay et al., 2010) or spelling (Alves et al., 2016; Hurschler Lichtsteiner et al., 2018), writing fluency does not improve. The same conclusion could be applied to sensory-motor handwriting treatments not centered on training writing fluency practices. In general terms, these programs improve the readability of handwriting and other handwriting measures, such as letter formation and spatial organization, but not writing speed (Weintraub et al., 2009; Salls et al., 2013). In the category of sensory-motor handwriting treatment, we found one exception, i.e. the study by Roberts et al. (2010). They reported a significant increase in handwriting speed; however, the authors mentioned that this gain in writing speed was clinically insignificant compared to other improvements the students obtained after the treatment. However, we have to be aware that there were not enough data to calculate the impact of sensory-motor handwriting intervention and to make informed conclusions.

In the reviewed research, we also found additional practices, involving highly structured and explicit multi-component writing instruction programs such as Peer-Assisted Writing Strategies (PAWS) (Puranik et al., 2017, 2018), Write Star (Case-Smith et al., 2011, 2012, 2014a,b), and I Can! (Van Waelvelde et al., 2017). These programs include skill-based instructional strategies and performance-based strategies used in combination. The PAWS program applies two theoretical and empirical frameworks for beginning writers. The first focus of the program is on teaching transcription skills, i.e., handwriting and spelling. The second focus is on writing as a mode of social action that allows a child to learn from interaction with a more knowledgeable other. The teacher models the lessons, and the feedback processes and learning occurs during interactions among students and teacher and between students acting as coaches and writers (Puranik et al., 2017, 2018).The Write Star program (Case-Smith et al., 2011, 2012, 2014a,b) includes six core elements: (1) a co-teaching model of two teachers and an occupational therapist, (2) the teacher and therapist model letter formation, (3) the students copy from the model and engage in repeated practice, (4) the students work in groups of

6-7 that rotate through sessions, (5) the teachers and therapist provide frequent feedback, encouraging self-evaluation, and praising the students' efforts, and (6) the teachers and therapist monitor and assess students' performance, combining skill- and performance-based writing intervention strategies. Regarding the I Can! program, it should be mentioned that this is a remedial handwriting program with a focus on self-regulated learning and applying motor learning principles combined with handwriting practices and a behavioral approach (Van Waelvelde et al., 2017). All these multicomponent programs are good examples of using a multi-element design approach. ES and meta-analysis results of the present study suggested that multi-component programs, i.e., a combination of skill-based and performance-based intervention incorporating peer-assisted learning strategies, could be an adequate approach to develop writing fluency in early writers.

The effectiveness of the self-regulated strategy to improve writing fluency is mixed. Jongmans et al. (2003) tested a handwriting self-instruction method centered on how to form letter shapes and sensory-motor-learning principles. They found that children in the treatment group did not improve in writing fluency. The ES of the rest of the studies in this category could not be calculated because data were not available. Geisler et al. (2009) examined the effects of students' self-counting of words on the total words written, showing that all five students increased the amount of writing they produced. Zumbrunn and Bruning (2012) implemented a self-regulated strategy development model of instruction involving teaching students' strategies for planning and organizing their writing, combined with self-regulation procedures, such as monitoring and goal setting. The authors describe that, after treatment, participants wrote stories that contained more essential components, were longer, and of better quality. Kasper-Ferguson and Moxley (2002) report on the results of student graphing and monitoring their writing fluency. Their primary goal was to increase writing fluency, and they found that the writing rates of all students improved over the course of the school year. It is worth mentioning in this category the study by Limpo and Alves (2018) that examined the effectiveness of combining self-regulation and handwriting training with a self-regulation only intervention. The results showed that the self-regulation only intervention was particularly uneffective at increasing writing fluency.

Additionally, performance feedback (PF) was shown to be effective in a number of academic domains, including writing, and it has been implemented with students at all ages (Eckert et al., 2009). Research into the effectiveness of feedback on behavior has a long history in Psychology, since feedback has been identified as a mechanism that leads to a change in behavior, because the student compares that feedback to some standard of performance and feels motivated either to reduce the discrepancy or to surpass the standard (Bandura, 1969).

The results from several reviewed randomized control trials (Hier and Eckert, 2014, 2016; Truckenmiller et al., 2014; Alitto et al., 2016; Koenig et al., 2016) have indicated that performance feedback is a simple-to-implement, time-efficient method to improve writing fluency in elementary-age students. Students engaged on a brief Curriculum Based Measurement in Written Expression (CBM-WE) probe delivered once per week over the course of several weeks. These probes consist of giving the students a prompt for writing a story. These prompts were read aloud to students as well as printed on their response sheets. Students were given one minute to plan their stories and three minutes to write their compositions. Performance feedback conditions included students receiving feedback regarding their performance on the CBM-WE probes from the previous session. In comparison to students who engaged in weekly writing practice without feedback, those who received feedback about their writing fluency demonstrated significantly greater growth in writing fluency over the course of the intervention. Further to the positive impact of the performance feedback intervention on students' writing fluency, teachers rated the PF intervention as acceptable on measures of social validity (Hier and Eckert, 2016) and as positively affecting students' self-efficacy, a variable that contributes to overall writing competence (Hier and Mahony, 2018). However, the effect of intervention maintenance was limited (Hier and Eckert, 2014; Hier and Mahony, 2018). These findings suggest that, in isolation, performance feedback may produce short-term desired effects on students' writing fluency growth, but explicit programming of generality may be required to produce long-term achievement gains. Although the performance feedback intervention leads to improvements in students' performance in writing fluency, research by Alitto et al. (2016) found that the combination of performance feedback, provided by teachers or peers, combined with goal setting, leads to better performance than either component alone. In contrast, a study by Koenig et al. (2016) showed that providing students with an additional goal-setting component did not improve students' writing fluency more than performance feedback alone.

Additionally, a study by Roth and Guinee (2011) showed that children made gains in sentence fluency after an interactive writing intervention in which the teacher provided powerful demonstrations of writing and delivered the clearest examples of instruction in response to the learners' needs; moreover, children had the opportunity to work together to solve problems. In the same vein, a study by Heskial and Wamba (2013) highlighted that kindergarten students benefit from engagement in a dialogue with their teacher, who read the feedback to them in order to support their development of a sense of story. Kindergarten students responded to teacher feedback in different ways, but the feedback contributed to an increase in writing fluency that was consistent and evident in the analyzed studies.

LIMITATIONS AND CONCLUSION

Interpretation of the findings for specific instructional techniques should be considered by the fact that the number of studies testing each practice was small. Additional research is needed to more fully test the effectiveness of these interventions.

We adopted a liberal, exploratory approach. Although this allowed us to optimize the findings from the available research, it also meant many of our analyses were underpowered. However, we indicated in each analyzed handwriting intervention category how much confidence can be placed in our results, based on the indicators of the quality of the included research (see **Table 4**).

The studies reviewed here allowed us to establish that handwriting treatments early in kindergarten and the primary grades compared to non-treatment enhance writing fluency for developing writers and may be a critical factor to improve and to prevent writing fluency difficulties for full range students as well as for students with learning disabilities. This finding provides support for the significance of developing automaticity of the transcription component of the Simple View of Writing for initial writers (Berninger et al., 2002).

The present study explored the nature of writing fluency interventions in languages considered to have a non-transparent orthography. Out of the seventeen studies included in the performed meta-analyses, fourteen were in English, one in French (Van Waelvelde et al., 2017), one in Portuguese (Limpo and Alves, 2018) and another one in Hebrew (Weintraub et al., 2009) (see **Table 1**).

The present review also provides some insight into the effectiveness of specific methods for teaching handwriting fluency. Handwriting/transcription instruction is an effective to method to improve writing fluency, especially when it is aimed at promoting writing automaticity and students receive explicit instruction in writing letters, words, and sentences fluently and accurately. The results also show that multi-component handwriting programs may boost and prevent handwriting fluency difficulties in kindergarten and first-grade children. Finally, performance feedback interventions with writing practice based on CBM-WE probes demonstrated significant effects on writing fluency improvements after treatment. Other handwriting interventions, such as sensory-motor handwriting or self-regulation strategies, do not seem to have a significant impact on improving writing fluency. However, the current results show that planning explicit methods of writing intervention has an impact on improving writing fluency in early writers and that writing fluency intervention can be a means of preventing writing difficulties and a motivation to improve writing skills throughout schooling and for use in everyday life.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

CL-E contributed to conception and design of the study and wrote the first draft of the manuscript. RP-L organized the database. JM-B performed the statistical analysis. CL-E, RP-L and JM-B wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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The Interface Between Reading and Handwriting

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Keywords: reading, handwriting, visual word form area, typical development, dyslexia, developmental coordination disorder

INTRODUCTION

Zelaznik and Goffman (2010) state: "Language production, whether spoken, signed, or written, is a motor activity" (p. 383). There are specific connections between the linguistic process of reading and the motoric process of handwriting, including how they develop, where and how they are instantiated within the brain, and what can occur when their underlying neurological processes are compromised.

This connection is reflected in even the earliest research regarding disorders of reading and writing. Broadbent (1872), Berlin (1887), and Kussmaul (1887) first reported that acquired brain damage could cause patients to lose their speech, reading, and writing skills even when their non-verbal cognition was preserved. English physician Morgan (1896) and Scottish ophthalmologist Hinshelwood (1900) believed that medical problems caused difficulties in reading and writing. Researchers Myklebust and Johnson (1962) described symptoms which they observed in many of 200 children with dyslexia, including subclinical disturbances in motor coordination.

THE DEVELOPMENT OF HANDWRITING

Children learn to recognize letters before becoming able to write them (Reutzel et al., 2019). A child first begins to scribble with no discernible pattern (Coates and Coates, 2016). Between the ages of 2 and 3 years, he/she learns to imitate shapes (vertical strokes, horizontal strokes, and circles). The child may be ready to begin writing when he/she is able to cross the body's midline to imitate an oblique cross (Feder and Majnemer, 2007). Even at this young age, children use different arm and hand movement patterns when drawing as opposed to writing. McCutchen (2006) concludes that, to a certain extent, even these young children can distinguish between drawing and writing. By age four, children write marks arranged in a line with regular spacing (Scott, 2012). Researchers have learned about children's handwriting development from measures as diverse as examining their visual-motor integration abilities, kinematics of their pen movements, and eye movements as they write (Fears and Lockman, 2020). Researchers have also explored dynamic measures including the velocity, acceleration, pressure, and tilt of writers' pens (Gargot et al., 2020) and their pause behaviors (Sumner et al., 2013; Alamargot et al., 2020).

Throughout the early school years, learning handwriting contributes to the child's overall writing development (Graham et al., 2008). Learning stroke sequencing helps young people to memorize letter shapes (Longcamp et al., 2005; Mangen and Velay, 2010; Stevenson and Just, 2014)—a skill that keyboarding alone does not necessarily accomplish. Children also recognize letters more efficiently when writing than when typing them (Longcamp et al., 2005). A student's handwriting legibility can influence whether he/she qualifies for special education services (Graham et al., 2008; Cahill, 2009), ultimately impacting the child's motivation and self-esteem (Gargot et al., 2020).

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READING AND HANDWRITING IN THE BRAIN

Accounts of the ways in which both reading and handwriting are instantiated in the brain are remarkably similar. Both involve hierarchical sequences of processing. In their *Local Combination Detector Model*, Dehaene et al. (2005) describe how the brain processes increasingly complex combinations of visual features *en route* to reading. Kemmerer (2015) summarizes seven consecutive stages of processing in this "assembly line." Processing begins when the retina of the eye perceives the visual stimulus and transmits information to the lateral geniculate nucleus of the thalamus. Here, cells process simple stimuli such as series of dots. Following this step, the brain's primary visual center in the occipital lobe is engaged. The occipital lobe integrates the representations of the thalamic cells to capture bars or lines of a variety of orientations; captures sections of contours or fragments of letters; recognizes entire letter shapes; supports invariant processing while ignoring superficial differences in font and case; and finally, processes bigrams (sequences of two letters) and quadrigrams (sequences of four letters).

Writing to dictation also follows a hierarchical sequence, in this case with five steps. First, when the ear hears the word, the brain recognizes the sound structure of the word. Next, the brain accesses the spelling of that word within the orthographic lexicon. Following that step, the *graphemic buffer*—a working memory system which temporarily holds the identities of the graphemes while the word is being written—is activated. Next, *allographic conversion* occurs, and the graphemes are translated from their abstract identities into concrete forms, depending upon whether the writer wishes to use print, cursive, uppercase, or lowercase letters. Subsequently, *graphomotor planning* occurs, and the brain instructs the motor system as to the size, direction, and sequence of movements to be executed. Finally, the motor act of handwriting occurs (Kemmerer, 2015).

The interface between reading and writing has its source in the brain. Reading and writing share some, but not all, neural substrates (Hillis, 2001; Tainturier and Rapp, 2001; Hillis and Rapp, 2004; Purcell et al., 2011). Within the cortex, the area most finely tuned for reading is the *visual word form area* (VWFA). This area is located within the lateral occipitotemporal sulcus and is lateralized to the left hemisphere. The VWFA may be activated by both reading and writing (especially for words with atypical spellings); however, the evidence from studies of brain injuries is equivocal on this point (Kemmerer, 2015). The dorsal premotor region facilitates both recognizing and writing letters (Velay and Longcamp, 2013). Exner's area is one of the main writing centers of the brain, and it is also activated during reading (Pattamadilok et al., 2016). The handwriting network described by Planton et al. (2013), including the supplementary motor area (SMA), pre-SMA, and putamen, is also activated during reading (Gosse et al., 2022). These findings indicate that writing actively facilitates fluent reading (Pattamadilok et al., 2016). As Kemmerer (2015) states, "when we see letters, our brains automatically recall the motor memories of how we manipulate a pen or pencil to produce them" (p. 219).

WHAT CLINICIANS NEED TO KNOW ABOUT THE INTERFACE

Individuals with reading differences/disorders including developmental dyslexia often experience persistent difficulties with handwriting (Sumner et al., 2016). Writing comprises the *central components* of language and orthography and the *motor/peripheral components* of execution (Planton et al., 2017). Gosse et al. (2022) used functional magnetic resonance imaging (fMRI) to examine the writing network in children with dyslexia. They discovered that these children experienced differences in cerebellar activation in both central and peripheral components. Thus, writing is not just a motor skill, as individuals with dyslexia may have difficulties in writing which are not directly caused by difficulties in graphomotor planning. Difficulties in handwriting may be related to difficulties in spelling, as students who struggle with spelling also tend to write more slowly and less fluently (Berninger et al., 2008; Hebert et al., 2018).

Dyslexia often does not occur in isolation but is comorbid with other neurodevelopmental differences such as developmental coordination disorder (DCD; Hill, 2001; Visser, 2003). Authors of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5; American Psychiatric Association, 2013) state that DCD has four diagnostic criteria: clumsiness, slowness, or inaccuracy in performing motor skills; difficulties that interfere with activities of daily living; early onset of symptoms; and symptoms that are not explained by intellectual disability, vision problems, or another underlying neurological condition. Children with DCD may experience difficulties dressing themselves (e.g., buttoning shirts or tying shoelaces), eating with utensils and without mess, playing physical games, using tools such as rulers and scissors in school, and—most relevant to the topic at hand—producing legible handwriting (American Psychiatric Association, 2013). Motor difficulties in DCD may occur in either gross- or fine-motor skills (Harris et al., 2015).

There is a significant overlap between the experiences of individuals with language learning differences and individuals with DCD. Both may demonstrate weak hand lateralization and may be inclined to reach across their body's midline with their non-preferred hand (Hill et al., 1998). According to Hodgson and Hudson (2017), this is because unlike most adults with neurotypical development, individuals with neurodiversity may demonstrate altered hemispheric mapping and reduced left-hemisphere activation during speech production (Whitehouse and Bishop, 2008; Illingworth and Bishop, 2009). There are differences between these profiles as well. Berninger and Amtmann (2003) and Hebert et al. (2018) suggest that handwriting and spelling engage separate processes. Handwriting engages orthographic coding, whereas spelling engages both orthographic and phonological coding.

Professionals—including speech-language pathologists, school psychologists, and general and special education teachers—who work with individuals experiencing difficulties in reading, motor performance, or both, must be aware of several concepts. First, the task of writing is comparable to that of a juggler keeping many balls in the air simultaneously. These "balls" include planning one's thoughts, spelling, executing legible handwriting (McCutchen, 2006), and writing accurately. Often, the flight of one ball is sacrificed to keep the others aloft. Gombert (1992) describes this as a state of *cognitive overload*. Helping children to write more efficiently and automatically can allow them to direct their cognitive resources toward planning and generating ideas rather than dwelling on accurate spelling and handwriting (Wanzek et al., 2017). In clinical parlance, it is often beneficial to implement *benign neglect*. Rather than criticizing every aspect of the child's message, the clinician should focus on one aspect (e.g., grammar, spelling, handwriting, punctuation...) during a given lesson and neglect all other aspects to decrease the child's frustration. Concentrating on letter-writing fluency (LWF) as an instructional goal may be beneficial, as Reutzel et al. (2019) mention that LWF predicts academic success even in college students.

Clinicians may execute a range of strategies to utilize this interface to improve the learning outcomes of their clients. Specifically, multimodal practice involving the physical formation of letters can enhance reading outcomes. One treatment for reading employing multiple modalities and enjoying support in the literature is the Orton-Gillingham approach. In this approach, clinicians emphasize multisensory input, encouraging children to engage their visual, auditory, and kinesthetic/tactile learning pathways while breaking down reading into its individual components (Sayeski et al., 2019). The Montessori method, originally pioneered by Italian psychologist Maria Montessori, involves activities such as tracing letters cut from sandpaper, drawing letters in shaving cream, and conducting activities which combine vision and a sense of space (Dehaene, 2009). The Lindamood Phoneme Sequencing Program (Lindamood and Lindamood, 1998) also incorporates oral-motor, visual, and auditory feedback during teaching. The Wilson Reading System is another multisensory approach which includes instruction in phonemic awareness, phonics, fluency, vocabulary, and comprehension (Duff et al., 2015). Teachers using Elkonin boxes instruct children in phoneme segmentation and blending through the manipulation of tokens (Ross and Joseph, 2019). These are just some examples of therapeutic techniques that can be used to direct the client's attention to both reading and handwriting skills through the use of multiple modalities. Improvements in spelling can lead to improvements in handwriting and vice versa (Hebert et al., 2018).

The use of technology (including iPad applications) can improve handwriting legibility and speed (John and Renumol, 2018), as well as other visuomotor skills, in even very young children (Dessoye et al., 2017; Axford et al., 2018; Butler et al., 2019). Technology may be beneficial beyond traditional intervention approaches within occupational therapy, such as an emphasis on repetitive or multimodal practice (Zachry et al., 2020). Using technology can be particularly valuable because it provides convenience to teachers and motivation to students (Aronin and Floyd, 2013; Campigotto et al., 2013; Kaur, 2017; Zachry et al., 2020). Practice with technology can also improve other fine-motor outcomes including manual dexterity (Butler et al., 2019).

DISCUSSION

Reading and handwriting share similarities at many levels. Their developmental progression and their instantiation within the brain substantially overlap. Researchers and clinicians should be aware of symptoms that occur when underlying neurological processes are compromised as well as therapeutic techniques that can support the development of these two skills. The multifaceted interactions between these two modalities of language deserve further attention within the literature, especially concerning their practical implications in clinical settings.

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Effects of a short and intensive transcranial direct current stimulation treatment in children and adolescents with developmental dyslexia: A crossover clinical trial

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Developmental Dyslexia (DD) significantly interferes with children's academic, personal, social, and emotional functioning. Nevertheless, therapeutic options need to be further validated and tested in randomized controlled clinical trials. The use of transcranial direct current stimulation (tDCS) has been gaining ground in recent years as a new intervention option for DD. However, there are still open questions regarding the most suitable tDCS protocol for young people with DD. The current crossover study tested the effectiveness of a short and intensive tDCS protocol, including the long-term effects, as well as the influence of age and neuropsychological processes at baseline on reading improvements. Twenty-four children and adolescents with DD were randomly assigned to receive active tDCS during the first slot and sham tDCS during the second slot or vice versa. Five consecutive daily sessions of left anodal/right cathodal tDCS set at 1 mA for 20 min were administered over the parieto-occipital regions. Reading measures (text, high frequency word, low frequency word, and non-word lists) and neuropsychological measures (visual-spatial and verbal working memory, phoneme blending, and rapid automatized naming tasks) were collected before, immediately after, 1 week and 1 month later the treatment. Our results showed that only the active tDCS condition improved non-word reading speed immediately after and 1 month later the end of the treatment compared with baseline. In addition, the improvement in non-word reading speed was significantly correlated with age and with neuropsychological measures (verbal working memory and phoneme blending) at baseline but only in the active tDCS condition. The current crossover study contributed to enforce previous effects of tDCS, including long-term effects, on non-word reading speed and to understand the effect of age and neuropsychological processes on reading outcomes. Our findings showed that tDCS could be a low-cost and easy-to-implement treatment option with long-term effects for children and adolescents with DD.

KEYWORDS

specific learning disorders, non-invasive brain stimulation, interventions, reading, neuroplasticity

Introduction

Among reading difficulties, Developmental Dyslexia (DD) is a severe and long-lasting impairment of reading skills acquisition, specifically characterized by inaccurate and/or non-fluent word recognition and poor spelling and decoding abilities, in absence of neurological, sensorial, and cognitive deficits or educational under-exposure (American Psychiatric Association [APA], 2013). With an estimated prevalence of 7% (Yang et al., 2022), DD consists of a neurobiological-based disorder that covers about 80% of all learning disabilities (Mee Bell et al., 2003; Shaywitz et al., 2007) and is distinguished by difficulties in reading comprehension at higher levels.

Although several interpretative theories of DD have been proposed over the years (for a review, see Peterson and Pennington, 2012), extensive evidence converges to consider DD as a multifactorial disorder with heterogeneous manifestations (Menghini et al., 2010). Accordingly, DD has been associated with neurofunctional abnormalities of a broad cerebral network in the left posterior hemisphere: a well-documented under activation of left temporo-parietal regions – mainly involved in lexical access and phonological processing – and left occipito-temporal regions – mainly involved in the fast word recognition – compared to typical readers (for a review, see Richlan, 2020). Moreover, parieto-occipital regions have been shown to be implicated in whole-word representations (Graves et al., 2008), in reading morphologically complex words (Zweig and Pylkkänen, 2009) and during the comprehension of complex linguistic units (Jobard et al., 2007).

Multiple neurocognitive domains were found to be impaired in children and adolescents with DD. Several studies have shown that children with DD often have difficulties in phonological and non-phonological skills, such as in working memory (Gathercole et al., 2006; Beneventi et al., 2010; Wolf et al., 2010; Menghini et al., 2011), auditory and visual selective attention (Hari and Renvall, 2001; Bosse et al., 2007; Roach and Hogben, 2007; Facoetti et al., 2010; Lallier et al., 2010; Franceschini et al., 2012; Zorzi et al., 2012), executive functions (Willcutt et al., 2005; Shanahan et al., 2006; Varvara et al., 2014), automatization of sub-skills (Nicolson and Fawcett, 1990; Nicolson et al., 2001), and implicit and procedural learning (Vicari et al., 2003, Menghini et al., 2006). There is also evidence for difficulties in motion perception, as supported by the magnocellular deficit theory, and for visual-perceptual impairments (Galaburda and Livingstone, 1993; Kevan and Pammer, 2008, 2009; Menghini et al., 2010; Boets et al., 2011; Gori et al., 2014).

Given its functional impairment and impact on learning, DD is recognized as a risk factor for reduced socio-economic outcomes (Carroll et al., 2005; Aro et al., 2019) and the onset of emotional-behavioral difficulties (Hendren et al., 2018; de Lima et al., 2020; Wang, 2021; Xiao et al., 2022). Although some treatments, especially those based on phonics, have shown some efficacy in improving reading skills in children and adolescents with DD (Galuschka et al., 2014; McArthur et al., 2018; Wanzek et al., 2018), there is still some variability in response and treatments are not effective for all children (Gabrieli, 2009; Toffalini et al., 2021). These reasons drive the need to provide further testing and validation of treatments in DD.

In this context, the use of non-invasive brain-based methods has been gaining ground in recent years as a new intervention option for children and adolescents with DD (Cancer and Antonietti, 2018). Among these non-invasive brain-based methods, transcranial direct current stimulation (tDCS) has been the most widely used technique to improve reading accuracy and speed in typical readers and readers with DD (for a review, see Turker and Hartwigsen, 2022), especially when combined with reading trainings (Finisguerra et al., 2019). tDCS is a safe and highly tolerated method (Buchanan et al., 2021) and involves the application of a direct, low current (usually 1–2 mA) to the scalp through two sponge electrodes (anode and cathode). It has been shown to induce persistent neural changes and modulate behavior (Nitsche and Paulus, 2000; Woods et al., 2016).

In children and adolescents with DD, several studies have demonstrated the beneficial effect of tDCS – stand-alone or in combination with reading training – on reading tasks, especially in non-word reading (efficiency, accuracy as well as speed), word reading fluency and word recognition speed, low-frequency word reading accuracy as well as text reading accuracy (for a review, see Turker and Hartwigsen, 2022).

Whereas, in children and adolescents with DD, the neurocognitive mechanisms modulated by tDCS and potentially associated with improvement in reading tasks have been investigated by only two studies. Specifically, Costanzo et al. (2016a) found that compared to baseline, a single session of left anodal/right cathodal tDCS on temporo-parietal regions as well as the reverse polarity montage significantly modulated neuropsychological processes (i.e., phoneme blending and verbal working memory) along with changes in reading. In addition, Lazzaro et al. (2021a) demonstrated that, compared with the reverse polarity montage, a single session of left anodal/right cathodal tDCS improved non-verbal neuropsychological processes (i.e., motion perception and modified attentional focusing) along with changes in reading.

However, although the results of non-invasive brain stimulation in DD are generally promising, randomized clinical trials (RCTs) are still few and have some methodological issues.

First, tDCS studies for the treatment of DD are characterized by small sample sizes with a maximum of 27 participants (Lazzaro et al., 2021b) and conducted mainly with between-subjects design.

Second, existing results are fundamentally heterogeneous (Costanzo et al., 2016b, 2019; Rios et al., 2018) probably due to high inter-subject variability. Indeed, it has been widely recognized that the influence of stable factors (demographical, neuroanatomical, and genetical), or transient/contextual factors such as vigilance, hormonal activity, participant engagement or task predisposition can significantly produce heterogeneous results and alter the generalizability of findings observed in tDCS studies (for a review, see Vergallito et al., 2022).

One possibility to overcome these limitations is to design studies with a larger number of participants and/or apply a crossover design. In fact, the crossover study design was introduced in clinical research to obtain an effect estimate with the same level of accuracy as a between-subjects design, increasing statistical power even with a small number of participants (Senn, 2002; Chow and Liu, 2009; Wellek and Blettner, 2012), and suppressing the inter-subject variability (Jones and Kenward, 2014; Lim and In, 2021).

Third, the medium- and long-term effectiveness of tDCS studies in DD has been poorly explored, and limited to studies in which stimulation was combined with reading training (Costanzo et al., 2016b, 2019; Lazzaro et al., 2021c; Mirahadi et al., 2022).

In this context, the current study represents the first RCT employing a crossover design to investigate the efficacy of a short and intensive multi-sessions stand-alone tDCS intervention in children and adolescents with DD. Further, to evaluate the after-effects of a stand-alone tDCS intervention, the present study aims to evaluate the persistence of observed results in the medium and long-term.

Furthermore, despite the extensive evidence regarding the implication of domain-general cognitive processes in the occurrence of DD (Menghini et al., 2010), neuropsychological processes related to reading improvement following tDCS have been poor explored (Costanzo et al., 2016a; Lazzaro et al., 2021a). To overcome this limitation, the current study aims to investigate neuropsychological measures related to reading (i.e., working memory, phoneme blending, and rapid automatized naming) to verify whether 5 days of tDCS can modulate these domain-general processes in addition to reading as well as whether these domain-general processes at baseline influence reading improvement following tDCS treatment.

We tested the effect of five consecutive daily sessions and the medium- (1 week later) and long- (1 month later) term effect of left anodal/right cathodal tDCS over parieto-occipital regions without reading training in 24 children and adolescents with DD. In addition to the documented strong effect of tDCS combined with concomitant training (Costanzo et al., 2016b, 2019; Lazzaro et al., 2021c), the results of previous studies (Turker and Hartwigsen, 2022) and our preliminary results (Lazzaro et al., 2021b) introduced the possibility of also considering short and intensive tDCS treatment without concomitant training in children and adolescents with DD. Furthermore, the choice to place bilateral tDCS on the parieto-occipital regions is based on evidence reporting their crucial role on whole-word representations (Graves et al., 2008), in reading morphologically complex words (Zweig and Pylkkänen, 2009) and during the comprehension of complex linguistic units (Jobard et al., 2007).

In light of this, we hypothesize that even short and intensive tDCS treatment can result in improved reading performance. The absence of a reading training associated with tDCS may help to understand the specific influence of five sessions of neurostimulation in inducing reading improvement and triggering medium- to long-term neuroplasticity processes. Furthermore, studying the effect of tDCS on neuropsychological measures that are most often impaired in DD may be a further step in understanding how reading may be modulated in relation to possible changes in domain-general processes.

Finally, starting from our previous results (Lazzaro et al., 2021c) and in accordance with studies indicating that pre-existing factors (e.g., age) may contribute to improvements after tDCS treatment (for a review, see Vergallito et al., 2022), we explored the association between age and reading improvement.

Indeed, individual factors influencing outcomes deriving from tDCS without reading training find merit to be investigated in order to improve the applicability of such treatment in children and adolescents with DD.

Materials and methods

Ethical committee

This study was performed under the Declaration of Helsinki and was approved by the local research ethics committee (process number 20120X002931). The study was registered at ClinicalTrials.gov (ID: NCT04244578).

Participants

Participants were enrolled during the daily clinical activities of the Child and Adolescent Neuropsychiatry Unit at the Bambino Gesù Children's Hospital (Rome).

The presence of DD was assessed by a team of expert clinicians, including a psychologist, a neuropsychiatrist, and a speech therapist according to the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5; American Psychiatric Association [APA], 2013), and using norm-referenced reading measures as text, word and non-word reading (Sartori et al., 2007; Stella and Tintoni, 2007; Cornoldi et al., 2010; Cornoldi and Colpo, 2012; Cornoldi and Candela, 2015). Participants met DD criteria when the accuracy or speed level was at least 1.5 standard deviations below the age mean. Children and adolescents with intellectual disability, a personal history of neurological diseases, a personal history of epilepsy or in a first-degree relative, other primary psychiatric diagnoses or comorbid neurodevelopmental disorder (e.g., attention deficit or hyperactivity disorder, depression, and anxiety), and had received treatment for DD in the 3 months prior to baseline screening were excluded. All participants had normal or corrected-to-normal vision.

After receiving or confirming the diagnosis of DD and ascertaining the inclusion criteria, the researcher asked the children and adolescents and their parents if they wished to participate in the study. Then, the objectives and design of the study, all related procedures and the effort required, and the basic principles of tDCS and its characteristics were presented in detail. The results of published studies over the years on the application of tDCS in children and adolescents with DD were also summarized to clarify the rationale of the proposed experiment. All participants and their parents agreed to participate in the study after the procedures had been fully explained and they gave written informed consent to the study.

As **Figure 1** depicts (CONSORT flow diagram), 33 children and adolescents were screened for clinical eligibility, 29 of them were recruited and participated in the study. After the exclusion of 5 participants (1 outlier; 4 drops-out), a total sample of 24 native right-handed Italian-speaking children and adolescents with DD fully completed the crossover design and were considered for the study.

After clinical eligibility screening at baseline, recruited participants were randomized into two groups *via* minimal sufficient balancing method (to prevent imbalances in the baseline): A_S_{Group} [who received active tDCS during the first slot and sham tDCS during the second slot; age range: 9–17 years; females, F/males, M: 5/7; non-verbal IQ (nvIQ; Raven, 2008, 2009) range: 92–123] and S_A_{Group} (who received sham tDCS during the first slot and active tDCS during the second slot; age range: 10–18 years; F/M: 5/7; nvIQ range: 93–130).

Means (standard deviations – SDs) for chronological age, nvIQ, and *z*-scores of the norm-referenced reading measures at baseline are shown on **Table 1**. At baseline, the two groups did not differ for age (p = 0.10), nvIQ (p = 0.20), and clinical norm-referenced measures of reading: Text (Accuracy: p = 0.56; Speed: p = 0.86), Word (Accuracy: p = 0.92; Speed: p = 0.21), and Non-word (Accuracy: p = 0.63; Speed: p = 0.11).

Sample size considerations

The sample size was calculated by *a priori* analysis in G*Power, version 3.1.9.7 (The G*Power Team, Düsseldorf, Germany).

To be conservative, we calculated the expected effect size (f) to medium/low and estimated it at 0.20.

With an estimated f = 0.20, α value = 0.05 (i.e., probability of false positives of 5%), β = 0.80 (i.e., at least 80% power), and a correlation among measures of 0.7, the sample size that was required for repeated-measures analysis of variance (RM ANOVA) with two conditions (Active vs. Sham) and four measurements (T0 vs. T1 vs. T2 vs. T3) was 22.

Study design and procedures

A double blind, randomized, sham-controlled, crossover clinical trial was conducted.

Children and adolescents with DD underwent five consecutive daily sessions of active or sham tDCS (first slot, week 1). In the first slot, outcome measures were randomly administered at baseline ($T0_1$), immediately after the end of the treatment ($T1_1$), 1 week later ($T2_1$), and 1 month later ($T3_1$) by an investigator blinded to the stimulation conditions. After a 1 month washout (after the end of the $T3_1$), children and adolescents who had received active tDCS during the first slot underwent five consecutive daily sessions of sham tDCS during the second slot, and vice versa. Similar to the first slot, in the second slot, outcome measures were administered randomly immediately before the start ($T0_2$) and after the end of treatment ($T1_2$), 1 week later ($T2_2$) and 1 month later ($T3_2$).

The study design and preliminary results – which include only participants who fully completed the first slot of either active or sham tDCS, assessment immediately post-treatment

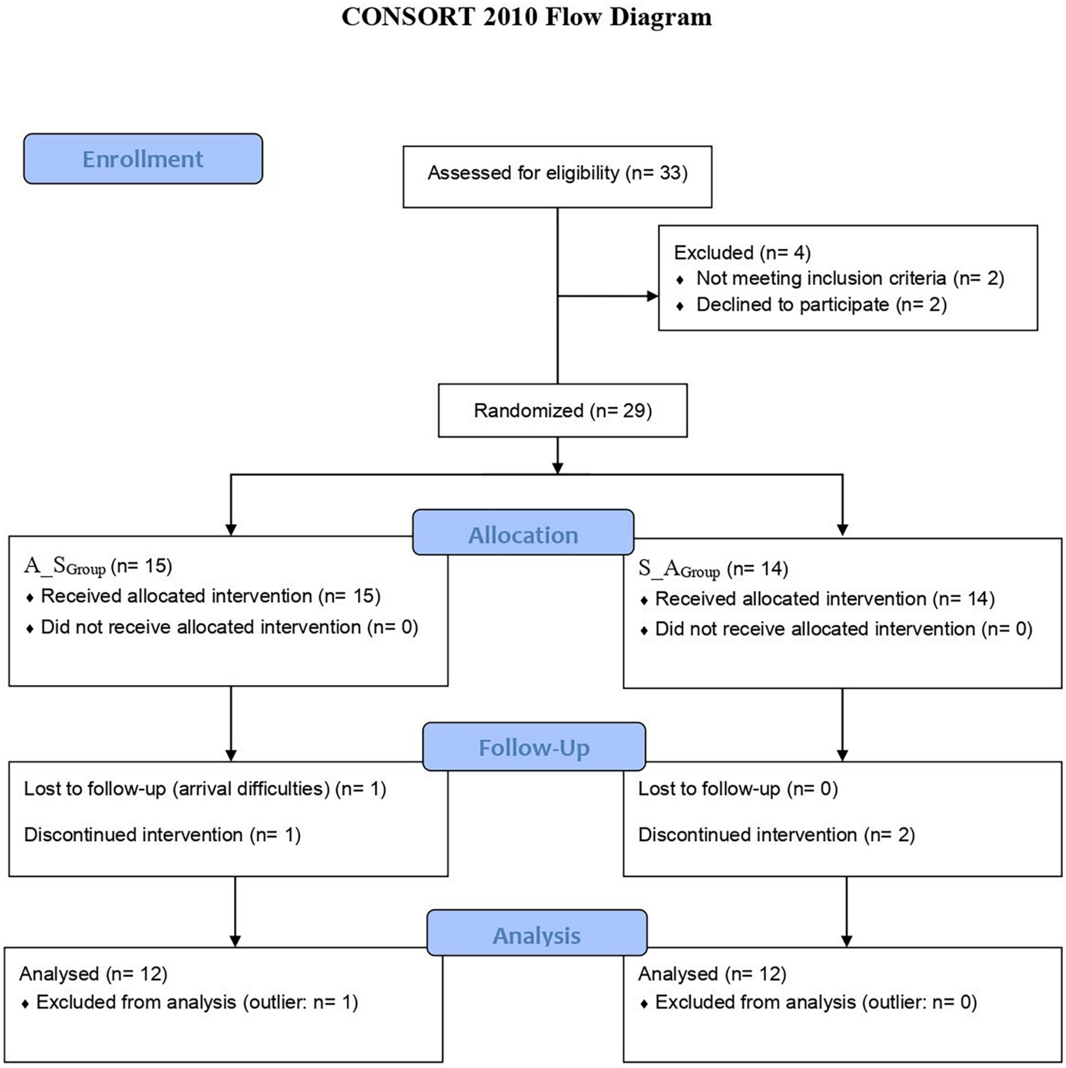

FIGURE 1
CONSORT flow diagram of the RCT.

and 1 week later – were already presented in Lazzaro et al. (2021a).

Here, we will report the results of participants who fully underwent the crossover RCT, including treatment sessions and follow-ups (**Figure 2**).

All activities related to the study were conducted in a research laboratory at the Child and Adolescent Neuropsychiatry Unit of the Bambino Gesù Children's Hospital in Rome.

Outcome measures

To avoid the repetition effect, different versions of each task were considered, randomized between baseline and follow-up assessments ($T0_1$, $T1_1$, $T2_1$, $T3_1$, $T0_2$, $T1_2$, $T2_2$, and $T3_2$). To control for the effects of fatigue, task order was counterbalanced between assessments.

An extensive description of the proposed tasks were reported in Costanzo et al., 2016a,b, 2019 and Lazzaro et al., 2021a,b,c.

Reading tasks

Several reading tasks were presented, including: a text of more than 400 syllables (TEXT), a list of 20 high-frequency words (HF – 10 trisyllabic and 10 bisyllabic), a list of 20 low-frequency words (LF – 10 trisyllabic and 10 bisyllabic), and a list of 20 non-words (NW – 10 trisyllabic and 10 bisyllabic). A behavioral pre-test was conducted in children and adolescents with typical reading to select different versions of each set of stimuli (TEXT, HF, LF, and NW) that were equivalent in terms of difficulty in reading accuracy and speed (for more details, see

TABLE 1 Means (SDs) of age, nvIQ, and *z*-scores of norm-referenced reading measures at baseline in the A_S_{Group} and S_A_{Group}.

	A_S_{Group} N = 12	S_A_{Group} N = 12	*t*-Value	*p*-Value
Age	12.42 (2.45)	14.24 (2.68)	1.73	0.10
nvIQ	109.83 (10.61)	104.08 (10.79)	−1.32	0.20
Text				
Accuracy[a]	−2.34 (1.45)	−3.15 (4.53)	−0.59	0.56
Speed[b]	−2.37 (0.57)	−2.42 (0.80)	−0.18	0.86
Word				
Accuracy[a]	−2.26 (1.47)	−2.13 (4.30)	0.10	0.92
Speed[c]	−5.70 (2.92)	−4.08 (3.27)	1.28	0.21
Non-word				
Accuracy[a]	−1.36 (1.03)	−1.75 (2.53)	−0.49	0.63
Speed[c]	−3.88 (1.72)	−2.61 (2.06)	1.65	0.11

[a]Number of errors. [b]Syllables/second. [c]Seconds. nvIQ, non-verbal Intelligence Quotient.

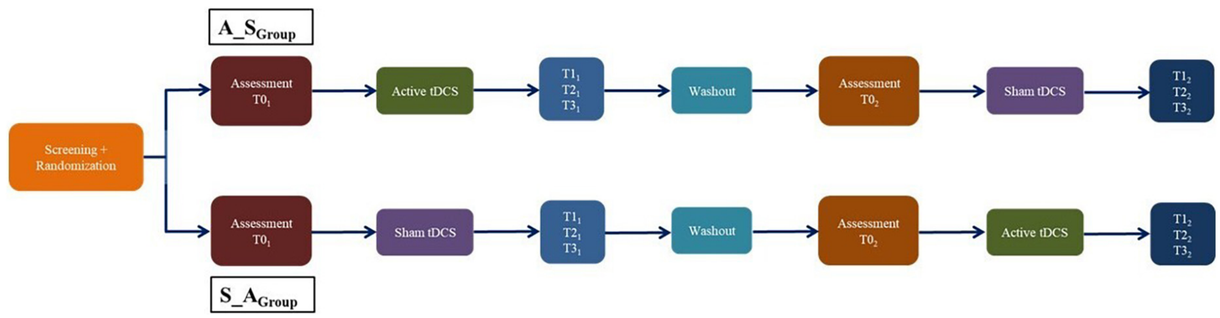

FIGURE 2
The crossover design.

Supplementary Table 1). Participants were asked to read aloud as rapid and accurate as possible.

For reading speed, the total time (in terms of seconds) taken to read HF, LF, and NW was measured. For TEXT, reading speed was calculated by dividing the total time (in terms of seconds) for reading completion by the total number of syllables spoken and multiplied by 100.

For reading accuracy, an error point was assigned in the presence of substitution, omission, addition of letters and in case of self-correction or hesitation during reading. For all reading tasks (TEXT, HF, LF, and NW), the percentage of accuracy was considered, calculated by multiplying the ratio of the number of correctly read stimuli to the total number of stimuli presented by 100.

Neuropsychological tasks

Working memory

Visual-spatial and verbal n-back tests were used to measure working memory.

The tests required participants to indicate whether the position of a colored box (visual-spatial n-back) moves to the same previous position or whether a pronounced letter (verbal n-back) matches the last pronounced letter (1-back). When the accuracy reached 80%, the difficulty increased and it was required to remember no longer the last position shown or the last letter pronounced, but the second-to-last (2-back), and, so on, the third-to-last (3-back), the fourth-to-last (4-back).

For both tests, an efficiency index (working-memory$_{Eff}$) was calculated due to the highest n-back passed (when the percentage of accuracy value was above equal to or greater than 80%) followed by the percentage of accuracy of n-backs failed (when the percentage of accuracy value is <80%). For example, if a child achieves level 2-back but fails at level 3-back with an percentage of accuracy of 60%, the efficiency index is 2.60.

Phoneme blending

In the phoneme blending task, participants had to put together phoneme sounds to compose a non-word. The number of correctly blended phonemes ($\text{Phonemes}_{\text{Acc}}$) and the total time in seconds for each non-word ($\text{Phonemes}_{\text{Time}}$) were calculated and considered.

Rapid automatized naming

Rapid automatized naming (RAN) test of letters ($\text{RAN}_{\text{Letters}}$) and colors ($\text{RAN}_{\text{Colors}}$) were administered. In $\text{RAN}_{\text{Letters}}$ and in $\text{RAN}_{\text{Colors}}$, participants had to name letters and colors aloud as quickly and accurately as possible, respectively. Total time in seconds was considered for each task.

Treatment

Direct current was delivered by a battery driven, direct current stimulator (BrainStim stimulation by E.M.S. s.r.l.—Bologna, Italy) *via* a pair of identical, rectangular (35 cm^2) saline-soaked sponge electrodes held fastened by elastic bands. According to the International 10–20 System, the anodal electrode was positioned on the site corresponding to PO7, situated over the left parieto-occipital areas, specifically between left occipito-temporal and left temporo-parietal regions. Conversely, the cathodal electrode was placed on the right side of the parieto-occipital areas, corresponding to PO8, situated between right occipito-temporal and right temporo-parietal regions.

In line with previous studies on reading (Costanzo et al., 2016b, 2019; Lazzaro et al., 2021c), we applied the left anodal/right cathodal tDCS montage. This methodological choice was mainly based on two reasons: (i) the well-known under activation of a distributed left hemisphere brain network in children and adolescents with DD (for a review, see Richlan, 2020); (ii) the polarity-specific effects of tDCS on reading (Turker and Hartwigsen, 2022), documented by studies showing that only left anodal/right cathodal placement induces positive changes (Costanzo et al., 2016a; Lazzaro et al., 2021a). Indeed, since anode generally facilitates neuronal activity and the cathode usually inhibits it, this montage is expected to push processing toward the left hemisphere, enhancing left lateralization. As already stated in Lazzaro et al. (2021b), the electrodes were placed according to studies reporting the involvement of the parieto-occipital regions in whole-word representations (Graves et al., 2008), in reading morphologically complex words (Zweig and Pylkkänen, 2009) and during the comprehension of complex linguistic units (Jobard et al., 2007).

In the active tDCS condition, the current slowly increased during the first 30 s to 1 mA (ramp-up) and, at the end of the stimulation, the current slowly decreased to 0 mA during the last 30 s (ramp-down). Between the ramp-up and ramp-down, a constant current was delivered for 20 min, with a density of 0.04 mA/cm^2.

In the sham tDCS condition, the same montage used in the active tDCS condition was applied, respectively left anodal PO7 and right cathodal PO8. The stimulation intensity was set at 1 mA, but the current was applied for 30 s and was ramped down without the participants' awareness. For more details, see Lazzaro et al. (2021b).

Statistical analyses

To evaluate a possible order effect of active tDCS and sham conditions, analyses of covariance (ANCOVAs) were run (see **Supplementary Table 2** for details).

The data were first examined for assumptions of normality and homogeneity of variance.

According to the Shapiro–Wilk test, the distributions of reading speed raw scores (TEXT, HF, LF, and NW) were found to be non-Gaussian. The raw scores were log-transformed and normally distributed. Therefore, to evaluate the effect of treatments on reading speed, repeated measures analysis of covariance (RM ANCOVAs) were run on each reading measure with Condition (Active vs. Sham) and Time (T0, T1, T2, and T3) as within-subject factors, and Age as covariate. *Post hoc* analyses were performed using Fisher's LSD test. Partial eta squares (η_p^2) were used as measures of effect sizes. Bonferroni's correction [p 0.05/4 RM ANCOVAs = 0.0125] was applied for multiple comparisons.

Non-parametric analyses were applied to analyze reading accuracy raw scores (TEXT, HF, LF, and NW) because the measures were non-Gaussian even after log-transformation. Therefore, generalized estimating equations (GEE) – an extension of generalized linear models – were run. The reading accuracy of TEXT, HF, LF, and NW was analyzed by fitting repeated measures regressions, using Condition (Active vs. Sham) and Time (T0, T1, T2, and T3) as predictors, and Age as covariate.

Significant main effects or interactions were performed by GEE-based pairwise comparisons with the least-significant difference test correction for multiple comparisons (for the approach see Santarnecchi et al., 2013; Borghini et al., 2018). Bonferroni's correction [p 0.05/4 GEE-based pairwise = 0.0125] was applied for multiple comparisons. Non-parametric analyses were also applied to analyze neuropsychological measures (see **Supplementary Tables 3**, **4** for details).

For post hoc comparisons, a p-value ≤ 0.05 was considered statistically significant.

For each reading speed measure, the difference between the score at baseline (T0) and the score at each time point (T1, T2, and T3), divided by the score at T0 and multiplied by 100 was considered [i.e., Changes at T1 (Δ_{T1}): (T0–T1)/T0 $\times$ 100; Changes at T2 (Δ_{T2}): (T0–T2)/T0 $\times$ 100; Changes at T3 (Δ_{T3}): (T0–T3)/T0 $\times$ 100]. Whereas, for each reading accuracy measure, the difference between the score at each time point (T1, T2, and T3) and the score at baseline (T0), divided by the score at T0 and multiplied by 100 was considered [i.e., Changes at T1 (Δ_{T1}): (T1–T0)/T0 $\times$ 100; Changes at T2 (Δ_{T2}): (T2–T0)/T0 $\times$ 100; Changes at T3 (Δ_{T3}): (T3–T0)/T0 $\times$ 100].

To evaluate a potential relation between age and changes between baseline and post-treatments (Δ_{T1}, Δ_{T2}, and Δ_{T3}) in reading tasks (speed and/or accuracy), Spearman's rank correlations (*rho*) were performed separately for active and sham tDCS condition on significant results identified by RM ANCOVAs and by GEE. Bonferroni's correction was applied for multiple comparisons.

To evaluate a potential relation between neuropsychological measures at T0 (visual-spatial and verbal working-memory$_{Eff}$, Phonemes$_{Acc}$, Phonemes$_{Time}$, RAN$_{Letters}$, and RAN$_{Colors}$) and changes between baseline and post-treatments (Δ_{T1}, Δ_{T2}, and Δ_{T3}) in reading tasks (speed and/or accuracy), partial Spearman's rank correlations (rho) were performed separately for active and sham tDCS condition, controlling for age, on significant results identified by RM ANCOVAs and by GEE. Bonferroni's Correction was applied for multiple comparisons.

Results

Effects of treatment on reading speed

Table 2 depicts means (SDs) of the main effect of Condition, Time, and the interaction Condition × Time for TEXT, HF, LF, and NW measures for both speed and accuracy.

Covarying for age, RM ANCOVA results on NW reading speed showed that the Condition effect [$F(1,22) = 1.01$, $p = 0.33$, $\eta_p^2 = 0.04$] and the Time effect [$F(3,66) = 1.17$, $p = 0.33$, $\eta_p^2 = 0.05$] were not significant, while the Condition × Time interaction was significant after Bonferroni's correction [$F(3,66) = 4.09$, $p = 0.01$, $\eta_p^2 = 0.16$]. *Post hoc* analyses demonstrated that following active tDCS, reading times decreased after the end of treatment (T0 vs. T1: $p = 0.012$), and 1 month after the end of the treatment (T0 vs. T3: $p = 0.002$) compared with baseline. However, following sham tDCS, no significant differences were observed immediately after (T0 vs. T1: $p = 0.48$), nor 1 week later the end of the treatment (T0 vs. T2: $p = 0.34$), nor 1 month later the end of the treatment (T0 vs. T3: $p = 0.21$) compared with baseline (see Table 2).

Covarying for age, no effects emerged for TEXT [Condition effect: $F(1,22) = 1.47$, $p = 0.24$, $\eta_p^2 = 0.06$; Time effect: $F(3,66) = 2.28$, $p = 0.09$, $\eta_p^2 = 0.09$; Condition × Time interaction: $F(3,66) = 0.43$, $p = 0.73$, $\eta_p^2 = 0.02$] nor for LF [Condition effect: $F(1,22) = 0.59$, $p = 0.45$, $\eta_p^2 = 0.03$; Time effect: $F(3,66) = 1.66$, $p = 0.18$, $\eta_p^2 = 0.07$; Condition × Time interaction: $F(3,66) = 0.98$, $p = 0.41$, $\eta_p^2 = 0.04$].

Similarly, Condition effect [$F(1,22) = 0.05$, $p = 0.83$, $\eta_p^2 = 0.04$] and Time effect [$F(3,66) = 1.05$, $p = 0.38$, $\eta_p^2 = 0.05$] were not significant in HF reading speed, while the Condition × Time interaction was found significant.

Similarly, the Condition effect [$F(1,22) = 0.05$, $p = 0.83$, $\eta_p^2 = 0.04$] and the Time effect [$(3,66) = 1.05$, $p = 0.38$, $\eta_p^2 = 0.05$] were not significant with respect to the reading speed of HF. In contrast, the Condition × Time interaction was found to be significant [$F(3,66) = 2.94$, $p = 0.04$, $\eta_p^2 = 0.12$]. *Post hoc* analysis showed no significant results when comparing the active and sham conditions at different time points [p always > 0.05].

Effects of treatment on reading accuracy

Covarying for age (see Table 2), GEE model results showed no significant effects for TEXT [Condition effect: Wald $\chi^2(1) = 0.02$, $p = 0.88$; Time effect: Wald $\chi^2(3) = 1.63$, $p = 0.65$; Condition × Time interaction: Wald $\chi^2(3) = 0.12$, $p = 0.98$], HF [Condition effect: Wald $\chi^2(1) = 0.02$, $p = 0.89$; Time effect: Wald $\chi^2(3) = 5.70$, $p = 0.13$; Condition × Time interaction: Wald $\chi^2(3) = 1.07$, $p = 0.79$], LF [Condition effect: Wald $\chi^2(1) = 0.92$, $p = 0.34$; Time effect: Wald $\chi^2(3) = 0.48$, $p = 0.92$; Condition × Time interaction: Wald $\chi^2(3) = 3.41$, $p = 0.33$], nor NW [Condition effect: Wald $\chi^2(1) = 2.62$, $p = 0.11$; Time effect: Wald $\chi^2(3) = 4.43$, $p = 0.22$; Condition × Time interaction: Wald $\chi^2(3) = 0.71$, $p = 0.87$].

Correlations between age and reading

In the active tDCS condition, significant and negative correlations were found between age and Δ_{T1} and Δ_{T3} NW reading speed (respectively, rho = −0.50, $p = 0.012$ and rho = −0.42, $p = 0.041$), whereby as age decreased, greater improvement in NW reading speed was observed. No correlation between age and Δ_{T2} NW reading speed emerged (rho = −0.38, $p = 0.07$). After Bonferroni's correction (p 0.05/3Δ = 0.016), a negative correlation between age and Δ_{T1} NW reading speed survived.

In the sham tDCS condition, no correlations between age and Δ_{T1}, Δ_{T2}, Δ_{T3} NW reading speed emerged (respectively, rho = 0.04, $p = 0.84$; rho = 0.23, $p = 0.29$; rho = 0.40, $p = 0.05$).

See Supplementary material for the correlations between age and non-significant reading measures identified by RM ANCOVAs and by GEE (Supplementary Table 5).

Correlations between neuropsychological measures and reading

In the active tDCS condition, significant negative correlations were found between verbal working-memory$_{Eff}$ at T0 and Δ_{T1}, Δ_{T2} and Δ_{T3} NW reading speed (respectively, $p < 0.005$, $p < 0.002$, and $p < 0.006$), so the lower the verbal working memory efficiency at T0 (more impaired), the greater the improvement.

TABLE 2 Means (SDs) of the main effect of condition, time and of the condition × time interaction for TEXT, HF, LF, and NW measures for both accuracy and speed.

Reading tasks		Condition		Time				Condition × time							
								Active tDCS				Sham tDCS			
		Active tDCS	Sham tDCS	T0	T1	T2	T3	T0	T1	T2	T3	T0	T1	T2	T3
TEXT	Accuracy[a]	93.65 (5.83)	93.17 (6.62)	93.19 (6.30)	93.31 (5.96)	93.58 (6.36)	93.57 (6.45)	93.84 (6.80)	93.70 (5.03)	93.55 (6.25)	94.03 (5.44)	93.04 (5.91)	92.92 (6.85)	93.62 (6.61)	93.11 (7.42)
	Speed[b]	55.99 (29.83)	55.43 (30.03)	59.73 (31.84)	55.25 (30.93)	55.33 (29.11)	52.52 (27.86)	59.38 (31.71)	56.95 (31.23)	54.44 (28.01)	53.20 (29.76)	60.08 (32.65)	53.55 (31.21)	56.22 (30.73)	51.85 (26.46)
HF	Accuracy[a]	92.76 (9.19)	93.03 (8.61)	93.39 (8.62)	92.19 (10.56)	92.66 (9.46)	93.35 (6.63)	92.81 (10.46)	92.19 (9.73)	92.71 (10.05)	93.33 (6.54)	93.96 (6.47)	92.19 (11.55)	92.61 (9.04)	93.37 (6.86)
	Speed[c]	24.49 (14.42)	25.35 (15.01)	25.65 (15.27)	24.22 (13.88)	24.91 (15.30)	24.92 (14.67)	25.79 (15.29)	24.25 (13.66)	23.27 (14.21)	24.67 (15.27)	25.50 (15.58)	24.18 (14.38)	26.55 (16.46)	25.17 (14.37)
LF	Accuracy[a]	87.03 (13.00)	86.19 (14.25)	86.88 (11.48)	85.36 (14.92)	86.65 (14.82)	87.56 (13.28)	87.08 (10.60)	87.60 (11.74)	86.15 (15.16)	87.29 (14.74)	86.67 (12.53)	83.13 (17.51)	87.16 (14.79)	87.83 (11.96)
	Speed[c]	34.78 (18.75)	34.81 (19.73)	36.15 (20.30)	33.55 (18.61)	34.71 (19.54)	34.77 (18.81)	35.83 (19.76)	34.38 (18.22)	33.73 (18.45)	35.17 (19.67)	36.46 (21.25)	32.72 (19.25)	35.68 (20.93)	34.37 (18.31)
NW	Accuracy[a]	81.07 (16.65)	79.33 (19.30)	80.21 (17.16)	78.02 (19.05)	80.51 (18.81)	82.06 (17.24)	81.98 (16.58)	80.52 (16.00)	78.85 (18.98)	82.92 (15.62)	78.44 (17.89)	75.52 (21.73)	82.16 (18.89)	81.20 (19.02)
	Speed[c]	38.61 (15.28)	37.67 (14.77)	40.13 (16.20)	37.52 (14.21)	37.81 (14.58)	37.11 (15.22)	41.96 (17.87)	36.96* (12.64)	38.52 (15.20)	37.00* (15.41)	38.29 (14.48)	38.08 (15.87)	37.09 (14.22)	37.23 (15.35)

[a]Percentage of accuracy, calculated as accuracy/total number of words × 100. [b]Seconds/syllables × 100. [c]Seconds. HF, high-frequency words; LF, low-frequency words; NW, non-words; T0, baseline; T1, immediately post-treatment; T2, 1 week later; T3, 1 month later.
*Significant difference from T0, $p < 0.01$.

Moreover, significant positive correlations were found between $Phonemes_{Time}$ at T0 and Δ_{T1} and Δ_{T3} NW reading speed (respectively, $p < 0.029$ and $p < 0.043$), so the longer the time taken to merge the non-word at T0 (more impaired), the greater the improvement.

After Bonferroni's correction [p 0.05/3Δ $\times$ 6 measures = 0.0028], a negative correlation between verbal working-$memory_{Eff}$ at T0 and Δ_{T2} NW reading speed survived.

No further correlations emerged [p always > 0.05]. The other correlations between neuropsychological measures at T0 and Δ_{T1}, Δ_{T2}, Δ_{T3} NW reading speed in the active tDCS and sham tDCS condition are shown in **Table 3**.

See **Supplementary material** for the correlations between neuropsychological measures at T0 and non-significant reading measures identified by RM ANCOVAs and by GEE (**Supplementary Tables 6**, **7**).

Moreover, the relation between neuropsychological measures at T0 and NW reading speed at T0 has been explored (see **Supplementary Table 8**).

Discussion

To date, this is the first RCT study of 24 children and adolescents with DD to test the effectiveness of multiple consecutive daily sessions of tDCS through a crossover design.

We found that only five consecutive daily sessions of active left anodal/right cathodal tDCS over parieto-occipital regions significantly improved NW reading speed at post-treatment follow-ups compared with baseline. Our previous studies (Costanzo et al., 2016b, 2019) demonstrated that three sessions per week for 6 weeks (for a total of 18 sessions) of left anodal/right cathodal tDCS combined with reading training improved NW reading speed by an average of 15 s compared to baseline. Compared with these previous studies (Costanzo et al., 2016b, 2019), in the present study we found that the average improvement in speed in NW reading compared with baseline is 5 s, which is 3 times lower than that previously obtained after 18 sessions of tDCS combined with reading training. As discussed (Lazzaro et al., 2021b), possible explanations for the less robust effect of non-invasive brain stimulation in the present study could be related to the reduced number of tDCS sessions compared with the previous studies and the absence of reading training associated with tDCS. The effect found is consistent with studies showing that the results of non-invasive brain stimulation depend not only on current intensity but also on the duration of stimulation (Nitsche and Paulus, 2000).

In addition, the present study extended to 1 month the positive effect of active tDCS on NW reading speed previously found at 1 week after the end of treatment (Lazzaro et al., 2021b). It should be noted that 5 sessions were sufficient to maintain up to 1 month the effect found immediately at the end of the treatment, similar to what happened after 18 sessions of tDCS combined with cognitive training (Costanzo et al., 2016b, 2019).

By analyzing the two results together, we provided evidence that a treatment of a few sessions, without training, has a stable effect, which is maintained at 1 month, although weaker.

Regarding correlations, we found that as age decreased, the NW reading speed improved immediately after and 1 month after the end of the active tDCS condition. A large body of literature has shown that age – and the related thickness of the skull, maturation of brain regions, hormonal disturbances, and neurotransmitter activity – is a determinant of neuroplasticity (Vergallito et al., 2022). Neural plasticity is one of the main mechanisms involved in the stimulation effects, which depends on the personal propensity to induce plasticity (Bandeira et al., 2021). This propensity tends to be more significant at a young age and decreases throughout life with a lower tendency to occur in later life (Ridding and Ziemann, 2010; Freitas et al., 2013).

However, the present results differ from those of our previous study (Lazzaro et al., 2021c), in which we documented that older children in the active tDCS group improved word reading speed more than younger children in each follow-up. One possible explanation for this discrepancy can be found in the methodological differences between the studies. In fact, in the previous study (Lazzaro et al., 2021c), tDCS was administered together with reading training, so it can be hypothesized that older children were able to use more complex cognitive strategies, taking more advantage of the cognitive training associated with tDCS. Therefore, the effects of tDCS would have been eventually triggered and critically reinforced by ongoing cognitive strategies, probably more exploited by older children, accelerating progress during training.

Considering the correlations between neuropsychological measures at baseline and reading improvement, we found that when verbal working memory and phoneme blending were worse at baseline, NW reading speed improved more immediately after the active tDCS condition and at long-term. Together with the verbal working memory, phonological skills are one of the main predictors of reading development (Melby-Lervåg et al., 2012), especially non-word reading, for which grapheme-to-phoneme mapping is required. It can be hypothesized that the children who have greater difficulty in phonological measures, such as phoneme blending and verbal working memory, are also the one who have greater difficulty in NW reading at baseline. Therefore, those who had greater impairment in phonological skills and verbal working memory, which mirror reading skills, were more likely to have increased reading abilities after active tDCS than those who had a reading deficit but lesser severity.

TABLE 3 Correlations between neuropsychological measures at T0 and Δ_{T1}, Δ_{T2}, Δ_{T3} NW reading speed, controlling for age, in the active and sham tDCS conditions.

Neuropsychological measures at T0

NW speed		Working-memory$_{Eff}$		Phoneme blending		RAN	
		Visual-spatial (*Rho*)	Verbal (*Rho*)	Accuracy[a] (*Rho*)	Time[b] (*Rho*)	Letters[b] (*Rho*)	Colors[b] (*Rho*)
Δ_{T1}	Active tDCS	−0.22	−0.57**	−0.10	0.46*	0.10	−0.08
Δ_{T2}		−0.02	−0.62**^	−0.18	0.38	−0.05	−0.02
Δ_{T3}		−0.15	−0.55**	−0.15	0.43*	−0.13	−0.40
Δ_{T1}	Sham tDCS	0.19	−0.13	0.03	0.21	0.08	0.07
Δ_{T2}		−0.06	−0.24	−0.17	0.14	0.16	0.33
Δ_{T3}		0.36	0.20	−0.07	−0.02	−0.20	−0.21

[a]Number of phonemes. [b]Seconds. RAN, rapid automatized naming; NW, non-words; Δ_{T1}, changes at T1; Δ_{T2}, changes at T2; Δ_{T3}, changes at T3.
*$p \leq 0.05$; **$p \leq 0.01$; ^significant after Bonferroni's correction ($p \leq 0.0028$).

Taking together our results on correlations, we showed that the improvement in NW reading speed after active tDCS, which is the most consistent finding in our studies (Costanzo et al., 2016b, 2019; Lazzaro et al., 2021b), is associated with age, level of phonological skills, and verbal working memory achieved by participants at baseline.

Our study had some limitations.

The first limitation was the absence of a direct comparison between the current tDCS protocol and longer stimulation protocols in which multiple tDCS sessions are offered without reading training.

Similarly, a direct comparison of tDCS protocols with and without reading training would be needed to clarify the magnitude of the effect of tDCS when the neural population is preactivated by training at the time of its application compared with when brain stimulation is administered alone. Further, although there is agreement on the usefulness of increasing cortical excitability in left hemispheric regions involved in reading processes, further studies investigating the effects of stimulation in contralateral areas are needed.

Another limitation was the lack of non-verbal neuropsychological measures (such as attention and visual-spatial perception), as we mainly focused on verbal neuropsychological measures and their relation to reading to understand how reading can be modulated by tDCS.

In addition, in the context of the promises of tDCS interventions, the role of participants' self-agency should be considered in further studies. Indeed, proposing stand-alone tDCS-based treatments could have implications for beliefs and self-representations. If improvement is achieved through external stimulation, without the active involvement of participant playing a passive role, there is a risk that the participant will lose self-confidence as an agent who is responsible for the results achieved and able to manage cognitive resources. The present study, despite the considerations just made, aimed to precisely measure the specific influence of tDCS in improving reading skills in the absence of additional stimuli, thus not involving paired task. Future studies, however, should consider the role of participants in the tDCS interventions.

Moreover, because DD can evolve over time with different clinical manifestations, a limitation of this study may be the consideration of a wide age range by including children and adolescents. However, this limitation was partially overcome by considering participants' age as a confounding variable and including it as a covariate in all models.

Conclusion

In conclusion, the current crossover RCT contributed to (i) enforce previous effects of tDCS, including long-term effects, on NW reading speed; (ii) understand the effect of age on tDCS delivered without concomitant training; and (iii) consider neuropsychological processes at baseline as one of the relevant factors contributing to reading improvement after tDCS.

Although we are far from identifying the most effective tDCS-based protocol, our results may have high translational power if we consider that our short and intensive intervention turns out to have beneficial consequences even in the long-term.

In fact, an elective first-choice treatment for children and adolescents with DD has not yet been demonstrated. Programs usually delivered involve at least 6 months of weekly meetings, with a high dropout rate, unsustainable costs to parents or the health care system, and long-term effects that are not well verified.

With these premises, sustainable and cost-effective interventions for DD are urgently needed. Considering our results, tDCS may indeed represent a neurobiologically based, low-cost, and easy-to-implement therapeutic option with long-term effects for children and adolescents with DD.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Bambino Gesù Children's Hospital, IRCCS. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

FC, SV, and DM designed the study. FC, GL, CV, and SR collected the data. AB, GL, and DM worked on data analyses. AB and GL drafted the manuscript, with support of DM and SV. DM and SV supervised the study. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.986242/full#supplementary-material

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Early oral language precursors of different types of reading difficulties in a consistent orthography

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The present longitudinal study examined whether early oral language skills of Greek-speaking children assessed in grade 1 can predict the type of reading difficulties (RD) in grade 2. Sixty-six typically developing (TD) children and eighty-seven children with RD were assessed on phonological awareness (PA), morphological awareness (MA), rapid automatized naming (RAN), and vocabulary in the mid of grade 1. Children were classified in the two groups based on whether they scored consistently low (below the 25th percentile) or typically (above the 25th percentile) on standardized measures of text-reading fluency and reading comprehension at the end of grade 1 and the beginning of grade 2. Next, children with RD were assigned to two subgroups: the first group included children (N = 28) with predominantly reading fluency difficulties (RFD) and the second group included children (N = 59) with single reading comprehension difficulties (RCD). A series of binomial logistic regressions showed that children's classification in an RD group than a TD group was predicted by PA, RAN, and vocabulary achievement. Subsequent multinomial logistic regressions indicated that vocabulary, PA, and MA predicted children's classification in the RCD subgroup more than in the TD group. Furthermore, lower PA levels and higher RAN score predicted the classification of children in the RFD group than in the RCD or the TD group. These findings highlight the contribution of early oral language assessment to the identification of children with RD and specific types of RD. Theoretical implications for the role of oral language in reading will be discussed as well as practical implications for implementing customized interventions to match children's educational needs on specific oral language deficits.

KEYWORDS

reading difficulties (RD), phonological awareness (PA), morphological awareness (MA), rapid automatized naming (RAN), vocabulary

Introduction

A substantial body of educational research has systematically shown that oral language skills are a cornerstone of reading acquisition (e.g., Chang et al., 2020; Lyster et al., 2021) and that when they are deficient, reading difficulties (RD) might emerge (e.g., Snowling and Melby-Lervåg, 2016; Snowling and Hulme, 2021). Several studies, which have thoroughly examined RD, support the existence of RD subtypes, which are associated with different underlying deficits in oral language skills (Stothard and Hulme, 1995; Leach et al., 2003; Catts et al., 2006, 2012; Torppa et al., 2007; Koriakin and Kaufman, 2017).

Children's RD subtypes usually refer to difficulties either only on word-level decoding or only on reading comprehension or both (e.g., Leach et al., 2003; Torppa et al., 2007; Catts et al., 2012). In consistent orthographies, like Greek, the majority of children, even those with RD, develop adequate reading accuracy early. As a result, reading fluency is the most sensitive assessment criterion to identify children with poor word-level reading ability (Porpodas, 1999; Seymour et al., 2003; Ziegler et al., 2010). Accordingly, children with RD can be classified into three subtypes: single reading fluency difficulties (RFD), single reading comprehension difficulties (RCD), and mixed difficulties (Koriakin and Kaufman, 2017; Torppa et al., 2020).

There is a general consensus that RD in word-level decoding is mainly associated with deficits in phonological processing skills, such as phonological awareness (PA) and rapid automatized naming (RAN) (e.g., Stothard and Hulme, 1995; Catts et al., 2006; Torppa et al., 2007), while difficulties in reading comprehension are the outcome of inadequately developed language comprehension skills, such as vocabulary and morphological awareness (MA) (e.g., Catts et al., 2006; Nation et al., 2010; Tong et al., 2011, 2014; Spencer et al., 2019).

Less is known about precursors of early RCD (Justice et al., 2013), despite the significant number of studies examining the oral language precursors of word reading/decoding difficulties early on reading development. The early detection of children's RCD is challenging, because their word reading skills, which are an integral part of understanding what they read, are not adequately developed (Koriakin and Kaufman, 2017).

Apart from RCD, examining RD of children at the word level is of equal importance, especially in consistent orthographies. As early as the end of the first grade, assessment of decoding capacity relies heavily upon measures of reading fluency (Seymour et al., 2003; Ziegler and Goswami, 2005). The ability of children with RD to read accurately might conceal the existence of RFD and subsequently delay an early detection. In view of the increased cognitive requirements of reading comprehension after the third grade, competition between processes required for fluent reading and understanding text may give rise to RCD, as well (Chall and Jacobs, 2003; Pikulski and Chard, 2005; Kang and Shin, 2019). However, there is a relative dearth of studies in consistent orthographies that examine the prognostic role of oral language skills for early RFD and their dissociation from RCD (see Torppa et al., 2007 for an exception).

Previous research has highlighted the relative importance of specific oral language skills on later reading failure indexed by various reading outcomes (Hulme and Snowling, 2014), and documented the multidimensionality of oral language skills in the first elementary grades (Mouzaki et al., 2020). However, the predictive value of a wider repertoire of oral language skills for specific RD subtypes remains unclear. Early identification of language precursors of RD and corresponding RD subtypes could facilitate the timely understanding of the structure of learning difficulties in the first stages of learning to read and provide useful insights toward effective intervention. Thus, the aim of the present study was to examine whether oral language skills in grade 1 (i.e., PA, RAN, MA, and vocabulary) could predict children's RD at the beginning of grade 2, as well as, their specific type of RD in the consistent Greek orthography.

The role of oral language skills in early reading development

Research evidence from various orthographies has repeatedly underlined the prominent role of phonological processing skills in early reading development (e.g., Papadopoulos et al., 2009; Caravolas et al., 2012; Melby-Lervåg et al., 2012; Landerl et al., 2019). In particular, PA which is defined as the ability of conscious identification and manipulation of phonological units of spoken words (Gombert, 1992), is a prerequisite for the understanding of the alphabetic principle (Byrne, 1996), which in turn is considered as a milestone for the development of children's early reading skills (Stanovich, 1986). In the early phases of reading acquisition, PA is strongly associated with the development of word reading skills (Muter et al., 2004; Lervåg et al., 2009; Vaessen and Blomert, 2013) as children rely to a greater extent on phonological decoding to read words. As a result, their ability to identify the relations between graphemes and phonemes, and to segment words into their phonemic parts is of crucial importance (Ehri, 2005). However, PA seems to be a stronger predictor of reading accuracy than of reading fluency in consistent orthographies (e.g., Georgiou et al., 2008; Landerl and Wimmer, 2008; Boets et al., 2010; Fricke et al., 2016; Landerl et al., 2019), which is more reliably predicted by RAN (Boets et al., 2010; Landerl et al., 2019).

RAN refers to children's ability to perform rapid and accurate naming of a series of familiar visual stimuli (e.g., objects, colors, digits, or letters) (Wolf and Bowers, 1999) relying on a wide range of cognitive processes which are equally important to reading development across different orthographies (see Georgiou et al., 2015; Landerl et al., 2019). Two main theories have been proposed to explain the close RAN-reading relationship. The first one suggests that RAN is related to reading because it is an index of how quickly children can gain access to and retrieve the phonological information of words which are stored in their mental lexicon (Wagner and Torgesen, 1987; Torgesen et al., 1997). The second theory attributes the contribution of RAN to reading development to its association with orthographic processing, claiming that RAN reflects children's sensitivity to frequently encountered orthographic patterns (Bowers and Wolf, 1993; Bowers et al., 1999). Accumulated research evidence has repeatedly shown that RAN is an important predictor of children's early word reading fluency (e.g., Georgiou et al., 2008; Papadopoulos et al., 2009, 2016; Furnes and Samuelsson, 2011; Araújo et al., 2015; Landerl et al., 2019; Huschka et al., 2021).

Apart from phonological processing skills, research has revealed additional oral language skills that may contribute to the development of early reading skills. For instance, MA, which reflects children's ability to intentionally identify and manipulate the smallest units of meaning (morphemes) (Carlisle, 1995; Kuo and Anderson, 2006), seems to uniquely contribute to children's reading development (e.g., Casalis and Louis-Alexandre, 2000; Desrochers et al., 2017; Diamanti et al., 2017; Deacon et al., 2018; James et al., 2020), by helping to integrate semantic, phonological, and orthographic features of words. In this capacity, MA can facilitate the formation of high-quality lexical representations of words (Kirby and Bowers, 2017). A number of studies have highlighted MA's prominent role to predict reading comprehension even in the early phases of reading development (e.g., Carlisle, 1995; Casalis and Louis-Alexandre, 2000; Müller and Brady, 2001; Diamanti et al., 2017; Manolitsis et al., 2017, 2019).

Finally, vocabulary has been also associated with early reading development and particularly has been observed repeatedly as an important predictor of reading comprehension (Muter et al., 2004; Protopapas et al., 2007; Ricketts et al., 2007; Verhoeven and van Leeuwe, 2008; Kim and Pallante, 2012; Diamanti et al., 2017). The importance of vocabulary for reading comprehension is supported by its function in semantic processing, contributing to the construction of high-quality lexical representations, which are in turn crucial for reading comprehension (Perfetti, 2007). On the other hand, the influence of vocabulary on the development of children's word reading skills, over and above the effects of other known language predictors (e.g., PA), is not strongly supported empirically (e.g., Kim and Pallante, 2012; Diamanti et al., 2017), and it seems to be rather restricted to irregular word reading (Ouellette and Beers, 2010).

Reading difficulties

A considerable body of educational research has focused on the examination and early identification of RD (e.g., Torppa et al., 2007; Hulme et al., 2015; Catts et al., 2016). Severe RD, commonly referred to as developmental dyslexia, generally refer to persistent problems with word decoding, despite adequate intelligence and the absence of negative effects from intrinsic or external factors, such sensory problems and socioeconomic adversities (Vellutino et al., 2004; Hulme and Snowling, 2014). The manifestation of children's RD at the word level may significantly depend on the consistency of the orthography that is studied (Ziegler and Goswami, 2005; Niolaki et al., 2014).

In more consistent orthographies children with RD are mainly distinguished by slow and laborious word decoding, as the high levels of regularity on the grapheme-phoneme correspondences enable them to reach adequate reading accuracy levels already from the end of the first grade (e.g., Wimmer, 1993; de Jong and van der Leij, 2003; Seymour et al., 2003; Patel et al., 2004; Ziegler and Goswami, 2005; Zoccolotti et al., 2005; Serrano and Defior, 2008). On the contrary, in less consistent orthographies reading accuracy difficulties may be more protracted and usually accompanied by RFD (Snowling, 2000; Seymour et al., 2003; Ziegler and Goswami, 2005; Share, 2008). However, during the last decades, an increasing number of studies have shown that young readers might present difficulties in reading comprehension despite intact reading accuracy and fluency levels (see Hulme and Snowling, 2014; Nation, 2019). This dissociation has gained particular research attention, and as a result, the research on the field of RD has now acknowledged the existence of two distinct groups of children with RD, namely, poor decoders and poor comprehenders (Elwér et al., 2013).

Furthermore, based on the Simple View of Reading which suggests that reading comprehension is the outcome of two factors–word decoding and oral comprehension skills (Gough and Tunmer, 1986), it has been argued that early identification of RCD could be facilitated by examining in detail the parameters that are related to these two influential factors (Catts et al., 2016). In line with that, it has been systematically shown across different alphabetic languages that the primary causes of RD involve language deficits, as they can negatively affect the development of both word decoding and reading comprehension skills (e.g., Catts et al., 2006; Landerl et al., 2013; Hulme and Snowling, 2014; Hulme et al., 2015; Landi and Ryherd, 2017). Empirical support for the close association between language problems and the manifestation of RD mainly derives from studies assessing differences between children with RD and typically developing (TD) readers on several facets of oral language (e.g., Casalis et al., 2004; Furnes and Samuelsson, 2010; Nation et al., 2010; Torppa et al., 2010; Tong et al., 2011; Berthiaume and Daigle, 2014).

Early oral language skills as precursors of reading difficulties

It is commonly accepted that phonological deficits are robust predictors of severe and persistent difficulties in word reading and are considered as the primary cause of dyslexia (Vellutino et al., 2004; Boets et al., 2010). It has been suggested that the phonological deficits of children with RD indicate that the phonological properties of words are not adequately depicted in children's lexical representations in their mental lexicon (Snowling, 2000). Deficits in PA and RAN have been identified as the strongest phonological predictors of RD (Landerl et al., 2013) reflecting children's weakness to analyze and process the phonological representations of words (PA deficit), as well as to quickly retrieve them from their long-term memory (Schmidt et al., 2020). The predictive value of early PA and RAN skills to later RD has been revealed by several retrospective longitudinal studies (e.g., Puolakanaho et al., 2007; Boets et al., 2010; Furnes and Samuelsson, 2010; Torppa et al., 2010; see also Snowling and Melby-Lervåg, 2016 for a meta-analytic review).

For instance, Puolakanaho et al. (2007) examined predictors of RD in Finnish-speaking children from the age of 3.5 years onward using logistic regression analyses, and identified PA and RAN along with family risk and letter knowledge as significant predictors of reading accuracy and/or fluency difficulties at the end of grade 2. Additionally, in a cross-linguistic study, Furnes and Samuelsson (2010) found through separate logistic regression analyses that preschool PA and RAN were significant predictors of reading accuracy/fluency difficulties at the end of grade 1 in both USA/Australian and Scandinavian children. Furthermore, early RAN was also a reliable predictor of RD at the end of grade 2 in both samples, whereas early PA was significantly associated with RD only in the English-speaking sample, possibly, because the effect of PA weakens on the prediction of RD in more consistent orthographies beyond the first elementary grades.

According to the double-deficit hypothesis, children with RD may present either single PA and RAN deficits or joint deficits in both phonological processing skills which are likely to cause more severe RD (Wolf and Bowers, 1999). However, research findings from studies in consistent orthographies question this notion by showing that a single PA-deficit is not strongly related to RD over time, as children manage to improve their reading performance (see Papadopoulos et al., 2009; Furnes et al., 2019).

During the school years, children with RD might present deficits in additional oral language domains beyond phonological processing skills (Nation and Snowling, 2004; Snowling et al., 2020). For example, MA deficits have also been identified as a risk factor for the manifestation of word decoding difficulties (Law and Ghesquière, 2017). Empirical evidence from various alphabetic orthographies has shown that dyslexic children tend to underperform chronological age-matched typical readers on various MA tasks (e.g., Joanisse et al., 2000; Casalis et al., 2004; Berthiaume and Daigle, 2014; Duranovic et al., 2014; Vender et al., 2017; Rothou and Padeliadu, 2019), although this finding was not fully confirmed by studies comparing dyslexic children with younger reading-level-matched controls (e.g., Casalis et al., 2004; Egan and Tainturier, 2011; Robertson et al., 2013). Moreover, in a longitudinal retrospective study conducted by Torppa et al. (2010) results revealed that MA of 3.5-year-old Finnish-speaking children discriminated between those defined as RD and typical readers at the end of grade 2, and directly predicted later reading accuracy and fluency. However, in the cross-sectional study of Rothou and Padeliadu (2019) with Greek-speaking 3rd graders, PA was the only significant predictor of reading status although children with dyslexia manifested MA deficits compared to typical readers.

Vocabulary has also been recognized as a potential predictive factor of dyslexia (van Viersen et al., 2017). Particularly, RD were also predicted by low vocabulary knowledge (Snowling et al., 2003) irrespective of familiar risk (FR) status (e.g., Duff et al., 2015). In their study with Dutch-speaking children van Viersen et al. (2017) found that FR-dyslexic children, identified at the end of grade 2, had lower receptive and expressive vocabulary scores than FR-non-dyslexics and typical controls from 23 months onward and from 17 months onward, respectively. The same pattern of findings emerged from the study of Torppa et al. (2010) with Finnish-speaking children, as FR-dyslexic children were distinguished from FR-non-dyslexic and control children based on vocabulary production. Therefore, it could be argued that vocabulary weaknesses can be present before reading development in poor readers, which suggests that difficulties manifested later in development might not be the direct outcome of limited reading experiences.

There is also evidence from studies mostly conducted in English demonstrating the decisive role of MA in the appearance of difficulties in reading comprehension (e.g., Nation et al., 2005; Tong et al., 2011, 2014; Adlof and Catts, 2015). Specifically, it has been shown that poor comprehenders have lower performance than age-matched good comprehenders in specific inflectional and/or derivational MA tasks (e.g., Nation et al., 2005; Tong et al., 2014; Adlof and Catts, 2015; MacKay et al., 2017). On the other hand, a recent study by Rothou (2019) with Greek-speaking 3rd graders showed that although poor comprehenders were outperformed by good comprehenders on specific inflectional MA skills, group differences did not persist after controlling for the effects of receptive vocabulary. Thus, the complexity of the orthographic system and morphology in different alphabetic languages may affect the role of MA. To our knowledge, there is no framework for the predictive value of early MA skills in discriminating poor comprehenders from average comprehenders.

Finally, several longitudinal studies have shown vocabulary deficits in poor comprehenders who were mainly identified in mid-childhood (e.g., Nation and Snowling, 1998; Catts et al., 2006; Nation et al., 2010). For instance, in a retrospective study Nation et al. (2010) found that poor comprehenders, identified at the age of 8, were outperformed by TD children of the same age on vocabulary assessed at the age of 6 years. Of particular relevance to the predictive power of vocabulary on subsequent reading comprehension status (i.e., division of children into those with good or poor reading comprehension) are the findings of Catts et al. (2016): they found that receptive vocabulary in kindergarten uniquely predicted RCD at the end of grade 3.

Overall, as shown by the above findings, there is a relative dearth of longitudinal studies that focus on the joint examination of critical oral language skills (PA, RAN, MA, and vocabulary) in predicting not only RD but also the specific type of RD. Specifically, to the best of our knowledge, it has not been adequately assessed across the early school years whether the above language skills differ regarding their importance in predicting difficulties in reading fluency and reading comprehension. The joint examination toward this direction of these skills in the context of Greek language and orthography might facilitate early identification and intervention, while at the same time, it is of particular educational interest for two reasons. First, Greek orthography is distinguished by regular and relatively highly predictable grapheme-phoneme correspondences (the consistency in terms of reading has been calculated to be around 95%) (Protopapas and Vlahou, 2009). Therefore, the primary constraint for children with RD is expected to be in reading fluency (e.g., Papadopoulos et al., 2009; Torppa et al., 2013). Second, Greek language is morphologically rich (Ralli, 2005), as all morphological processes (inflection, derivation, and compounding) are characterized by very high productivity (Ralli, 2003). Thus, it is quite intriguing to assess whether MA has a pivotal role in the early identification of children's RD.

The present study

The aim of the current longitudinal study was to examine in a sample of Greek-speaking children whether early oral language skills (PA, RAN, MA, and vocabulary) assessed in grade 1 can predict RD, as well as the specific type of children's RD, in grade 2. The following research questions and respective hypotheses were addressed by our study.

Do oral language skills in grade 1 predict children's reading difficulties in grade 2?

Based on accumulated research documenting the critical role of oral language skills on reading development (e.g., Chang et al., 2020; Lyster et al., 2021) and that oral language deficits are the primary cause of RD (e.g., Hulme and Snowling, 2014; Snowling and Melby-Lervåg, 2016; Snowling and Hulme, 2021), we hypothesized that poor oral language skills in grade 1 will significantly predict the classification of children with RD in grade 2 (H1). Particularly, it was expected that low levels of PA and RAN (e.g., Puolakanaho et al., 2007; Furnes and Samuelsson, 2010; Torppa et al., 2010), as well as of MA (e.g., Casalis et al., 2004; Torppa et al., 2010) and vocabulary (e.g., Catts et al., 2016; van Viersen et al., 2017) will be significant predictors of difficulties in learning to read.

Do oral language skills in grade 1 predict the type of children's reading difficulties in grade 2?

Given that poor PA and RAN skills are considered as the distinctive characteristic of severe and persistent difficulties in reading fluency (Vellutino et al., 2004; Landerl et al., 2013) and that they can also predict children's word RD (e.g., Stothard and Hulme, 1995; Catts et al., 2006; Puolakanaho et al., 2007; Furnes and Samuelsson, 2010; Torppa et al., 2010), we hypothesized that low PA and high RAN scores in grade 1 will significantly predict children's RFD in grade 2 (H2). Additionally, in light of evidence showing that RCD are related to broader language deficits focused on reading features that are associated with meaning and in particular lexical-semantic knowledge (e.g., Nation et al., 2005, 2010; Catts et al., 2006; Tong et al., 2011, 2014; Spencer et al., 2019), we hypothesized that low levels of MA and vocabulary in grade 1 will significantly predict children's RCD in grade 2 (H3).

Materials and methods

Participants

The sample of the present study was part of a larger longitudinal study which followed approximately 260 first-grade children from 23 public mainstream elementary schools in the city of Heraklion, Greece, through grade 2. Participants were selected after asking classroom teachers to nominate from the pool of children with written parental consent those they considered as most likely to display literacy difficulties in the long term, and were native speakers of Greek without any formal diagnosis of intellectual, neurodevelopmental, or sensory disorder. For each nominated child, we selected at random one of his/her classmates with the same gender and with written parental consent. For the purpose of the present study, we selected 153 children (70 females; mean age = 79.13 months; SD = 3.45, at the first time of assessment) who met the selection criteria to be assigned to one of the three groups (i.e., RFD, RCD, and TD).

Measures

Non-verbal intelligence

Non-verbal intelligence was measured with the Greek standardization of Raven's Colored Progressive Matrices

(Raven, 1956; Sideridis et al., 2015). Cronbach's alpha in the standardization sample was 0.90 (Sideridis et al., 2015).

Phonological awareness

Two *Elision tasks*, one with real words and one with pseudowords, and one *Blending task* were administered to assess PA. Elision tasks (see Manolitsis et al., 2019) comprised four practice items and 24 experimental items, each. Items were equally distributed in four blocks of increasing difficulty. Children listened to one item at a time and were asked to extract a particular onset, rime, syllable, or phoneme from it and say what was left. Each task was discontinued after four errors in a given block. The *Blending task* consisted of four practice items and 28 experimental items in ascending order of difficulty and was adapted from Manolitsis and Georgiou (2015). A series of distinct sounds were orally presented and the children were asked to join them together to form a whole word. In the first three items, they had to combine two syllables, in the next six an onset and a rime, and in the remaining items a sequence of two to ten phonemes. The task was terminated after four consecutive errors. Cronbach's alphas for the PA tasks in our sample were 0.94, 0.94, and 0.90, respectively. A participant's score in each task was the percentage of correct responses.

Rapid automatized naming

A *Digit Naming* task was used for the assessment of RAN adopted from Landerl et al. (2019). Children were instructed to name from left to right as fast and precisely as they could the names of four repeated digits (5, 4, 7, and 2) which were semi-randomly arranged on two separate cards in four rows of six. To confirm children's familiarity with the names of the presented digits, a practice trial was administered. The corresponding names of the four digits in Greek are */ˈpende/* for five, */ˈtesera/* for four, */eˈfta/* for seven, and */ˈðio/* for two. A participant's score was the average time in milliseconds to name both cards.

Morphological awareness

Three oral tasks were used for the assessment of MA adopted from Manolitsis et al. (2017). The *Word Analogy* task consisted of 20 items which were evenly distributed to evaluate awareness of inflectional and derivational morphology. Children had to recognize the morphological relation in a presented pair of words and then to use that relation to complete a second pair of words [e.g., /aˈrxizo/ : /aˈrxizume/ :: /ðuˈlevo/: (/ðuˈlevume/)–"I start" : "We start" :: "I work": ("We work") and /ˈskavo/ : /ˈskapsimo/ :: /ˈtrexo/ : (/ˈtreksimo/)–"I dig": "the digging" :: "I run" :: ("the running")]. Prior to formal testing, two practice items for each morphology condition were presented. A discontinuation rule of six consecutive errors was applied. Cronbach's alpha reliability coefficient was 0.92. The *Manipulation of Derived Word Forms* task included a derivation and a decomposition subscale and was used to assess children's awareness of derivational morphology. Both subscales consisted of ten items. In the derivation subscale, children were instructed to produce the correct derived form of a presented base word by altering it with suffixation to complete a sentence [e.g., /ˈxroma/ : /i iˈkones ˈine (xromatiˈstes)/–"color" : the images are ("colored")]. In the decomposition subscale, children had to transform a derived word into a base word to complete a sentence [e.g., /isixazo/ : /eˈγo ˈime (ˈisixos)/–"I quieten" : "I am" ("quiet")]. For each subscale, two practice items preceded formal testing. The task was discontinued after six consecutive errors. Cronbach's alpha was 0.88. The third task was the *Compound Word Production* task which consisted of 15 items evaluating children's awareness of lexical compounding. Children were asked to orally produce the compound word, that could result from a presented pair of words, by properly modifying the target words into stems to pronounce correctly the resulting compound [e.g., "How could we say?" /ti ˈfluða tis paˈtatas/ "the peel of the potato" > (/pataˈtofluða/ "potato peel") or /ˈmia xriˈsi ˈmiγa/ "a golden fly" > (/xriˈsomiγa/ "may beetle")]. The task was discontinued after four consecutive errors. Cronbach's alpha was 0.89. A participant's score in each task was the percentage of correct responses.

Vocabulary

Expressive vocabulary was measured with the "*Vocabulary*" subscale of the Greek standardization of the Wechsler Intelligence Scale–Fifth Edition (WISC-V^{GR}; Stogiannidou et al., 2017), comprised of four picture items for oral naming (i.e., scored with 1 point for correct answers) followed by 25 words (i.e., scored with 2, 1, and 0 points) evaluating children's vocabulary depth knowledge, as children were asked to verbally define them. The task was discontinued after three consecutive 0-point responses. For each participant, the maximum score on this scale was 54. The average split-half reliability coefficient (odd vs. even items) across all age groups in the standardization sample was 0.83 (Stogiannidou et al., 2017).

Reading fluency

The *Text-Reading Fluency* subscale of a Greek standardized measure for the assessment of reading skills (Padeliadu et al., 2019) was used to measure reading fluency. A 247-word passage about an ancient Greek myth was presented to children and they were instructed to read it as fast and precisely as they could in 1 min. A participant's score was the total number of correctly read words within 1 min. Test–retest reliability in the standardization study was $r = 0.98$ (Padeliadu et al., 2019).

Reading comprehension

Two different Greek-standardized sentence-completion tests were used to assess reading comprehension in each grade. Sentence comprehension tasks were preferred instead of passage-based tasks as participants were in the early phases of learning to read. Both included sentences in ascending order of difficulty, with respect to word number and semantic information. In the first grade, the "Reading and Sentence Completion Test" (Porpodas, 2008) was administered, which consisted of 16 items and children had to complete a sentence with a missing word by selecting among three alternatives the one that matched. Testing was terminated after three consecutive errors. Similarly, in the second grade, the "Screening Test of Reading Ability" (Tafa, 1995) was used, which included 42 items, and children were instructed to choose among four options the one that correctly completed a sentence with a missing word within a time limit of 40 min. Cronbach's alphas were 0.94 and 0.87, respectively.

Procedure

Measures were administered by trained research assistants (postgraduate students of psychology or education) in a quiet room at children's schools at three measurement time points. In the first measurement (M1), non-verbal intelligence and oral language skills were evaluated during two 20-min individual sessions in the mid of grade 1 (January–March). In the second measurement (M2), reading fluency was assessed in a short individual session and reading comprehension in a group session of 10 children at the end of grade 1 (May–June). Finally, in the third measurement (M3) reading fluency and reading comprehension were assessed again at the beginning of grade 2 (November–December) during an individual session and a 40-min group session of 10 children in each group, respectively. The study had the approval of the Ministry of Education in Greece and the Ethics Committee of the University of Crete.

Statistical analysis

Participants were, initially, classified into RD and TD groups, based on their performance on standardized measures of reading fluency and reading comprehension, excluding those who scored below 70 on non-verbal intelligence (five children in total and four of them belonged to the RD group). The RD group (N = 87; 39 females) comprised children performing below the 25th percentile on tests of reading fluency and/or reading comprehension in both M2 and M3. Children who performed at or above the 25th percentile on reading fluency and reading comprehension in both M2 and M3 were assigned to the TD group (N = 66; 31 females).

In addition, children with RD were classified into two subgroups: one with predominantly RFD (N = 28; 15 females) and one with single RCD (N = 59; 24 females). The RFD group consisted of those children who performed below the 25th percentile on reading fluency in both M2 and M3, irrespective of their performance on reading comprehension. It should be mentioned that among children with RFD the majority (N = 25) scored below the 25th percentile on reading comprehension, as well, in both M2 and M3, while there were only three children with single RFD (i.e., reading comprehension performance equal or above the 25th percentile either in M2 or M3). On the other hand, the RCD group encompassed those children who scored below the 25th percentile on reading comprehension, but not on reading fluency, in both M2 and M3.

To examine whether oral language skills in grade 1 could predict which children were more likely to present RD in grade 2, as well as the specific type of children's RD, binomial and multinomial logistic regressions were conducted, respectively, with oral language skills as the independent variables and children's group classification (i.e., RD vs. TD and RFD vs. RCD vs. TD) as the dependent one. Before that, an examination of the oral language variables used in the analyses showed no missing values and extreme outliers. Moreover, composite scores for MA and PA in grade 1 were created, by averaging the percentage correct scores of the respective component tasks. Cross correlations among PA component tasks were $r > 0.70$ and among MA component tasks were $r > 0.46$.

Results

Preliminary analyses

Tables 1–4 present the descriptive statistics for the four reading groups (i.e., RD, TD, RFD, and RCD) for all the measures used in the present study. Independent-samples t-tests with Bonferroni adjustment corroborated that children with RD performed significantly lower than TD children on reading fluency and reading comprehension in both grades (see **Table 1**), as well as on all measures of oral language skills (see **Table 3**). Interestingly, regarding the differences in reading performance between children with RFD and RCD, the results from the independent-samples t-tests with Bonferroni adjustment revealed that although the latter group outperformed the former on reading fluency in both grades and on reading comprehension in grade 1, there was no statistically significant difference between them on reading comprehension in grade 2 (see **Table 2**). Finally, it was also indicated that although children with RCD outperformed children with RFD on all PA and RAN tasks, there was no statistically significant difference between them in MA and vocabulary measures (see **Table 4**).

Oral language skills predicting reading difficulties

A binary logistic regression was performed to examine whether oral language skills measured in grade 1 could predict children's RD in grade 2. Results indicated that our model was statistically significant $\chi^2(4) = 107.02$, $p < 0.001$ and explained

TABLE 1 Means (M) and standard deviations (SD) for the reading measures assessed in the first two grades for the RD and the TD group.

Measures	RD group				TD group				*t*-test[1] grade 1	*t*-test[1] grade 2
	Grade 1		Grade 2		Grade 1		Grade 2			
	M	SD	*M*	SD	*M*	SD	*M*	SD		
Text-reading fluency	21.61	10.16	33.32	14.72	46.64	17.05	64.26	18.06	10.59*** *d* = 1.78	11.67*** *d* = 1.91
Reading comprehension[2]	7.25	4.88	10.72	2.71	14.94	0.78	23.85	6.05	14.45*** *d* = 2.20	16.42*** *d* = 2.80

[1]Bonferroni correction was performed for two comparisons in both grades ($p < 0.025$).
[2]Two different measures were used for the assessment of reading comprehension in grades 1 and 2.
RD, children with reading difficulties; TD, typically developing children.
***$p < 0.001$.

TABLE 2 Means (M) and standard deviations (SD) for the reading measures assessed in the first two grades for the two RD subgroups.

Measures	RFD group				RCD group				*t*-test[1] grade 1	*t*-test[1] grade 2
	Grade 1		Grade 2		Grade 1		Grade 2			
	M	SD	*M*	SD	*M*	SD	*M*	SD		
Text-reading fluency	10.14	3.33	18.36	9.33	27.05	7.37	40.42	11.01	14.73*** *d* = 2.96	9.15*** *d* = 2.10
Reading comprehension[2]	4.57	4.05	10.36	3.50	8.53	4.75	10.90	2.26	3.80*** *d* = 0.87	0.75 *d* = 0.18

[1]Bonferroni correction was performed for two comparisons in both grades ($p < 0.025$).
[2]Two different measures were used for the assessment of reading comprehension in grades 1 and 2.
RFD, children with predominantly reading fluency difficulties; RCD, children with single reading comprehension difficulties.
***$p < 0.001$.

67.5% of the variance (Nagelkerke R^2) in our sample, classifying correctly 85.6% of the children. Furthermore, the sensitivity and specificity levels of our model were quite satisfactory, as it predicted correctly 87.4% of the children with RD and 83.3% of the children without RD, respectively. Children's RD status was significantly predicted by the vast majority of oral language skills, except for MA, which presented borderline statistical significance ($p = 0.052$) (see **Table 5**). Particularly, results showed that the lower the performance on PA and vocabulary the more likely it was to belong in the RD group, as a one-unit score increase decreased the odds of presenting RD by a factor of 0.95 and 0.84, respectively. In addition, children who performed worse at RAN tasks were more likely to present RD, with a one-unit increase increasing the odds of presenting RD by a factor of 1.21.

Furthermore, a multinomial logistic regression was, initially, conducted to examine whether oral language skills assessed in grade 1 could predict the type of children's RD (i.e., RFD or RCD) in grade 2. PA, MA, RAN, and vocabulary were used as

TABLE 3 Means (M) and standard deviations (SD) for all the measures of oral language skills and non-verbal intelligence assessed in the first grade for the RD and the TD group.

Measures	RD group		TD group		*t*-test grade 1
	M	SD	*M*	SD	
Non-verbal IQ	92.59	11.71	105.30	12.80	6.39** *d* = 1.04
Phonological awareness[a]	36.57	17.44	70.38	18.68	11.52** *d* = 1.88
Word elision[1]	33.67	22.12	72.47	21.59	10.86** *d* = 1.77
Pseudoword elision[1]	27.73	21.94	65.72	25.59	9.87** *d* = 1.61
Blending[1]	48.32	16.10	72.94	17.04	9.14** *d* = 1.49
Morphological awareness[a]	35.37	15.29	61.19	20.24	8.66** *d* = 1.44
Word Analogy[1]	33.56	23.61	58.03	29.49	5.70** *d* = 0.93
Derivation[1]	55.69	21.69	77.05	21.94	6.00** *d* = 0.98
Compounding[1]	16.86	16.10	48.48	25.98	8.70** *d* = 1.46
Vocabulary[b]	11.52	3.59	14.88	3.18	6.02** *d* = 0.98
RAN digits	20.31	4.53	16.03	2.83	7.16** *d* = 1.13

[a]Composite percentage score.
[b]Raw score.
[1]Bonferroni correction was performed for three comparisons in each grade ($p < 0.016$).
RD, children with reading difficulties; TD, typically developing children.
**$p < 0.001$.

TABLE 4 Means (M) and standard deviations (SD) for all the measures of oral language skills and non-verbal intelligence assessed in the first grade for the RFD and the RCD group.

Measures	RFD group		RCD group		*t*-test grade 1
	M	SD	*M*	SD	
Non-verbal IQ	91.61	12.55	93.05	11.37	0.54 *d* = 0.12
Phonological awareness[a]	24.98	11.10	42.07	17.26	4.79** *d* = 1.10
Word elision[1]	22.47	16.01	38.98	22.74	3.45* *d* = 0.79
Pseudoword elision[1]	12.80	13.70	34.82	21.62	4.93** *d* = 1.13
Blending[1]	39.67	14.26	52.42	15.37	3.70** *d* = 0.85
Morphological awareness[a]	35.81	12.87	35.16	16.42	0.20 *d* = 0.04
Word Analogy[1]	39.64	19.48	30.68	24.97	1.83 *d* = 0.40
Derivation[1]	55.89	22.15	55.59	21.66	0.06 d = 0.01
Compounding[1]	11.90	11.81	19.21	17.38	2.30 *d* = 0.49
Vocabulary[b]	12.07	3.55	11.25	3.61	0.99 *d* = 0.23
RAN digits	23.76	4.13	18.67	3.74	5.75** *d* = 1.32

[a]Composite percentage score.
[b]Raw score.
[1]Bonferroni correction was performed for three comparisons in each grade ($p < 0.016$).
RFD, children with predominantly reading fluency difficulties; RCD, children with single reading comprehension difficulties.
*$p < 0.01$; **$p < 0.001$.

TABLE 5 Results of binary logistic regression predicting children's RD.

Measures	*B*	SE	Wald	OR	CI
Constant	3.37	2.04	2.73	29.07	–
Phonological Awareness[a]	−0.05**	0.02	10.18	0.95	0.92–0.98
Morphological Awareness[a]	−0.03	0.02	3.77	0.97	0.94–1.00
Vocabulary	−0.17*	0.08	4.57	0.84	0.72–0.99
RAN	0.19*	0.08	5.29	1.21	1.03–1.43

[a]Composite percentage score.
RD, children with reading difficulties; TD, typically developing children; SE, standard error; OR, odds ratio; CI, 95% confidence interval.
*$p < 0.05$; **$p < 0.01$.

predictors of children's membership in the RFD or RCD groups, with TD as the reference category. The model was statistically significant, −2 log likelihood = 167.108 and $\chi^2(8) = 151.42$, $p < 0.001$, and explained 71.8% of the variance (Nagelkerke R^2) in children's group membership, classifying correctly 73.9% of them. The classification accuracy of our model for each one of the three groups (i.e., RFD, RCD, and TD) was 57.1, 69.5, and 84.8%, respectively. Moreover, results indicated that children who performed lower on vocabulary, PA, and MA, were more likely to belong in the RCD group than in the TD group, with a one-unit increase in these three oral language skills decreasing the odds of presenting RCD by a factor of 0.83, 0.96, and 0.97, respectively (see **Table 6**). On the other hand, children's classification in the RFD group than in the TD group was predicted by lower scores on PA and RAN performance, as a one-unit increase in PA decreased the odds of presenting RFD by a factor of 0.87, while a one-unit increase in RAN task performance increased the odds of presenting RFD by a factor of 1.60 (see **Table 6**).

Discussion

The current study longitudinally examined whether oral language skills (PA, RAN, MA, and vocabulary) assessed in grade 1 could predict RD, as well as the different RD subtypes (RFD or RCD), in grade 2. Overall, the pattern of our findings showed that (a) PA, RAN and vocabulary were strong predictors of children's RD in the early phases of learning to read in Greek and (b) individual differences in specific oral language skills play a key role in children's classification in specific RD groups (i.e., RFD or RCD). Particularly, PA, MA, and vocabulary distinguished the RCD from the TD group, whereas only PA and RAN contributed significantly in distinguishing the RFD from the TD group. Below, we discuss these findings in accordance with each research question and corresponding hypotheses.

Early oral language skills as predictors of reading difficulties

Our findings indicated that children with RD had lower performance than TD children on all oral language skills assessed in the middle of grade 1. In general, this evidence seems to support further the view that RD are associated with earlier deficits in oral language skills (e.g., Vellutino et al., 2004; Hulme and Snowling, 2014; Snowling and Melby-Lervåg, 2016; Snowling and Hulme, 2021) and reinforces the existing findings from *ex post* facto studies comparing children with RD and TD (e.g., Torppa et al., 2010; Dandache et al., 2014; Law and Ghesquière, 2017; Kargiotidis et al., 2021).

However, our findings partially confirmed the first hypothesis (H1) as they indicated that the classification of children with RD in grade 2 was jointly predicted only by PA, RAN, and vocabulary, but not by MA. Surprisingly, in our study, we expected that MA would predict group membership given that the vast majority of children with RD had RCD. However, the presence of children who also had deficits in reading fluency may have reduced the contribution of MA. Indeed, research evidence in Greek has repeatedly shown that early MA skills do not predict word reading fluency as opposed to reading comprehension (e.g., Diamanti et al., 2017; Manolitsis et al., 2017, 2019). On the other hand, in the more consistent Finnish orthography, Torppa et al. (2010) showed that preschoolers' MA was one of the oral language skills that distinguished children with RD from TD.

TABLE 6 Results of multinomial logistic regression predicting children's type of RD.

	RFD group					RCD group				
Measures	***B***	**SE**	**Wald**	**OR**	**CI**	***B***	**SE**	**Wald**	**OR**	**CI**
Intercept	−2.53	2.80	0.81	–	–	3.92	2.10	3.49	–	–
PA[a]	−0.14***	0.03	18.63	0.87	0.82–0.93	−0.05**	0.02	7.37	0.96	0.92–0.99
MA[a]	−0.02	0.03	0.50	0.98	0.93–1.03	−0.03*	0.02	4.07	0.97	0.94–1.00
Vocabulary	−0.07	0.12	0.37	0.93	0.74–1.18	−0.19*	0.08	5.07	0.83	0.70–0.98
RAN	0.47***	0.12	15.04	1.60	1.26–2.03	0.15	0.09	2.78	1.16	0.98–1.37

[a]Composite percentage score for phonological awareness (PA) and morphological awareness (MA).
RD, reading difficulties; RFD, children with predominantly reading fluency difficulties; RCD, children with single reading comprehension difficulties; SE, standard error; OR, odds ratio; CI, 95% confidence interval. Reference category = Typically developing children.
*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Nevertheless, based on our results early oral language skills seem to contribute to the identification of RD in Greek-speaking children in line with previous findings in other consistent orthographies (Puolakanaho et al., 2007; Furnes and Samuelsson, 2010; Torppa et al., 2010). This finding supports the notion (Nation and Snowling, 2004; Snowling et al., 2020) that oral language deficits of children with RD are not limited to the phonological domain (see also Torppa et al., 2010). In our results, vocabulary was an additional significant predictor of children's RD status. Vocabulary deficits in RD as compared to TD children have been found previously in consistent orthographies (Torppa et al., 2010; van Viersen et al., 2017, but see Rothou and Padeliadu, 2019 for an exception in vocabulary differences between dyslexics and non-dyslexics in grade 3). Differences between studies might be due to the different sample age ranges. Also, taking into account the nature of children's RD in the present study, as previously mentioned, we consider that further longitudinal research in Greek should be undertaken from preschool years to upper primary school grades to investigate whether the underlying deficit in early vocabulary skills may signify subsequent pure RD rather than broader literacy difficulties.

Early oral language skills as predictors of different reading difficulties subtypes

Further analyses indicated that children's early oral language skills in grade 1 are differentiated regarding their importance in predicting later difficulties in different reading outcomes (i.e., reading fluency and reading comprehension). Specifically, we found that PA and RAN emerged as significant predictors of children's classification in the RFD (in comparison to the TD) group in grade 2, confirming our second hypothesis (H2). This finding seems to converge with the findings of previous retrospective studies in consistent orthographies (Puolakanaho et al., 2007; Boets et al., 2010) in which young dyslexic children had scored significantly lower on both phonological skills as compared to their non-dyslexic peers at an earlier point in time. In fact, our data corroborate the study of Puolakanaho et al. (2007) on Finnish-speaking children, which indicated that PA and RAN were powerful predictors of children's dyslexia status, as defined primarily by poor reading fluency in grade 2.

Although in consistent orthographies PA did not emerge as a reliable longitudinal predictor of reading fluency across grades 1 and 2 (e.g., Georgiou et al., 2010; Furnes and Samuelsson, 2011; Fricke et al., 2016; Landerl et al., 2019), its predictive power in group membership for learning difficulties is not surprising. PA and RAN are well-established strong concurrent predictors of severe and persistent difficulties in word reading (Papadopoulos et al., 2009; Landerl et al., 2013; Moll et al., 2016). Rothou and Padeliadu (2019) in their work with dyslexic Greek-speaking children in grade 3, provided evidence for the predictive power of PA to distinguish between dyslexic children with a weakness in text reading fluency from typical developing readers.

Furthermore, we found that PA, MA, and vocabulary were significant predictors of children's classification into the RCD group (by comparison to the TD group) in grade 2. We hypothesized that oral language skills related to meaning, like MA and vocabulary, could predict children's RCD (H3). Interestingly, our results supported a predictive role for PA, possibly due to the nature of the reading comprehension test used in the present study in grade 2, which may assess both reading comprehension and fluency due to the time limit needed for its completion. Previous research evidence in Greek has shown the contribution of PA to children's performance on this test (Manolitsis et al., 2017; Pittas, 2017).

Our finding on the predictive value of MA toward RD subtype classification extends previous research showing MA deficits among poor reading comprehenders. However, most of the studies in this field have been conducted in English with mid-childhood children (e.g., Nation et al., 2005; Tong et al., 2014; Adlof and Catts, 2015; MacKay et al., 2017). At that age, according to Nation (2019), MA difficulties of poor reading comprehenders might be a consequence of reading comprehension failure. On the contrary, we assessed MA skills at a time when Greek students have not fully developed basic reading skills (grade 1). Undoubtedly the contribution of different facets of early MA to reading comprehension in the early phases of reading development is well-established (Carlisle, 1995; Casalis and Louis-Alexandre, 2000; Müller and Brady, 2001; Diamanti et al., 2017; Manolitsis et al., 2017). Present findings provide further support for the role of MA in RCD especially if we consider the nature of the tasks involved that did not require higher order thinking processes. Specifically, early reading comprehension was assessed through sentence completion tasks that depended highly upon morphosyntactic awareness. It seems that the rich morphological system of the Greek orthography necessitates the employment of morphological skills and strategies from early on for achieving text understanding-especially at the sentence level. Similarly, our results highlighted the importance of vocabulary in classifying children in the RCD group, in line with studies conducted in English (e.g., Nation et al., 2010; Catts et al., 2016) and Greek (Rothou, 2019). Although a different research design was followed in these earlier studies, both receptive vocabulary (Catts et al., 2016; Rothou, 2019) and expressive vocabulary (Nation et al., 2010) were found to be associated with difficulties in reading comprehension. In the present study, we found that expressive vocabulary may accurately distinguish children with RCD from TD children. Future research is needed to examine the predictive value of different types of vocabulary indices toward identifying RCD, given that receptive vocabulary may be more weakly related to RD than expressive vocabulary (see Ouellette, 2006). Overall, the above findings suggest that early weaknesses in semantic language skills, such as MA and vocabulary, may place children at risk for later RCD.

Limitations

There are some potential limitations to this study which might serve as a basis for further research. Firstly, our findings regarding RD and RD subtypes should be interpreted in the context of the diagnostic criteria and measures used here to classify children in these groups. For instance, assessing reading comprehension only with close tasks might not allow for a more precise estimation of children's RCD and their associated skills, because children's performance on this particular type of task depends more on lower-level skills (e.g., decoding) than on more demanding higher-level processes (e.g., inference making) (Kendeou et al., 2012; Collins et al., 2017). Thus, future research could implement a wider repertoire of measures to assess reading comprehension together with additional oral language and cognitive skills (e.g., listening comprehension and inference making) which are critical for its development. Secondly, the vast majority of children in the RFD subgroup did not present single RFD. They also presented accompanying difficulties in reading comprehension in both grades. Thirdly, all oral language skills examined here were not measured before the start of formal reading instruction and, therefore, these skills may have been affected by the method of reading instruction children received. Moreover, in contrast to PA and MA, RAN and vocabulary were assessed by a single measure, which may have affected the validity of the assessment of these oral language skills. Finally, assessment of oral language skills has not included listening comprehension evaluation, which is a well-known predictor of literacy difficulties and reading comprehension (Conti-Ramsden and Durkin, 2012), and might influence some of the effects emerged in the present study.

Educational implications

Our findings have substantial psychoeducational implications for the early identification of children with RD and particularly of children with specific types of RD. The present study underlines that deficits in oral language skills other than phonological skills could contribute to the early identification of children with RD, aligning better with a multiple-deficit model (Pennington et al., 2012; Ring and Black, 2018). Also, it underlines that deficits in specific oral language skills could distinguish children with different RD types (i.e., RFD or RCD) from typical readers. Therefore, the implementation of a comprehensive preventive model aiming to enhance a broad array of oral language skills seems essential for children with RD. Moreover, the implementation of an intervention policy that will focus on specific oral language skills could assist children with different types of RD to overcome their underlying linguistic limitations.

Conclusion

In summary, this is the first study focused on the joint examination of critical oral language skills (PA, RAN, MA, and vocabulary) in predicting RD and the specific type of RD in the Greek language. Three findings of the present study are of particular interest. First, we found that the evaluation of oral language skills at the beginning of primary school (grade 1) provides a powerful tool for the early identification of children who will display RD later (grade 2). Second, in line with a growing number of studies suggesting that a deficit in the phonological domain of language alone is not sufficient to predict RD, we found that PA and RAN along with vocabulary may accurately distinguish children with RD from TD children. Third, in line with other sources of evidence showing the existence of different RD subtypes with underlying deficits in different oral language skills, we found that PA and RAN could discriminate children with RFD, while PA, MA, and vocabulary could discriminate children with RCD, as compared to TD children. Overall, these findings highlight the underlying broader linguistic deficits of children with RD, which are not limited to the phonological domain. Therefore, a more suitable conceptualization of multiple deficits instead of a deficit in a single domain, as suggested by Pennington (2006), should guide the future research in RD.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

The study was approved by the Ministry of Education in Greece as well as the Research Ethics Committee of the University of Crete. Written consent from parents and schools was also obtained prior to testing. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

IG wrote most part of the manuscript and was responsible for the coordination of writing this manuscript. AK developed the measures of this study, collected the data in schools, ran the analyses, and wrote parts of the manuscript. AM supervised the data collection and contributed to the writing of the manuscript.

GM conceptualized the research project, supervised the data collection, and contributed to the interpretation of the findings and the writing of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Event-related potential and lexical decision task in dyslexic adults: Lexical and lateralization effects

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Developmental dyslexia is a specific learning disorder that presents cognitive and neurobiological impairments related to different patterns of brain activation throughout development, continuing in adulthood. Lexical decision tasks, together with electroencephalography (EEG) measures that have great temporal precision, allow the capture of cognitive processes during the task, and can assist in the understanding of altered brain activation processes in adult dyslexics. High-density EEG allows the use of temporal analyses through event-related potentials (ERPs). The aim of this study was to compare and measure the pattern of ERPs in adults with developmental dyslexia and good readers, and to characterize and compare reading patterns between groups. Twenty university adults diagnosed with developmental dyslexia and 23 healthy adult readers paired with dyslexics participated in the study. The groups were assessed in tests of intelligence, phonological awareness, reading, and writing, as well as through the lexical decision test (LDT). During LDT, ERPs were recorded using a 128-channel EEG device. The ERPs P100 occipital, N170 occipito-temporal, N400 centro-parietal, and LPC centro-parietal were analyzed. The results showed a different cognitive profile between the groups in the reading, phonological awareness, and writing tests but not in the intelligence test. In addition, the brain activation pattern of the ERPs was different between the groups in terms of hemispheric lateralization, with higher amplitude of N170 in the dyslexia group in the right hemisphere and opposite pattern in the control group and specificities in relation to the items of the LDT, as the N400 were more negative in the Dyslexia group for words, while in the control group, this ERP was more pronounced in the pseudowords. These results are important for understanding different brain patterns in developmental dyslexia and can better guide future interventions according to the changes found in the profile.

KEYWORDS

developmental dyslexia, cognitive profile, electroencephalography, potentials related to events, hemispheric lateralization

Introduction

Developmental dyslexia (DD) is a neurobiological disorder that brings challenges to the person for decoding words, resulting in poor spelling and reading fluency skills. These difficulties typically result from a deficit in the phonological, visual, auditory, and orthographic components of language, being the use of written language deficient, which is often unexpected relative to other cognitive skills and adequate classroom teaching instruction (Lyon, 2003; Schumacher et al., 2007; Handler and Fierson, 2011; American Psychiatric Association [APA], 2014; Nergård-Nilssen and Hulme, 2014). In this sense, we can consider DD as a spectrum of a variety of cognitive and neurobiological changes that reflect behavioral deficits (Carioti et al., 2021).

According to the literature, DD manifests itself differently throughout development and across languages and orthographies (Borleffs et al., 2019; Carioti et al., 2021). Orthographic consistency may be an important factor in the manifestation of symptoms and cognitive profile of DD, also as cross-linguistic aspects (Reis et al., 2020). Differences in orthographies can be attributed to spelling depth as well as syllabic complexity and these aspects directly influence the acquisition and development of reading skills. Word reading is a more complex task for deep orthographies than for superficial ones and, as a result, when dyslexics become adults there is a reduction in the gap when compared to normal readers. Although, this pattern is not a sign of better reader performance itself, but can be explained by the orthographic transparency in written languages such as Spanish, Italian, and Portuguese for example (Carioti et al., 2021).

Although the diagnosis occurs predominantly in childhood, cognitive, and neurobiological patterns remain in adulthood. In children, difficulties affect word decoding skills as well as losses are present in establishing the relationship between spelling patterns and word pronunciation (Handler and Fierson, 2011; Snowling and Hulme, 2012). Symptoms in adult life are presented differently due to the occurrence of compensatory behaviors and strategies developed to minimize reading and academic or non-academic impairments (Schelke et al., 2017). Therefore, compensatory mechanisms are developed throughout the life-span to reduce functional impairment such as greater activation of the left superior temporal region and inferior parietal region in working memory tasks, as well as greater activation of the left inferior frontal gyrus in phonological discrimination tasks (Nergård-Nilssen and Hulme, 2014; Soriano-Ferrer and Piedra Martínez, 2017; Mahé et al., 2018). However, neurobiological and cognitive markers of dyslexia remain over their lifetime (Schelke et al., 2017).

Although difficulties in cognitive skills such as working memory, phonological awareness, and rapid automatic naming are also present in adulthood, difficulties in reading and writing skills are the main cognitive markers (Soriano-Ferrer and Piedra Martínez, 2017; Carioti et al., 2021). One of the main indicators of adult dyslexia is spelling and letter problems stemming from a lack of orthographic knowledge. As long regular readers benefit from successful synchronization between different cerebral systems related to visual, auditory, and semantic processes during reading, dyslexics present asynchrony between the visual and auditory systems in the brain, termed the asynchrony phenomenon (Breznitz, 2002; Nergård-Nilssen and Hulme, 2014). At the same time, the meta-analysis from Soriano-Ferrer and Piedra Martínez (2017) about neurobiological basis of Dyslexia confirms the absence of hemispheric lateralization in dyslexic children and adults during written language tasks.

Lexical decision tasks provide cognitive assessments of the processes underlying word recognition skills. The task paradigm allows the evaluation of lexical access accuracy and speed, as well as the lexicon development level (Balota and Chumbley, 1984; Berberyan et al., 2021). Lexical decision tasks help to verify the orthographic-semantic (word) and phonological (pseudowords) processing in word recognition (Shaul, 2013). In lexical decision tasks, brain activity is different for words, and pseudowords, taking into account that performance differences can also be explained by differences in decision making (Shaul et al., 2012; Shaul, 2013; Berberyan et al., 2021). Also, differences in lexical decisions tasks. This differentiated pattern of word-related brain activity is not present in dyslexic adults, reflecting the orthographic and phonological deficits present in this learning disability (Shaul et al., 2012; Shaul, 2013).

In this context, research on lexical decision tasks with the recording of high-density EEG measures can help us to understand the neurophysiological processes underlying reading providing information before the appearance of a behavioral response. Measurements of neuronal activity using high-density electroencephalography (EEG) have been used in studies with people with dyslexia because they have good temporal accuracy, enabling inferences about cognitive processes during the lexical decision task (Ozernov-Palchik and Gaab, 2016; Perera et al., 2018a).

High-density EEG allows the use of temporal analysis through event-related potentials (ERPs). ERPs are characterized by being sensitive to cognitive parameters triggered by a specific task (Caylak, 2009), and these tasks may be reading tasks. In general, some studies that recorded ERPs in dyslexic children and adults have found, when compared to normal readers data, changes in latency and amplitude in potentials related to visual processing (Kast et al., 2010; Dujardin et al., 2011), orthographic (Taroyan and Nicolson, 2009; Waldie et al., 2012), semantics (Horowitz-Kraus and Breznitz, 2008; Hasko et al., 2013), and cognitive (Taroyan and Nicolson, 2009; Shaul et al., 2012) that are involved in word recognition. Word recognition involves the ability to see a word and recognize its pronunciation effortlessly and instantly. To develop automaticity in word recognition, instructions in phonological awareness, decoding

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with good skills and knowledge of spelling rules and grapheme-phoneme conversion are required, and finally visual recognition of words (Murray, 2016). Furthermore, differentiated brain activity patterns in dyslexic adults were also observed using EEG measurements (Perera et al., 2018b).

Some ERPs are relevant in word reading and lexical decision analysis in DD. The ERP differences found in dyslexic adults may be related to sub-efficient neural mechanisms (Mahé et al., 2018). Studies have shown that dyslexics present linguistic processing of different patterns in early components (P100, P200, N100, and N2), associated with sensory-perceptual processing and the physical characteristics of stimuli (Taroyan and Nicolson, 2009; Dujardin et al., 2011; Mahé et al., 2018). In dyslexic adults, lower latencies and lower left hemisphere activation of this ERP were reported, as well as greater right hemisphere activation for pseudo object visualization (Mayseless and Breznitz, 2011).

In particular, early components P100 and N170 can also be related to the processing of orthographic structure and letter position in the word, which is important for the recognition of the visual form of word characteristics (Araújo et al., 2015). Some authors (Carreiras et al., 2014; Coch and Meade, 2016; Mahé et al., 2018) report N170 greater amplitudes in normal readers during the reading process of real words, as well as phonological sensitivity and how the sounds of letters form words, showing a lexicality effect. The greater N170 amplitude in response to words and spelling sensitivities is not present in dyslexic adults, and this ERP difference can be a hallmark of the neurobiological profile of DD (Mahé et al., 2013; Carreiras et al., 2014). Furthermore, N2, ERP measured between 135 and 205 ms can also be related to lexical access and showed lower amplitudes in adult dyslexics compared to good readers (Mahé et al., 2018). In addition to possible group differences, it is important to report hemispheric effects concerning the component called N1–measured between 150 and 180 ms (Araújo et al., 2015), present with greater amplitude in the left hemisphere of both dyslexics and good readers.

Regarding later processing during word reading, the N400 is a linguistic component that is sensitive to semantic manipulation (Kutas and Federmeier, 2011). Furthermore, other linguistic manipulations of items, such as word frequency, can modify this component activity (Kutas and Federmeier, 2011). During word recognition processing, both words, pseudowords, or stimuli with sound or orthographic irregularity, reflect changes in N400. This ERP is sensitive to factors prior to recognition stages such as orthographic neighborhood, frequency, and orthographic and phonological similarity, and may be associated with memory and retrieval of linguistic information (Kutas and Federmeier, 2011). Changes in the N400 component reflect compensatory changes in adult dyslexics, whose semantic aspects are processed through morphology as a way to compensate for phonological impairments (Cavalli et al., 2017).

Another component that may be altered in DD is P600, which is described as related to syntactic violation (grammar-imposed restrictions) (Kutas and Federmeier, 2011). This is observed in both the visual and auditory stimuli. van Herten et al. (2006) suggest that the P600 also reflects the engagement of executive and cognitive processes in error monitoring and reprocessing services to resolve the uncertainty of responses during linguistic processing, analyzing, and reanalyzing processes already carried out.

Considering the importance of spelling regularity and the distinct cognitive profiles found in cross-linguistic studies, the present research aims to elucidate the electrophysiological bases underlying cognitive processing and hemispheric activity triggered by a lexical decision task in dyslexic Brazilian adults. The aim of this study was to compare and measure the ERP patterns of adults with DD, Brazilian Portuguese readers, and control readers, as well as to compare reading patterns between the groups to verify possible orthographic influences on the cognitive profile of the groups. From this, the study can contribute to a better understanding of EEG and the cognitive basis of dyslexia can present itself in Brazilian Portuguese.

Materials and methods

Participants

A total of 20 university adults diagnosed with developmental dyslexia (DG-Adults) and 23 good readers paired with dyslexics (CG-Adults) participated in this study. For the diagnosis of the group of adults with dyslexia, neuropsychological assessments were performed at the Laboratory of Cognitive and Social Neuroscience in which the group participants had a cognitive profile compatible with DD. To ensure homogeneity among the participants, the pairing was performed according to age, gender, and education level. Thus, participants' ages ranged from 18 to 41 years (M = 24.97 + 4.73; p = 0.603). Of the 43 participants, 56.5% were women (DG-Adults = 13, CG-Adults = 13; p = 0.532), and all had undergraduate courses ongoing or finished. All participants were assessed using a broad battery of neuropsychological, reading, and writing tests to meet the inclusion and exclusion criteria. Inclusion criteria: (1) level of intelligence assessed by the Wechsler Adult Intelligence Scale at or above average (above the 25th percentile) and (2) delay in reading and writing skills in relation to subjects with the same education level for the group of participants with dyslexia and reading and writing skills in the middle range or higher for the control group. Exclusion criteria: Participants with comorbid psychiatric, neurological, truancy, or vision problems were excluded.

Instruments

Wechsler Adult Intelligence Scale assesses intellectual ability through measures of verbal IQ, performance IQ, and global IQ. In addition, it assesses four cognitive domains that underlie intellectual skills: verbal comprehension, working memory, perceptual organization, and processing speed (Wechsler, 2004).

Word Reading Competence Test 2 (WRCT-2): is composed of 80 items, which are formed by pairs that involve the auditory and visual presentation of a word, which may or may not be congruent. The pairs can be congruent, in which case the spoken word and written word are identical, or incongruent, in accordance with specific types of errors in the written words. The incongruent pairs are of four types: written words with visual changes of letter position in the word, letter omission, word with phonological changes, and words with visual confusion of letters (de Oliveira et al., 2009; de Oliveira, 2014; Oliveira et al., 2014; Dias et al., 2016).

Word Dictation Writing Test for adults (WDWTA): The test consists of 50 items in which it seeks to assess the ability to spell irregular words that depend on the use of proper spelling rules, which are dictated by the subject (de Oliveira, 2014).

Phonological awareness test 2 (PAT-2): The PAT-2 is a test adapted to the adult population and has 183 the same items as the children's version (Capovilla et al., 2011). The test consists of 64 items divided into subtests of rhyme, alliteration, syllabic addition, syllabic subtraction, phonemic addition, phonemic subtraction, syllabic transposition, phonemic transposition, and pun. Each item has a semantic distractor, phonological distractor, inverse-rule distractor, and unspecific distractor (de Oliveira et al., 2008; de Oliveira, 2014; Oliveira et al., 2014).

Lexical Decision Task: The lexical decision task was created considering the feasibility criteria for the application and recording of electrophysiological responses in the high-density electroencephalogram. The test consists of 540 items, consisting of 180 regular words, 180 pseudowords, and 180 quasi-words. The stimuli were selected according to psycholinguistic properties of length and frequency in the Portuguese language. The syllabic structure of the stimuli was counterbalanced between the structures CVCVCV, VCVCV, CCVCVCV, and VCCVCV. In addition, the number of letters of the stimuli varied between 5 and 7 letters, so there was no influence of the variable length during the processing of the items. All words have a medium or high frequency in Portuguese according to the Corpus NILC Universidade de São Carlos.[1] Regarding regularity, regular and rule words were selected. The quasi-words are divided into three categories: 60 pseudohomophones, 60 visual exchanges, and 60 phonological exchanges. Such categorization is based on the study by Proverbio and Adorni (2008). The pseudowords were constructed from sequences of decodable letters and syllables, but not derived from real words. Considering this factor, the frequency values of bigrams of the task stimuli with five and six letters were measured, according to data from Justi and Justi (2009). The results showed that the pseudowords present bigrams with very low frequency in the Portuguese language (mean of 19.64, SD = 1.37). The test stimuli were prepared in bitmap format files (BMP) with a resolution of 800 × 600 pixels. The font used was Courier New, black, bold type, size 18 on a white background. Each stimulus appears on the screen for 2 s, after they disappear, the subject must press a button if he judges the word as real or invented, followed by a screen with a picture of an eye so that the subject can blink. After the response is emitted, a blank screen with a central cross appears for 3 s for the subsequent presentation of the next stimulus. The lexical decision task items were presented in six blocks of 90 items each, and the items in the categories were randomized along the blocks. The number of correct answers, omissions errors (i.e., not pressing the button), and reaction time. Response times of incorrect responses and those shorter than 100 msec or longer than 2.5 SD above the subject's mean were eliminated. **Figure 1** shows the sequence of presentation of the lexical decision task screens on the right.

1 http://www.linguateca.pt/ACDC/

Equipment

128-channel Electroencephalography Device, Electrical Geodesics, Inc., Eugene, OR, USA model EEG System 300. The equipment is composed of an amplifier model Net Amps 300, transformer with isolation, articulated arm to support the amplifier, license for acquisition, and data analysis software Net station, six Geodesic hydrocele model electrode networks, Macintosh CPU for data acquisition, 23″ monitor for data monitoring, software for calculating the sources generating the signals (GeoSource Estimation Software), package for Event Related Evoked Potential (PST, Inc., Savannah, GA, USA), E-prime workstation to couple to EEG (*Net Station*), computer desktop Dell, hardware for the experiments, 17″ Liquid Crystal Display (LCD) monitor with video *splitter and switch*, b response for Electrical Geodesics, Inc (EGI), *single clock*, Audio Visual (AV) device.

Procedures

The study was conducted in accordance with the requirements of the ethics committee of Mackenzie Presbyterian University, after evaluation and approval of the research project (CEP/UPM no. 1305/12/2010). The participants were contacted and informed of the research objectives. After reading and signing the letter of information and the term of consent, neuropsychological and computerized reading and writing

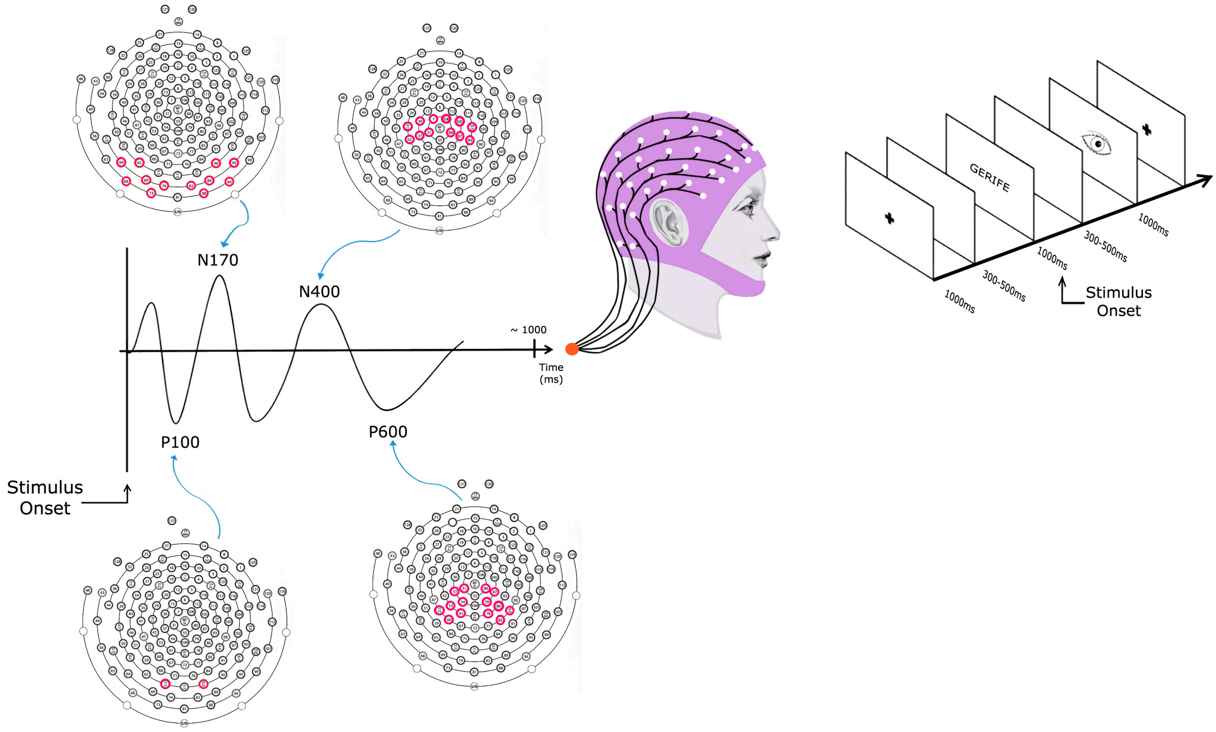

FIGURE 1
A schematic presenting the event-related potential (ERP) to lexical decision task stimulus obtained by averaging the electroencephalography (EEG) signal of multiple stimulus presentations. The data was collected with a 128-channel array of scalp electrodes from which the EEG was recorded. The electrodes chosen for the four components were: P100 (Occipital), N170 (Occipital-Temporal), N400 (Central), and P600 (Central-Parietal). In the electrode's figures, the purple circles indicate which electrodes were used for each component.

assessments were performed. Evoked potentials were recorded using a Geodesic EEG System 300. Regarding the collected EEG tracing, a pre-processing phase was initially carried out, which contained: (a) 0.1 Hz filter (*High Pass Filtering*), (b) 30 Hz (*Low Pass Filtering*), (c) segmentation of the trace considering the 200 ms prior to the presentation of the screen containing the proposal and the decision and the 1,200 ms after, (d) artifact detection was performed before averaging to discard epochs in which eye movements, blinks, excessive muscle potentials, or amplifier blocking occurred. Artifacts were considered as channels with a Max-Min variation greater than 200 μV (with a time window of 640 ms). Those with more than 20% of artifacts were considered as bad channels and were automatically rejected. In addition, bad segments were considered those with more than 10 bad channels or blinking.

After the pre-processing phase, the post-processing phase followed, which included: (a) replacement of bad channels with interpolated values based on neighboring channels, (b) average of the potentials obtained in the segmentation considering the factors described above (a data file was created containing all evoked potentials incorporating data from all participants), and (c) correction for the baseline, which is the tracing obtained in portions of 200 ms prior to the presentation of stimuli. The data were then subjected to statistical processing considering the mean amplitude for the occipital P100, occipitotemporal N170, parietal N400, and center-parietal late positive complex (LPC) potentials as dependent variables. The occipital P100 was analyzed in the temporal window between 30 and 150 milliseconds and the selected electrodes were #70 and 83. The occipitotemporal N170 component was analyzed in the temporal window of 140–270 milliseconds. Left hemisphere electrodes n° 64, 65, 68, 69, 73, and 74 were selected, as well as the right hemisphere electrodes n° 82, 88, 89, 90, 94, and 95. The potential N400 of the central-parietal region was analyzed in the temporal window between 300 and 500 ms. Electrodes no. 7, 30, 31, 36, 37, and 42 were selected in the left hemisphere, as well as the following right hemisphere electrodes: 80, 87, 93, 104, 105, and 106. Finally, the center-parietal P600 component was analyzed in the temporal window between 450 and 850 ms. Electrodes # 60, 61, 53, 54, 37, 31, 42, and 52 were selected for the analysis of the left hemisphere, and electrodes # 80, 87, 93, 79, 86, 92, and 85 were selected for LPC analysis in the right hemisphere. The choice of electrode sites and time windows for measuring and quantifying ERP components of interest was chosen based on previous literature that showed that the components usually reach their maximum over these areas

(Proverbio and Adorni, 2008; Dujardin et al., 2011). **Figure 1** presents the electrodes that were analyzed for each component.

Data analysis

To understand if the control and dyslexia groups differed in relation to their cognitive profile, we conducted several Student's *t*-tests comparing both groups for the WAIS-III, WDWTA, WRCT-2, and PAT-2 measures. We also compared the performance of both groups for the behavioral data in the lexical decision task. Both groups were compared in terms of accuracy, reaction time, and missions. We also calculated Cohen's d to analyze the effect size.

To compare the electrophysiological responses of both groups in the lexical decision task, we carried out several repeated measures ANOVAs. For the within factor, we used the hemisphere of the brain and the lexicality of the words in the task. For the between-factor analysis, we used the dyslexic-control group. We also calculated the generalized eta squared (η^2) to analyze the effect size of the findings. For all analyses, we considered a significant *p*-value of <0.05.

Results

The performance of each group was evaluated using the WAIS-III, WDWTA, WRCT-2, and PAT-2. We compared the two groups to understand the differences in the profiles of each group. Their performance and the differences between the groups are shown in **Table 1**. No differences were found in the WAIS-III and PAT-2 measures, but significant differences were observed in WDWTA-2 and WRCT-2 (p = 0.033). A large effect between both groups was found in all WDWTA and WRCT-2 measures, with the exception of the time in the WDWTA, which was marginally large.

Lexical decision task: Behavioral data

In the lexical decision task, we compared both groups for each measure. The plot of each group dispersion in the lexical decision task is shown in **Figure 2**. Significant differences were found in the number of correct answers in words (p = 0.045, d = 0.76), pseudowords (p = 0.002, d = 1.56), and quasi words ($p < 0.001$, d = 1.51). For reaction time, significant differences of large magnitude were present in words (p = 0.006, d = 1.02), pseudowords (p = 0.002, d = 1.33), and quasi words (p = 0.009, d = 1.13). Regarding omissions, significant differences of large magnitude were found in pseudowords (p = 0.009, d = 1.28) and quasi words (p = 0.046, d = 0.89), and no differences were found for regular words (p = 0.123, d = 0.66).

Lexical decision task: Electroencephalography data

We evaluated four different components of the EEG measures during the lexical decision task and analyzed the effects of lexicality, group, and hemisphere. We also observed an interaction between these factors. The effects and interactions are listed in **Table 2**.

The P100 amplitude means were higher in the right hemisphere in both groups. The means of P100 in the DG were greater for the pseudowords in both hemispheres, while in the CG, the mean of the left P100 was greater in the pseudowords and in the right P100 for the quasi-words. **Figure 3** shows the P100 components of the different groups.

Regarding the N170 component data, the mean amplitudes of the N170 were more negative in the control group and in the left hemisphere. It is noted, in general, that the mean N170 in the dyslexia group was higher in the right hemisphere, while the opposite pattern was observed in the control group. Regarding lexicality, the amplitude means were higher for words, followed by quasi-words and pseudo-words. **Figure 4** illustrates the mean amplitudes of the N170 in both hemispheres for both groups.

Regarding the N400 component, the mean amplitudes of the centro-parietal N400 in the dyslexia and control groups were greater in the left hemisphere. Amplitudes were more negative in the Dyslexia group for words, while in the control group, the N400 was more pronounced in the pseudowords. Furthermore, the mean amplitude of this potential was greater in the left hemisphere. The marginal interaction effect between hemisphere and group indicated that in the dyslexic group, the N400 amplitudes were smaller in the left hemisphere. **Figure 5** illustrates the mean N400 amplitudes in the left and right hemisphere of the dyslexic and control groups in the different lexical classes of the lexical decision task.

Regarding the P600 component, the mean amplitude values in the center-parietal region were lower in the dyslexic group and higher in the left hemisphere in both groups. The P600 amplitude was greater in the left hemisphere, and the dyslexic group had reduced amplitudes. Regarding lexicality, the P600 was more pronounced for words and higher than for pseudowords and quasi-words. **Figure 6** illustrates the mean P600 amplitudes in the left hemisphere (electrode 54) and right hemisphere (electrode 79) of the dyslexic group (above) and control (below) in the different lexical classes of the lexical decision task.

Discussion

The aim of this study was to compare and measure the ERP patterns of adults with DD, Brazilian Portuguese readers, and control readers, as well as to compare reading patterns between the groups to verify possible orthographic influences on

TABLE 1 Mean and standard deviation (SD) for the control and dyslexia group and their comparison.

Tests	Measures	Control mean (SD)	Dyslexia mean (SD)	*t*	*P*-value	Cohen's d
WAIS-III	Total IQ	120.80 (11.17)	119.20 (11.65)	0.31	0.758	0.14
	Verbal IQ	115.40 (10.46)	109.10 (19.50)	0.90	0.383	0.40
	Executive IQ	123.60 (8.97)	115.60 (23.55)	1.00	0.336	0.57
	Verbal comprehension	116.10 (8.89)	102.90 (26.49)	1.49	0.163	0.67
	Perceptual organization	122.20 (8.74)	109.40 (27.46)	1.40	0.188	0.63
	Working memory	112.30 (15.40)	95.80 (29.07)	1.59	0.136	0.71
WDWTA	Total number of correct answers	43.30 (3.83)	31.60 (10.02)	3.45	**0.005**	1.54
	Time (in ms)	5567.15 (1499.21)	7310.33 (2727.86)	1.77	0.098	0.79
WRCT-2	Total number of correct answers	72.40 (4.77)	61.60 (5.72)	4.59	**<0.001**	2.05
	Time (in ms)	1130.73 (432.45)	1819.39 (807.94)	2.38	**0.033**	1.06
PAT-2	Total number of correct answers	54.2 (7.54)	49.7 (7.99)	1.30	0.211	0.58
	Time (in ms)	15096.38 (1436.93)	17959.32 (5032.82)	1.73	0.113	0.77

WDWTA, Word Dictation Writing Test for adults; WRCT-2, Word Reading Competence Test for adults; PAT-2, phonological awareness test 2. Bold values are significant results.

TABLE 2 The effects and interactions for the P100, N170, N400, and P600 components of the electroencephalography during the lexical decision task, their *p*-values, and their effect size.

Effects and interactions	P100		N170		N400		P600	
	p	η^2	*p*	η^2	*p*	η^2	*p*	η^2
Lexicality	0.502	0.001	0.591	<0.001	**0.029**	**0.007**	**0.019**	**0.009**
Group	0.632	0.004	0.564	0.007	0.601	0.006	0.061	0.085
Hemisphere	**0.038**	**0.005**	**0.010**	**0.034**	**0.013**	**0.020**	**<0.001**	**0.023**
Lexicality × group	0.162	0.005	0.368	0.001	0.473	0.002	0.311	0.003
Hemisphere × group	0.421	0.003	0.067	0.017	0.054	0.012	0.607	<0.001
Hemisphere × lexicality	0.571	<0.001	0.340	0.002	0.269	0.003	**<0.001**	**0.005**
Hemisphere × lexicality × group	0.804	<0.001	0.238	0.002	0.176	0.004	0.952	<0.001

Bold values are significant results.

the cognitive profile of the groups. Regarding behavioral data, dyslexics did not presented deficits in phonological awareness in PAT-2 and WAIS verbal and working memory measures. Although some studies describe these changes in the profile of dyslexics in relation to good readers (Nergård-Nilssen and Hulme, 2014; van Setten et al., 2016), in adulthood these changes are more variable and seem to depend on orthographic regularity (Carioti et al., 2021). The fact that we did not find disadvantages in dyslexics can be explained by the orthographic transparency of Portuguese. According to Reis et al. (2020), dyslexia symptoms are less marked in clear orthographies and phonological awareness appears to be less of a problem in adulthood. On the other hand, significant losses were found in reading, and writing skills, both in accuracy and speed. Deficits in reading and writing are the most important cognitive markers in the cognitive profile of dyslexic adults in transparent orthographic systems (Carioti et al., 2021). The dyslexic group presented low performance in accuracy on the reading task by recognizing words and pseudowords–WRCT-2, which was also verified in van Setten et al. (2016), Paz-Alonso et al. (2018), and Ozernov-Palchik et al. (2021). The writing data followed the same pattern from the reading ones, since the WDWTA results from the dyslexic group were significantly lower than the normal readers and writing impairments keep being a cognitive feature in the profile of dyslexic adults (Shaul, 2012; Nergård-Nilssen and Hulme, 2014).

Regarding the results of the lexical decision task, the same pattern of difficulties of dyslexic readers in relation to good readers for the measures of accuracy and speed of linguistic processing was observed, as well as a greater number of omission items. These results corroborate the findings of other studies on lexical decision tasks (Bergmann and Wimmer, 2008; Mahé et al., 2012). The results showed a longer reaction time and a higher omission rate for quasi words for both groups of readers in the present study. In the study by Mahé et al. (2012), both typical and dyslexic readers had longer reaction times and higher numbers of errors in pseudowords derived from real words, and this pattern was even higher in the dyslexic group. Taroyan and Nicolson (2009), Shaul et al. (2012), and Shaul (2013) also found similar behavioral results. These results may indicate word identification processes related to orthographic familiarity of stimuli, in which proximity to real words makes

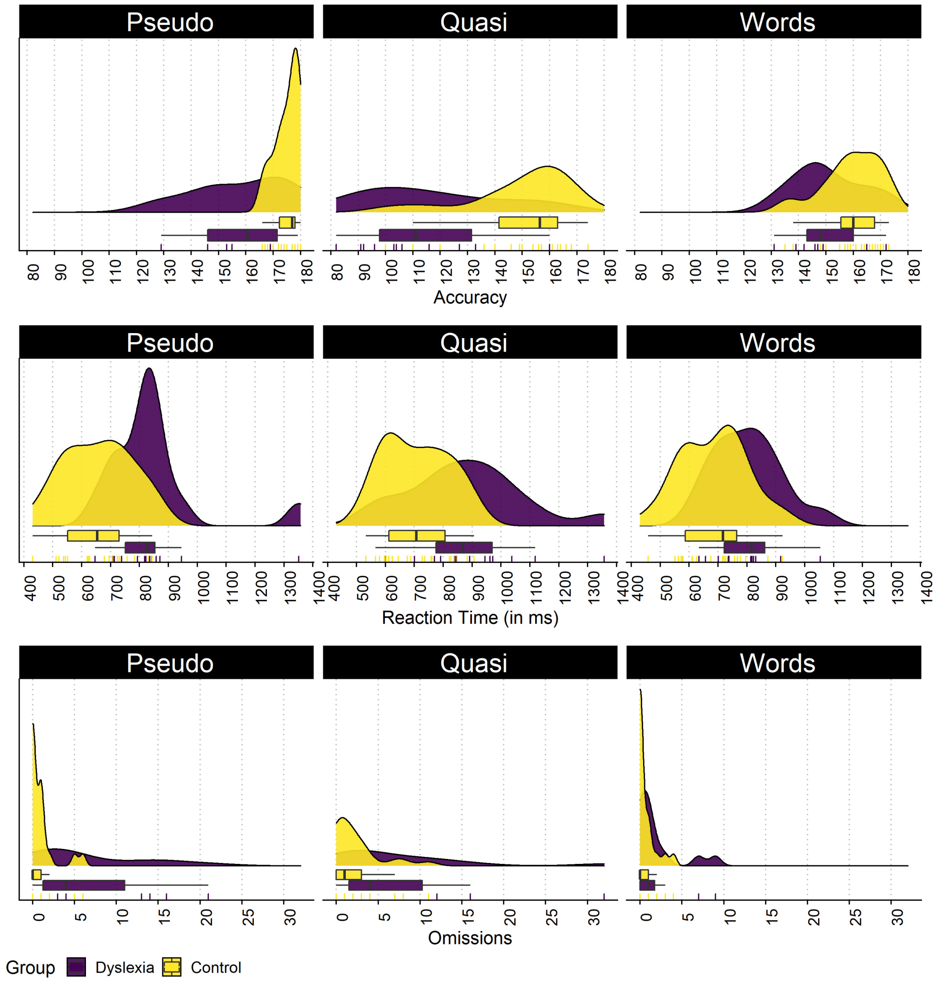

FIGURE 2
Distributions of the control and dyslexia group for the total number of correct answers, the reaction time, and the total number of omissions in the lexical decision task. The density plots present the density estimate of each variable, the boxplot present the median and quartiles, and the rugs present each data point individually.

stimulus analysis difficult (Taroyan and Nicolson, 2009; Mahé et al., 2012).

Regarding the electrophysiological data, the P100 component presented a similar amplitude pattern in both groups, with larger amplitudes in the right hemisphere. The P100 component has been associated with visuospatial attention and in the detection of physical properties of stimuli, that can present alteration in dyslexic readers (Dujardin et al., 2011). The present study did not find group differences concerning the amplitude of this component, however, comparing the average amplitudes in relation to the type of stimuli, high amplitudes of P100 can be observed in the DG for pseudowords in both hemispheres, while for CG the same component was higher in the right hemisphere for pseudowords and quasi words. Dujardin et al. (2011) found smaller amplitudes of P100 in the occipitotemporal area in the left hemisphere during pseudoword processing in dyslexics. In the present study, this pattern was observed in dyslexics, which may indicate changes in early brain activity related to non-specialization in the beginning processing of the visual form of words.

Regarding N170, the present study found a hemispheric effect, with more negative amplitudes in the CG and the left hemisphere. In addition, the mean N170 in the DG group was higher in the right hemisphere during quasi-word processing. This brain activation profile is seen in functional neuroimaging studies in which dyslexics do not show hemispheric specialization, but a right-lateralized activation pattern (Soriano-Ferrer and Piedra Martínez, 2017). In processing linguistic stimuli such as word reading, the right hemisphere is activated and ends up being inhibited by the left hemisphere when the word meaning is found (Shaul et al., 2012). This pattern did not appear to occur in the dyslexic group.

In the present study, the mean amplitude of this component was greater in words, followed by quasi-words

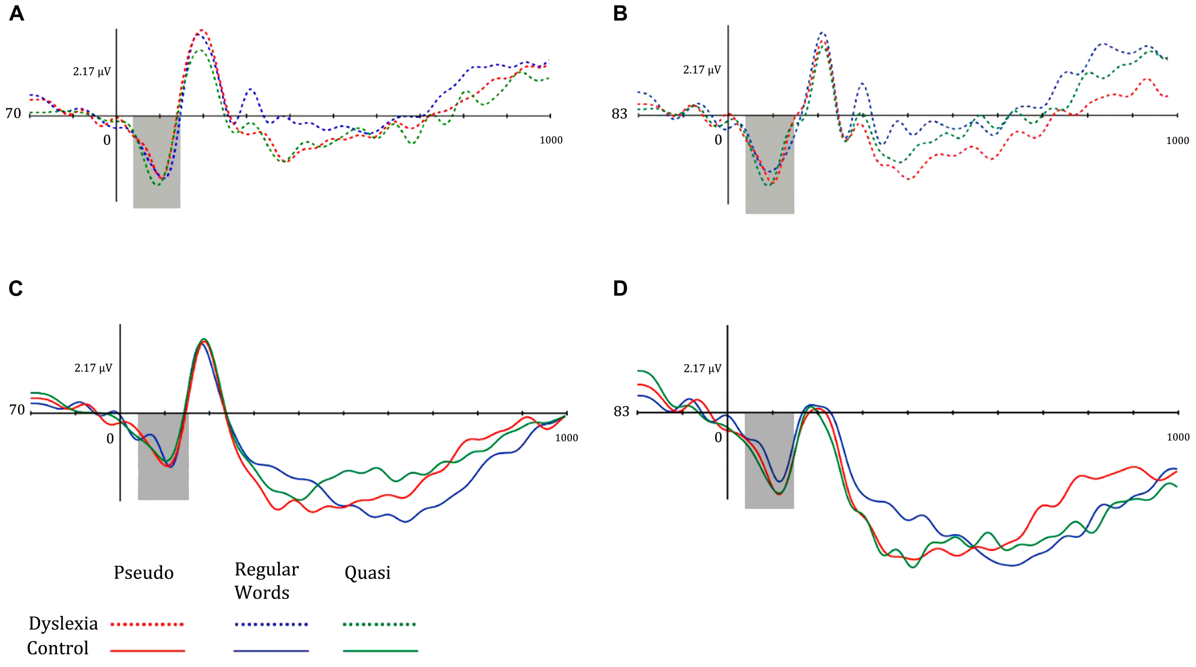

FIGURE 3
Mean amplitude of the P100 component for **(A)** dyslexia group and left hemisphere, **(B)** dyslexia group and right hemisphere, **(C)** control group and left hemisphere, and **(D)** control group and right hemisphere. Dotted lines represent the dyslexia group, while solid lines represent the control group. Red-colored lines represent pseudo words, blue-colored lines represent regular words, and green-colored lines represent Quasi words.

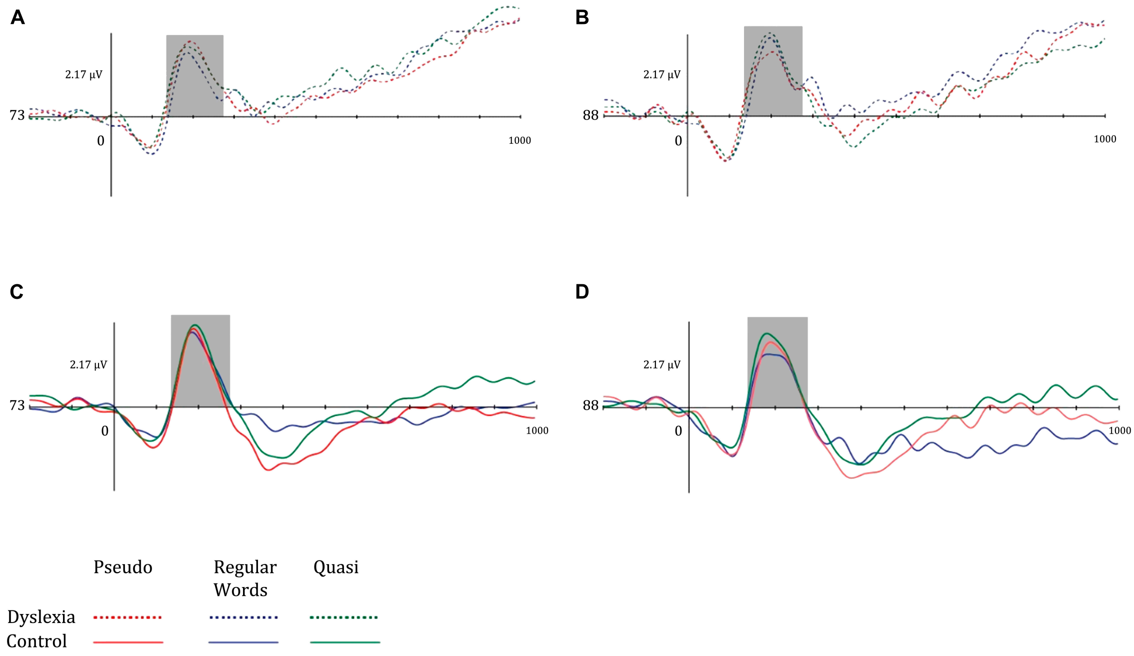

FIGURE 4
Mean amplitude of the left occipitotemporal N170 component for **(A)** dyslexia group and left hemisphere, **(B)** dyslexia group and right hemisphere, **(C)** control group and left hemisphere, and **(D)** control group and right hemisphere. Dotted lines represent the dyslexia group, while solid lines represent the control group. Red-colored lines represent pseudo words, blue-colored lines represent regular words, and green-colored lines represent Quasi words.

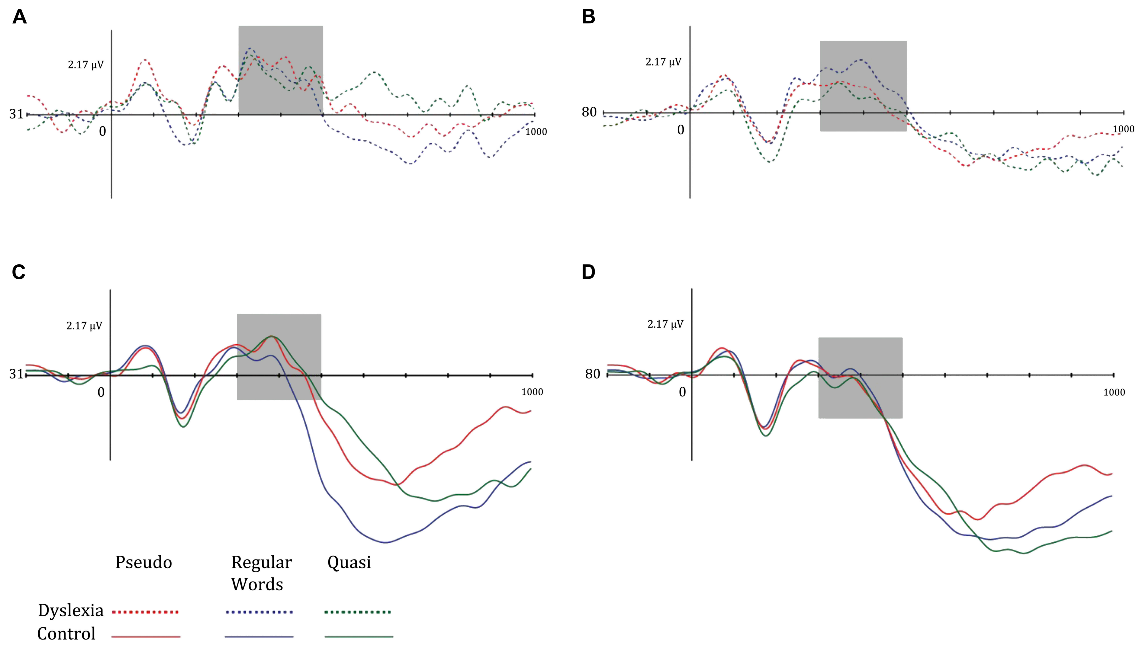

FIGURE 5
Mean amplitude of the left mid-parietal N400 component for **(A)** dyslexia group and left hemisphere, **(B)** dyslexia group and right hemisphere, **(C)** control group and left hemisphere, and **(D)** control group and right hemisphere. Dotted lines represent the dyslexia group, while solid lines represent the control group. Red-colored lines represent pseudo words, blue-colored lines represent regular words, and green-colored lines represent Quasi words.

and pseudowords, thus showing that the closer the proximity to the appropriate orthographic pattern, the greater the amplitude of the N170 component. This component is related to the initial recognition of linguistic stimuli, as well as differentiates orthographic stimuli from symbols and is related to the lexicality of the stimuli (Casaca, 2017). Even if we didn't find a lexicality effect, we can check that N170 is related with sensitive to spelling familiarity (Coch and Mitra, 2010), and involves lexical access (smaller range for unfamiliar words), in addition to indicating parallel processing between the visual recognition of words and access to their lexical representations (Araújo et al., 2015). The study by Casaca (2017) with adults who are good readers and speakers of Portuguese also found only a marginal effect in relation to the N170 component and lexicality effect. Therefore, this effect may be related to the processing of linguistic information from Portuguese, since for good readers the effect is not found either.

From this, dyslexics process orthographic information less efficiently and more slowly, with reduced activity in the left occipitotemporal region, which is responsible for orthographic identification and phonological integration. Thus, this information is not properly accessed (Savill and Thierry, 2011). Thus, this impairment of information processing and integration, which results in changes in the activity of the N170 as shown in this study, as well as difficulties in the judgment of words as found in the lexical decision test (LDT). From this, dyslexics present impairments in visual and phonological integration, as well as in lexical processing. These results also corroborate what was found by Mahé et al. (2012), who showed that dyslexics did not show a hemisphere effect in relation to the type of stimulus, as was observed in the control group.

Korinth et al. (2012), when analyzing the relationship of the N170 in readers with and without reading fluency problems, found that the ERP was higher for linguistic stimuli in the left hemisphere. Furthermore, there was a positive correlation between N170 and reading speed, as more fluent readers had a greater amplitude of N170 for linguistic stimuli. According to the authors, impairments in the analysis of physical structures of stimuli prevent further lexical processing, corroborating the findings of the present study, since dyslexics did not present the hemispheric specialization of N170 and seemed to process linguistic stimuli as distinct categories in the right hemisphere as a compensation mechanism.

Sensory deficits in perception and discrimination of the phonological characteristics of stimuli are observed in different languages, being these deficits considered universal (Goswami et al., 2011). Studies with different languages have shown changes in the N170 component (for review, see Premeti et al., 2022), so this deficit may be independent of linguistic regularity.

Data from N400 showed a hemispheric effect (p = 0,013) with greater amplitudes in left hemisphere in both groups. In the present study, we also found a general lexicality effect

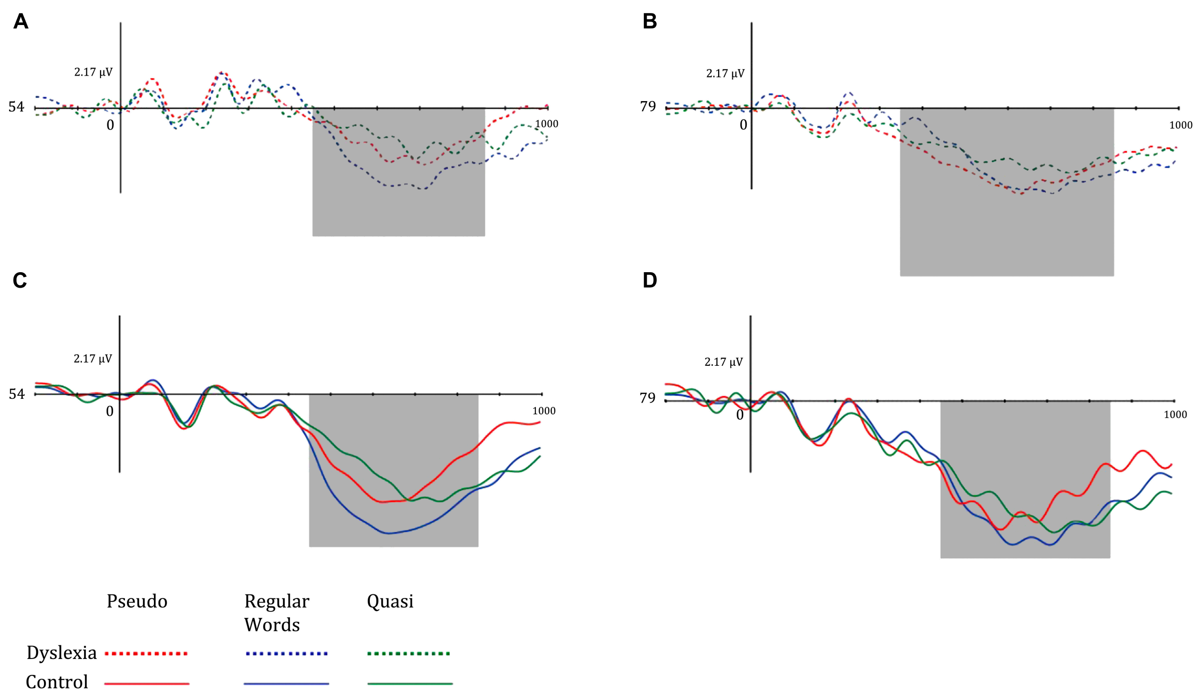

FIGURE 6
Mean amplitude of the left mid-parietal P600 component for **(A)** dyslexia group and left hemisphere, **(B)** dyslexia group and right hemisphere, **(C)** control group and left hemisphere, and **(D)** control group and right hemisphere. Dotted lines represent the dyslexia group, while solid lines represent the control group. Red-colored lines represent pseudo words, blue-colored lines represent regular words, and green-colored lines represent Quasi words.

(p = 0.029). Amplitude means from dyslexics were more negative in words, whereas in the controls, it was more pronounced in pseudowords. Studies with lexical decision tasks show that N400 is more negative for pseudowords than words, showing a lexicality effect, with an inverse effect on word frequency (Coch and Mitra, 2010; Berberyan et al., 2021). This effect occurs since the pseudowords do not have a lexical representation and therefore the lexical identification process requires additional effort, with the N400 being the initial process of the decision process and responsible for memory retrieval (Berberyan et al., 2021). This effect was observed only for the CG of the present study, and this result may show the semantic changes in word processing during the lexical decision. Shaul et al. (2012) also found a differentiated pattern of activation in relation to words and pseudowords derived from real words.

The N400 component is concerned with grapheme-phoneme conversion and lexical access, as well as lexical-semantic interpretation. Studies in different languages show mixed results regarding differences between dyslexic and good readers. The inconsistency in the results of this component may be related to several factors such as the task, type of stimulus, age of the participants, or reading difficulty (Premeti et al., 2022). Furthermore, since the N400 component is related to grapheme-phoneme and lexical-semantic and orthographic conversion processes, linguistic regularity can influence the mechanisms of linguistic information processing by dyslexic readers and good readers. The study by Lima (2008) discusses the importance of grapheme-phoneme conversion for an intermediate orthography such as Portuguese. The study sought to analyze the effect of grapheme-phoneme conversion on phonological processing from the effect of word and pseudoword stimulus extension. The results showed that this effect occurs depending on the task, reading aloud or lexical decision, and that in intermediate orthographies the modulation of extension effects is more apparent for Portuguese since grapheme-phoneme correspondence is used in tasks that the task presents phonological salience, however, it is not the exclusive strategy of phonological processing, being the lexical access also relevant in the processing of words. Thus, the activation of the N400 component is related to the relevant cognitive processes during the reading of words in Portuguese, which involves both grapheme-phoneme conversion and direct lexical access. Thus, different languages and linguistic regularities have different grapheme-phoneme conversion rules and, therefore, learning and reading difficulties are not the same (Carioti et al., 2021). Thus, the results of the present study may indicate that for Brazilian Portuguese, the processes of lexical access and grapheme-phoneme conversion shown in the behavioral results also reflect difficulties with brain functioning.

As seen in the N400 amplitude pattern, the P600 results also indicate a lexicality effect ($p = 0.019$) with greater amplitude for words, corroborating the literature (Berberyan et al., 2021). The greater amplitude for words is associated with word frequency and the semantic integration that occurs during lexical decision tasks (Berberyan et al., 2021). Grammatical violations cause semantic consequences that interfere with syntactic aspects of the language, which causes amplitude changes in N400, as well as changes in P600 due to the effect of sensitivity to syntactic changes (Kutas and Federmeier, 2011). The P600 results indicated greater amplitudes in the left hemisphere in both groups ($p < 0.001$) and smaller amplitudes in dyslexics, contrary to the results found by Cavalli et al. (2017), who found greater amplitudes in dyslexics and discussed these data considering compensatory mechanisms resulting from impairments in early word processing. Thus, dyslexics in the present study seem to require more time to process stimuli than in the study mentioned above, since they cannot process stimuli in the late time window. In addition, the DG showed longer reaction time and omission in behavioral data, indicating that they needed more time to process linguistic stimuli. readers access visual and auditory channels in parallel and process information from perceptual channels to linguistics in the left hemisphere. Dyslexics, on the other hand, do not have the characteristics of the words stored in the lexicon, and need to access visual patterns and later the auditory ones, with the visual information arriving late to auditory processing and the information being processed in the right hemisphere. Information processing in dyslexics is based on early processing in the right hemisphere (Shaul, 2013).

As the P600 is involved in the processing of items with linguistic incongruity or is related to the re-analysis of information (Savill and Thierry, 2011), it seems that the dyslexics in the present study are processing linguistic information still in a late time window (pseudowords with greater linguistic inconsistencies), while the controls re-evaluate the previously decided answer (greater for words). Thus, dyslexics do not show automaticity in reading words, and consequently have lower P600 amplitudes, as well as higher omission and reaction time rates. In addition, P600 has smaller amplitudes under task conditions that have greater uncertainty in stimulus assessment and categorization. Thus, in word recognition tasks, more familiar words may be more easily recognized and have greater P600 amplitudes (van Hees et al., 2017). Thus, when decisions are taken with absolute certainty, the P600 presents greater amplitude, which strengthens the above hypothesis and reaffirms uncertainty in the decision-making process of dyslexics when faced with linguistic stimuli.

From the results described above, cognitive and linguistic processing during decision tasks is altered in adult dyslexics both concerning behavioral and neurophysiological data. The linguistic regularity of Portuguese seems to have a distinct effect on neurophysiological processing and ERPs. However, the literature is scarce regarding the discussion regarding ERPs and different activation patterns compared in different orthographies. New studies need to be conducted with this objective. This study was not carried out without any limitations. One of them is the sample size. Since the total sample consists of 43 participants, this study can be low-powered. Thus, the findings presented in this study should be taken cautiously. Future studies should look into similar effects with a bigger sample to confirm them. A second limitation is that although no significant difference was found between the groups in the WAIS-III, Cohen's d was high, indicating a possible confounding effect.

Conclusion

It is concluded that there is a reorganization of brain activity in dyslexic adults, with a predominance of the right hemisphere and little differentiation between lexical categories and recognizable or unrecognizable linguistic stimuli. In addition, dyslexics have much slower word processing than good readers, in addition to having significant impairments since the beginning of written language processing in the brain. The linguistic regularity of Portuguese may have influenced the neurophysiological processing of reading, and further studies are needed seeking to identify the influence of orthography to differentiate readers and the distinct brain processing from that.

Data availability statement

The data supporting the conclusions of this article will be made available by the authors upon request, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Mackenzie Presbyterian University Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

Author contributions

PS and DO designed the study, collected the data, analyzed the data, and wrote the manuscript. AC wrote the manuscript. PL and PB analyzed the data and wrote the manuscript. EM designed the study, analyzed the data, and wrote and revised the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Visual attention span as a predictor of reading fluency and reading comprehension in Arabic

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Introduction: Visual attention span is a measure of multielement parallel processing. Individuals with higher visual attention span are expected to allocate more attention to letters within strings, which boosts letter identification and translates into more efficient reading. Given the high visual complexity of the Arabic writing system, we expected visual attention span to be an important predictor of reading in the Arabic language.

Methods: Native Arabic readers from Grade 4 and Grade 5 were recruited in Iraqi schools. We assessed the contribution of visual attention span to their reading fluency performance in tasks of fully vowelized word and pseudo-word reading, non-vowelized text reading, and written text comprehension. Their phonological awareness, IQ, and single letter processing speed were further evaluated.

Results: Results showed that visual attention span was a significant unique predictor of all the reading measures. Visual attention span and phonological awareness accounted for a similar amount of variance in word and pseudo-word reading fluency. Visual attention span was a far higher predictor than phonological awareness for text reading fluency and the sole predictor of text comprehension.

Discussion: The role of visual attention span to reading is discussed by reference to current word recognition models. Higher involvement of visual attention is expected in vowelized script to compensate for increased crowding in the presence of diacritics. Visual attention would thus contribute to sub-lexical orthographic parsing and favor orthography-to-phonology mapping, in particular for the pseudo-words that do not benefit from efficient lexical feedback. In non-vowelized script, higher visual attention would enhance the accurate and fast identification of root letters within words, thus resulting in faster word recognition.

KEYWORDS

Arabic reading, reading fluency and comprehension, visual attention span, phonological awareness, vowelized script, non-vowelized script

Introduction

There is growing evidence that phonological awareness (PA) and visual attention span (VAS) independently contribute to explain inter-individual variations in reading outcomes (Valdois et al., 2019a; Perry and Long, 2022). PA reflects the capacity to identify and manipulate phonological units (like phonemes, rimes, or syllables) within spoken words. Higher PA is expected to contribute to efficient orthography-to-phonology mapping at the sublexical level, which would promote novel word (or pseudo-word) decoding and contribute to word-specific orthographic knowledge acquisition for fast word recognition (Share, 1999; Ziegler et al., 2014; Castles et al., 2018; Pritchard et al., 2018). VAS is a measure of multi-element parallel processing skills in the visual modality. It is defined as the number of distinct elements that can be simultaneously processed in a visual array and depends on the amount of visual attention available for processing (Bosse et al., 2007; Frey and Bosse, 2018; Valdois, 2022). Higher VAS reflects the fact that a higher amount of visual attention capacity is deployed for letter identification within strings, leading to process more letters simultaneously. This ability is thought to support the processing of orthographic chunks as wholes, which boosts reading fluency (Lallier and Carreiras, 2018; Valdois et al., 2019a). Beyond PA, the involvement of VAS to reading has been mainly studied in Western European languages, thus in alphabetic languages that differ in orthographic transparency, but use a small inventory of relatively simple characters (mainly, Latin letters) to transcribe spoken words (Verhoeven and Perfetti, 2021). Modulation of reading performance by VAS might differ in the languages that use more complex written characters, and for which character identification is more attention-demanding. Recent studies have shown that VAS is predictive of reading in Chinese, a language that uses a large inventory of complex characters (Zhao et al., 2017, 2018; Huang et al., 2019; Chan and Yeung, 2020; Cheng et al., 2021). However, the concurrent involvement of PA was not examined in most of these studies and when it was, inconsistent findings were reported (Zhao et al., 2018; Cheng et al., 2021). The present study focuses on the Arabic language, a Semitic language that is particularly challenging for the visual system due to the high visual complexity of its characters and the use of a cursive script so that individual characters are not well segregated within words (Verhoeven and Perfetti, 2021). Our main purpose was to determine whether PA and VAS are concurrent predictors of reading fluency in Arabic and whether VAS might contribute to Arabic reading more substantially than PA, due to the visual complexity of its writing system.

The Arabic orthography

Arabic orthography is characterized by high visual complexity. First, many letters share the same basic shape and only differ by the number and location of dots associated with this basic shape (e.g., ت ث ب; Saiegh-Haddad and Henkin-Roitfarb, 2014). These letters are very similar graphically, which makes letter processing (i.e., letter detection, recognition, or identification) difficult, either presented in isolation or within strings (Ibrahim et al., 2002; Eviatar et al., 2004; Abdelhadi et al., 2011; Eviatar and Ibrahim, 2014). Second, Arabic is written in a cursive script, so that letters can ligate to the preceding or following letter. However, the combination of position and ligation changes the form of many letters. Thus, most Arabic letters change in shape depending on whether they appear at the beginning, middle, or end of a word. As a result, letter processing is a challenge for beginning, or even more advanced, native Arabic readers (Verhoeven and Perfetti, 2021).

Word recognition is also challenging for the visual system. Arabic words are composed of a root and a pattern morpheme. Roots are typically made of three consonants that convey the core meaning of the word, while patterns are primarily vocalic, corresponding to long vowels (sometimes augmented with certain consonants) that convey morphosyntactic and phonological information. Precise encoding of both the identity and relative position of root letters is critical for word processing in Arabic, as several different roots share the same letters but in a different order (Frost, 2012). The consonantal root letters combine with the word pattern to derive content words (verbs and nouns). However, morphology is non-concatenative. Arabic words are always composed by intertwining root-morphemes with word-pattern morphemes. For example, the three consonantal root-morpheme "k-t-b" when combined to the word-pattern "CaCiC" derives the word "katib" (writer) but combination with the pattern "maCCuuC" derives the word maktuub (written). Thus, word processing requires the orthographic processing system to pick up precise information on the identity and relative order of root letters that can be dispersed within the word in many different positions. This is particularly challenging for the visual system given that fast root processing is critical for efficient word recognition (Velan and Frost, 2011; Perea et al., 2014; Shalhoub-Awwad and Leikin, 2016).

Moreover, each word can be written using two orthographic versions of the Arabic script. In fully vowelized script, short vowels are indicated using diacritics that appear below or above the letters within the whole pattern of the written word. Indeed, the addition of vocalic patterns to the consonant letters of the root only provides partial phonological information on word pronunciation. Diacritics complement this information, yielding to infer a unique pronunciation of the written word. The vowelized script is mainly used in children books at the beginning of literacy instruction. In the non-vowelized script, diacritics are omitted, which inflates the number of homographs and makes decoding heavily dependent on context. The two scripts differently tax the cognitive system. In fully vowelized script, the use of diacritics is useful in facilitating phonological processing, but addition of the diacritic marks increases words' graphical complexity which additionally tax visual processing. Thus, the addition of short vowels enhances reading accuracy in beginning readers (Abu-Rabia, 1997, 2001) but further increases processing time (Roman and Pavard, 1987;

Saiegh-Haddad and Schiff, 2016). Faster reading is typically reported for non-vowelized words (Ibrahim, 2013; Taha, 2016; Abu-Liel et al., 2021) but efficient reading then relies on the processing of larger (morphological) units (Frost, 2005) and is more dependent on context (semantic and syntactic information).

The cognitive processes involved in reading

It is well established that learning to read builds upon PA (Ehri et al., 2001; Melby-Lervåg et al., 2012), and that PA is important for reading acquisition across languages (Caravolas et al., 2013; Moll et al., 2014). Although the vast majority of research on the role of PA on reading acquisition has been undertaken in Western European languages (Share, 2008), a growing number of studies supports the involvement of PA in reading in other language families (for a review in Chinese, see Song et al., 2016). With respect to the Arabic language, the PA-reading relationship was consistently reported in both vowelized and non-vowelized script (Abu-Rabia et al., 2003; Elbeheri and Everatt, 2007; Smythe et al., 2008; Taibah and Haynes, 2011; Farran et al., 2012; Abu Ahmad et al., 2014; Asaad and Eviatar, 2014; Ghanem and Kearns, 2015; Tibi and Kirby, 2018, 2019).

Beyond phonology, reading also involves visual mechanisms for the accurate identification of letters within strings. Current word recognition models make clear statements about the mechanisms at stake (Norris, 2013; Phénix et al., 2016). These models postulate a first level of visual feature detection for letter identification. The letters that share more visual features are more prone to be confused with one another, so that their accurate identification requires longer processing time. Successful letter identification is thus more demanding in languages, like Arabic, that use a set of visually complex letters, many of which share high visual similarity (Pelli et al., 2006; Boudelaa et al., 2020). Letter visibility within strings is further modulated by visual acuity (Nazir et al., 1991; Whitney, 2001) and lateral interference between letters, i.e., crowding (Pelli et al., 2007; Norris and Kinoshita, 2012). Letter identification decreases with eccentricity (i.e., distance of the letter from gaze position) due to the limits imposed by visual acuity. It is further affected by crowding effects, the fact that identification is degraded by the proximity of adjacent letters (Bouma, 1970; Martelli et al., 2009; Whitney and Levi, 2011). Although visual acuity is not sensitive to the orthographic system properties, crowding effects might be more detrimental in a language like Arabic, in which most letters are connected through ligature within words. Further, crowding might affect letter processing in vowelized script more than in non-vowelized script, due to the presence of additional diacritic marks (Hermena et al., 2015).

Finally, letter identification within strings is affected by visual attention (Lien et al., 2010; Waechter et al., 2011). Recent models of word recognition assume that visual attention acts as a filter that enhances letter identification under the attentional focus (Phénix et al., 2018; Ginestet et al., 2019; Valdois et al., 2021a). Visual attention is then conceived as a Gaussian distribution that deploys over the word letter string. The letters that receive more attention are more accurately and faster identified, which at least in part counter-balances the detrimental effects of poor letter discriminability, low visual acuity, and crowding. Thus, visual attention might be particularly relevant to explain inter-individual variability in learning to read in Arabic.

The measure of visual attention span (VAS) is typically used in behavioral studies to estimate the amount of visual attention available for letter string processing (Valdois, 2022). Children with higher VAS read more accurately and faster than children with lower VAS (Bosse et al., 2007; Bosse and Valdois, 2009; Zoubrinetzky et al., 2014, 2016; Valdois et al., 2021b) and VAS abilities measured prior to literacy instruction predict later reading skills (Valdois et al., 2019a). Significant involvement of VAS on reading has been reported in a variety of languages, like English (Bosse et al., 2007; Chen et al., 2016; Cirino et al., 2022), Brazilian Portuguese (Germano et al., 2014), Spanish (Lallier et al., 2014), Greek (Niolaki and Masterson, 2013), Dutch (van den Boer et al., 2013, 2014, 2015; Van den Boer and de Jong, 2018), or Chinese (Zhao et al., 2017, 2018; Chen et al., 2019; Huang et al., 2019; Cheng et al., 2021). Importantly, the contribution of VAS to reading achievement has been found independent of the effects of PA in both typical (Bosse and Valdois, 2009; van den Boer et al., 2013, 2015; Van den Boer and de Jong, 2018; Valdois et al., 2019a) and dyslexic/poor readers (Bosse et al., 2007; Germano et al., 2014; Zoubrinetzky et al., 2014, 2016; Chen et al., 2016; Valdois et al., 2021b). Evidence that VAS and PA are independent cognitive skills is further supported by neurobiological studies showing that VAS relies on the activation of brain regions, the superior parietal lobules, that belong to the dorsal attentional brain network and differ from those involved in PA and oral language tasks (Peyrin et al., 2011, 2012; Lobier et al., 2012a, 2014; Reilhac et al., 2013; Valdois et al., 2019b; see also Liu et al., 2022).

The few studies that investigated the VAS-reading relationship in Arabic readers reported modulations of VAS due to the Arabic orthography constraints and variations of the VAS-reading relationship depending on the Arabic script (Awadh et al., 2016; Lallier et al., 2018). Awadh et al. (2016) measured VAS abilities in highly educated Arabic, French, and Spanish adult readers through standard five-letter report tasks (Valdois, 2022). Despite matching for physical length (thus, visual acuity) and control for crowding, Arabic readers exhibited lower VAS than French or Spanish readers. This suggests that letter identification may be more attention demanding in Arabic, due to the visual complexity of letters, so that lesser letters would be simultaneously identified within strings. However, Awadh et al. (2016) reported no significant correlation between VAS performance and text reading fluency in their highly educated Arabic participants. Lallier et al. (2018) hypothesized that the VAS-reading relationship may vary depending on the Arabic script. They administered a visual one-back VAS task to Grade 4 native Arabic readers who were asked to read the same texts in either the vowelized and non-vowelized script. Results showed no relationship of VAS with text reading, whatever the script. However, a relationship emerged in the subgroup of Arabic children who were more proficient in non-vowelized than in vowelized text reading. Although the interpretation of these findings is not straightforward, they might suggest a higher development of VAS in children who are better at reading non-vowelized texts. Overall, only a couple of studies have investigated the potential contribution of VAS to reading performance in the Arabic language. The contribution of PA is more documented but no study explored the concurrent effects of PA and VAS on reading skills in Arabic.

The present study

Our aim in the current study was to examine the unique contribution of VAS to reading skills (word, pseudo-word, and text reading) in monolingual native Arabic children, after control of PA. We expected that variations in VAS would constrain the number of characters (letters and/or diacritics) that would be simultaneously identified within the written string, thus contributing to reading fluency, independently of PA. Although both PA and VAS were expected to relate to reading performance, we anticipated that the magnitude of the relationship would vary depending on the reading subskills and Arabic script. Assuming that pseudo-word reading relies more on phonological decoding than word (or text) processing and that PA is involved in the acquisition of mappings between sub-lexical orthographic and phonological units, we expected PA to contribute more to pseudo-word than word or text reading. In contrast, the reading of non-vowelized texts should rely more on lexical (morphological and semantic) knowledge through the processing of larger orthographic units, a condition that would be more demanding on VAS than PA skills. We further examined whether and to what extent VAS and PA predicted unique variance in non-vowelized text comprehension. Assuming that reading in non-vowelized script involves root morpheme identification for word core meaning processing and reliance on contextual information (thus relying on orthographic chunks); VAS was expected to further predict text comprehension while PA might less strongly contribute, if any.

Materials and methods

Participants

One hundred and thirty-four monolingual native Arabic speakers from Grade 4 and Grade 5 were recruited in six primary schools of the Babylon area in Iraq. In Iraqi schools, children are exposed to vowelized orthography during the first 2 years of literacy instruction. They are familiarized with the non-vowelized script in Grade 3 and almost exclusively confronted to non-vowelized materials in later grades. Thus, Grade 4–5 participants were expected to have good reading expertise in non-vowelized script while remaining sufficiently familiar with the vowelized script. Twenty outliers were detected using the Mahalanobis robust distance (Minimum Covariance Estimation; Leys et al., 2018), so that the sample size was reduced to 114 students (62 males). The participants had a mean age of 124 months (SD = 4 months). All of them had normal audition and normal or corrected-to-normal vision. They were reported to attend school regularly and had no history of neurological illness or brain damage. Their general cognitive abilities were tested by a fluid intelligence test, the Progressive Matrices Standard (version for Arab populations: Hammadi, 2012), showing a mean score of 26.82 (SD = 5.64). Official authorizations from the Iraqi ministry were obtained for experimentation at school together with written informed consent from each child legal guardians.

Measures

The test session included reading tasks of word and pseudo-word reading in vowelized script and tasks of non-vowelized text reading for the estimation of reading fluency and written text comprehension. Two phonological awareness tasks of rhyme judgment and phoneme deletion, and two VAS tasks of whole and partial letter report were further administered together with a control task of single letter identification threshold. All tasks were created for the experiment[1]. The children were tested individually in a quiet room of their school.

Reading assessment

Text reading

The children were asked to read aloud a text that was entitled: "The Beautiful Butterfly and the Little Child." The text was proofread by Iraqi linguists from al Qadisiyah University and the University of Babylon who checked that the language level used in the text was appropriate for fourth and fifth grade readers. The text consisted of 181 words, most of which were non-vowelized except for a few words which required diacritics to resolve semantic ambiguity. The text was presented in black on a white sheet accompanied by colored drawings. Participants were asked to read the text aloud as quickly and accurately as possible. Reading was stopped after 2 min or the reading time recorded if lower than 2 min. Text reading fluency was computed for each participant as the number of words accurately read per minute.

1 Unfortunately, Cronbach's alphas are not reported for the different tasks. By-item scores were lost due to technical problems preventing any measure of inter-item homogeneity.

Word reading

In the absence of resources on Arabic word frequency for children in Iraq, we created a database of the words which children were exposed to during the three first years of literacy instruction. The database provided the number of occurrences of each vowelized word together with their length. Forty vowelized words were selected that varied in length from 3 to 8 letters and were randomly chosen in the different quartiles of occurrence. The words had an average length of 5.05 letters (SD = 1.63) and included 2.3 (SD = 1.7) diacritics on average. They had an orthographic frequency of 145.20 per million on average, according to the ARALEX database (Boudelaa and Marslen-Wilson, 2010). The list of words is provided in Appendix. The words were presented listed in column, one word below the other, printed in black on a white sheet. The children were asked to read the words aloud as accurately and as quickly as possible. Reading time and reading accuracy were recorded. The number of words correctly read per minute was calculated for each participant.

Pseudo-word reading

A list of 20 pseudo-words was created for the purpose of the study. The pseudo-words were derived from real words by changing the location of two letters to construct a new pronounceable letter string that included at least one non-existing root or pattern (e.g., the pseudo-word وَلْصَنَا /wals'ana/was built from the word وَصَلْنَا/was'alna/). All pseudo-words were written with diacritics (i.e., vowelized). They had an average length of 5.10 (SD = 0.88) letters, ranging from 3 to 6 letters, and included 2.95 diacritics (SD = 0.78) on average. The pseudo-words were presented in column, one below the other, printed in black on a white sheet. The children were warned that the items to be read were invented words and they were asked to read them aloud as accurately and as quickly as possible. Pseudo-word reading fluency was computed for each participant as the number of pseudowords accurately read per minute.

Text reading comprehension

Three short stories were taken from websites offering stories for children. The texts written without diacritics were adapted to the comprehension level of 10–11 years-old students. They were submitted to specialists of the Arabic language to verify their relevance and linguistic integrity. The children were asked to read each text silently. Each text was followed by six questions and a multiple choice between four possible responses. The questions were of three types: (1) the easier ones required searching for a word or part of a sentence that was explicitly provided in the text (four questions for the first text, one question for the second and one for the third); (2) a second set of questions required making inferences from the text, thus relying on more in-depth analysis of the text meaning (one question for the first text, two for the second and three for the third); and (3) the third set required a good comprehension of the whole text making the child able to choose the title that best summarized the whole text meaning (one question for each text). The number of correct responses for the six questions of each of the three texts was recorded (max = 18).

Phonological awareness

The words used in the two phonological tasks were extracted from the children reading books. A composite score was created by addition of scores on the two phonological tasks (max = 31).

Rhyme oddity detection

At each trial, the participant heard three spoken words, all but one of which shared a common rhyme. The participant had to detect the odd word. For example, the child was asked which word was the odd one among "زين (zyn)-عين (Eyn)-بَزاز (bzAz)." (expected response: بَزاز/bzAz). All three words were short and of high frequency. The position of the odd word was randomly varied through the different trials. The 16 trials were preceded by four training trials for which children received feedback. The dependent variable was the number of odd words accurately identified (max = 16).

Phoneme deletion

A spoken word (5.8 phoneme-long on average, from 3-to-8 phonemes) was orally pronounced by the examiner followed by a phoneme. The child had to mentally remove the phoneme and respond saying what was left. For example, the child was asked: "What is أليفة (Alyfp), if you remove the/f/? The phoneme to be deleted was randomly located in the initial, medial, or final part of the word. Fifteen target words were presented, preceded by a six-word training session. The dependent variable was the number of correct responses (max = 15).

Assessment of visual attention span and single letter identification

Two tasks of whole and partial letter report were used to assess VAS abilities. A task of single letter identification threshold was further administered to control for single letter processing speed. The letter report tasks were displayed on a PC computer using E-prime software (E-prime Psychology Software Tools Inc., Pittsburgh, United States). A preliminary study carried out on an independent group of 15 participants revealed that their performance was very low when confronted to strings of five Arabic letters, the string length typically administered to evaluate VAS skills using Latin letters. As a result, and based on evidence that even adult skilled readers could only process an average of 3.68 out of five Arabic letters when briefly presented within VAS tasks (Awadh et al., 2016), the two tasks of whole and partial report were administered using strings of four Arabic letters.

Whole and partial report

Stimuli

Ten consonants were selected from the 28 letters of the Arabic alphabet (/ي/ه/ك/ط/ص/ف/ع/د/ح/ث). The set of consonants was chosen to include only one copy of each of the basic forms of

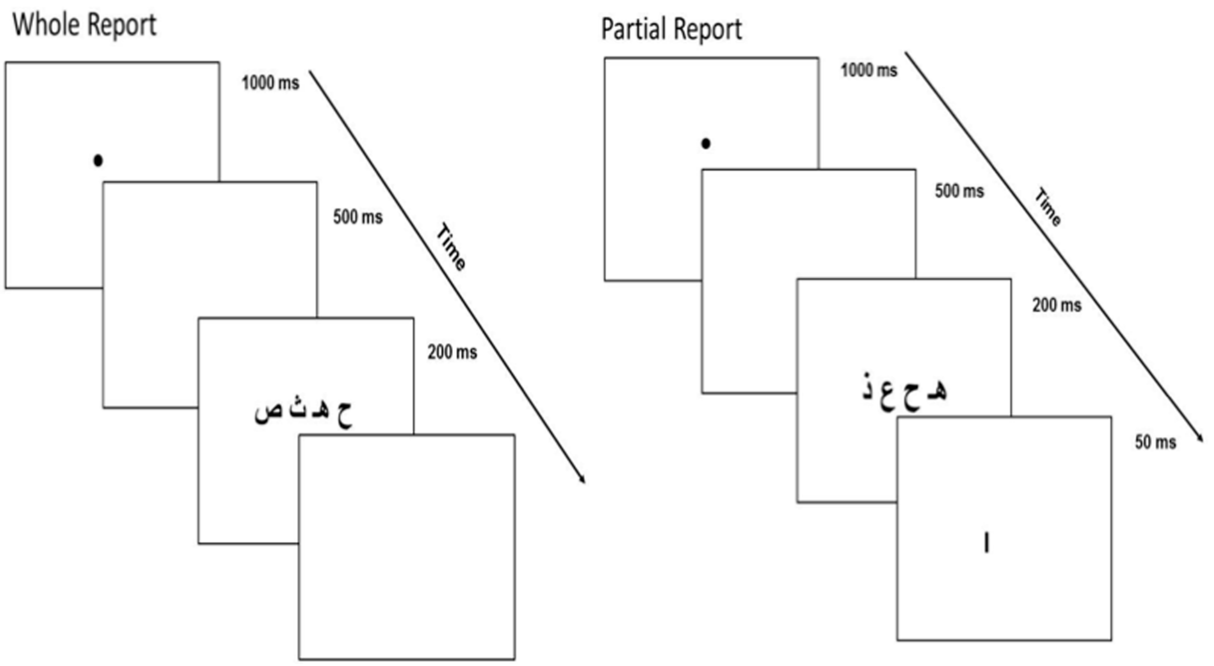

FIGURE 1
Illustration of the whole and partial report tasks using Arabic letters.

Arabic letters. Thus, only one of the letters that shared the same basic shape was selected (for example, we only selected the leftmost from the three following letters, ب, ت, ث). Random four letter-strings were then built up from the 10 consonants. The strings contained no repeated letters. The four-consonant strings never matched the root or the pattern of a real word. The letters were displayed in black on a white background. Each character string subtended an angle of 4.2° (7 mm high) with a distance of 0.57° between the edges of each character to minimize crowding effects. Twenty four-letter strings were displayed in the whole report condition, 40 in partial Report.

Procedure

At the beginning of each trial, a central fixation point was presented for 1,000 ms followed by a blank screen for 500 ms. Then, a letter-string was displayed centered on the fixation point for 200 ms, a presentation duration long enough for an extended glimpse, yet too short for a useful eye movement. In the whole report task, children had to report verbally as many letters as possible immediately at the offset of the string. In partial report, a vertical bar indicating the location of the letter to be reported was displayed 1.1° below the target letter, immediately after the letter-string disappeared. Participants were asked to report the cued letter only. In both tasks, the experimenter pressed a button to start the next trial after the participant's oral response. The experimental trials were preceded of 10 training trials for which participants received feedback. No feedback was given during the experimental trials. The dependent measure was the number of letters accurately reported (identity, not location) across the 20 trials in whole report (max = 80) or across the 40 trials in partial report (max = 40). To balance the contribution of each task, a VAS composite score (expressed as a percentage) was computed using the following relation: Composite $VAS_{score} = (Global_{score} + 2 \times Partial_{Score}) \times 100/2 \times 80$. An illustration of the global and partial report tasks is provided in Figure 1.

Letter identification processing efficiency

To control for single letter processing skills, each of the 10 letters used in the VAS report tasks were randomly presented (five times each) with the same physical characteristics as in the VAS tasks. Presentation duration was varied (33, 50, 67, 84, and 101 ms) so that each letter appeared once at each presentation duration. At the offset of the letter, a mask (13 mm high, 37 mm wide) was displayed for 150 ms. Participants were asked to name the letter immediately after its presentation. The test trials were preceded of 10 practice trials (two for each presentation duration) for which participants received feedback. The identification threshold was then calculated for each child as the minimum presentation duration that yielded at least 80% accurate identification.

Results

Descriptive statistics

Table 1 provides descriptive statistics of participants' performance for all the predictive variables and reading outcomes. Scores on reading fluency, VAS, and text comprehension were normally distributed. As shown on Table 1, raw scores on the

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TABLE 1 Means and standard deviations (SD), Median, Minimum (min), and Maximum (max) scores for the whole measures of IQ, single letter identification threshold, reading, phonological awareness (PA), and visual attention span (VAS).

	Mean	SD	Median	Min	Max
IQ	26.82	5.64	27.00	8.00	36.00
Identification threshold	94.50	21.31	97.50	52.00	133.00
Reading tasks					
Long words (wpm)	14.32	6.04	13.04	1.71	34.29
Short words (wpm)	17.44	6.50	15.48	6.36	38.71
Pseudo-words (wpm)	12.25	4.96	11.89	0.00	26.15
Text reading (wpm)	95.52	44.17	95.50	27.00	172.00
Text comprehension (/18)	14.20	2.87	14.00	8.00	18.00
Phonological awareness					
Phoneme deletion (/15)	13.17	2.48	14.00	5.00	15.00
Rhyme oddity (/16)	13.84	2.52	15.00	7.00	16.00
PA composite score	27.01	4.42	29.00	14.00	31.00
Visual attention span					
Whole report (/80)	60.61	9.39	62.00	40.00	79.00
Partial report (/40)	29.18	5.32	28.50	17.00	39.00
VAS composite score	89.79	13.67	92.00	57.00	114.00

phonological awareness tasks were relatively high, with a mean performance of 13.17 out of 15 on the phoneme deletion task and of 13.84 out of 16 on the rhyme oddity detection task. As the normality assumption was not verified on the measures of phonological awareness, the Yeo-Johnson transformation (Yeo and Johnson, 2000) was used to ensure symmetry of the distributions for these variables. On average, 60.61 letters were accurately reported in the whole report VAS task, suggesting that three out of the four letters were identified on average at each trial. The letter identification threshold measure showed that a presentation duration of 94.5 ms (ranging from 52 to 133 ms) on average was required for the accurate identification of at least 80% isolated letters.

Correlation analyses

Simple and partial correlation coefficients (after controlling for the effect of IQ) between all the measures are reported in Table 2. As shown on Table 2, all the measures corresponding to the same construct were positively and highly correlated (all $ps < 0.001$), suggesting good between-test reliability. Correlation coefficients close to 0.60 were found among the different reading tasks (from 0.58 to 0.62). The two measures of phonological awareness correlated at 0.57, thus justifying computation of a composite score as the sum of performance on the two tasks. In the same way, a composite weighted VAS score was computed from scores on the two tasks of whole and partial report that correlated at 0.69.

More interesting for the present purpose, the composite measures of VAS and PA correlated significantly with all the reading fluency measures, except for PA and text reading comprehension. Children with higher PA showed higher reading fluency; those with higher VAS exhibited better performance in both reading fluency and text comprehension. Moreover, as expected assuming that PA and VAS tap different cognitive skills, none of the VAS measures significantly correlated with any of the PA measures.

Regression analyses

Regression analyses were conducted to explore the unique contribution of VAS to reading fluency and text comprehension. We used the R stats package within the R environment (R core development team, 2020) for statistical computing to run linear regressions. Four regression models were computed, one for each of the reading outcomes, namely word and pseudo-word reading fluency, text reading fluency, and text comprehension. The effects of grade level (Grade 4 and Grade 5), IQ, and letter identification threshold were controlled for in all four models. Table 3 presents the unique contribution of VAS and PA (and the control variables) to the different reading outcomes.

The whole model accounted for 23.2 and 45.2% of variance, respectively, for word and pseudo-word reading fluency, 76.6% of variance in text reading fluency, and 20.1% in written text comprehension. As can be seen in Table 3, the unique contribution of VAS to reading fluency was significant for all tasks, showing that higher VAS was associated with more proficient reading fluency. VAS contribution was particularly high for text reading fluency, accounting for 60.6% of unique variance. For pseudo-word fluency, VAS accounted for 25% of variance, while its

TABLE 2 Pearson's correlation coefficients (above the diagonal) and partial correlations (below the diagonal) after control of IQ (adjusted using a Bonferroni correction).

	2	3	4	5	6	7	8	9	10	11	12
1. IQ	0.19	0.28	0.27	0.23	0.26	0.05	0.18	0.31	0.19	0.25	0.27
2. Word reading (wpm)	-	0.64***	0.60***	0.30	0.39**	0.24	0.36*	0.33*	0.49***	0.33	0.45***
3. PW reading (wpm)	0.62***	-	0.65***	0.30	0.54***	0.34*	0.50***	0.52***	0.59***	0.28	0.60***
4. Text reading (wpm)	0.58***	0.62***	-	0.52***	0.39**	0.37**	0.43***	0.79***	0.79***	0.52***	0.86***
5. Comprehension	0.26	0.25	0.49***	-	0.21	0.18	0.22	0.53***	0.31	0.22	0.45***
6. Phoneme omission	0.36**	0.50***	0.34*	0.16	-	0.56***	0.88***	0.20	0.33*	0.28	0.29
7. Rhyme judgment	0.24	0.34*	0.37**	0.17	0.57***	-	0.89***	0.27	0.29	0.26	0.30
8. Phono composite score	0.34*	0.47***	0.40**	0.19	0.88***	0.89***	-	0.26	0.35*	0.31	0.34*
9. VAS whole report	0.29	0.47***	0.78***	0.50***	0.12	0.27	0.22	-	0.70***	0.42***	0.91***
10. VAS partial report	0.47***	0.57***	0.78***	0.28	0.30	0.28	0.33*	0.69***	-	0.48***	0.93***
11. Identification threshold	0.29	0.23	0.49***	0.18	0.23	0.25	0.28	0.37**	0.45***	-	0.49***
12. VAS composite score	0.42***	0.57***	0.85***	0.41***	0.24	0.30	0.30	0.91***	0.93***	0.45***	-

***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

TABLE 3 Predictors of the reading outcomes.

Dependent variables	Word reading (wpm)			PW reading (pwpm)			Text reading (wpm)			Text comprehension		
Equation results:	$R = 0.266$; Adj.$R^2 = 0.232$; $F(5,108) = 7.828$***			$R = 0.477$; Adj.$R^2 = 0.452$; $F(5,108) = 19.680$***			$R = 0.776$; Adj.$R^2 = 0.765$; $F(5,108) = 74.7$***			$R = 0.236$; Adj.$R^2 = 0.201$; $F(5,108) = 6.67$***		
Predictors	β	t	ΔR^2	β	t	ΔR^2	β	t	ΔR^2	β	t	ΔR^2
Grade level	0.163	0.934	0.008	−0.057	−0.386	0.001	0.198	2.044	0.037*	0.300	1.680	0.025~
IQ	0.038	0.439	0.002	0.112	1.529	0.021	0.015	0.321	0.001	0.101	1.143	0.012
Identification threshold	0.110	1.123	0.115	−0.102	−1.226	0.014	0.125	2.291	0.046*	0.009	0.088	<0.001
PA composite score	0.206	2.293	0.046*	0.340	4.484	0.157***	0.124	2.505	0.055*	0.050	0.543	0.003
VAS composite score	0.293	2.882	0.071**	0.515	6.004	0.250***	0.724	12.888	0.606***	0.358	0.543	0.099***
Constant	−0.075	−0.652	-	0.026	0.269	-	−0.090	−1.427	-	−0.14	−1.172	-

***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

contribution was relatively low for word reading fluency (7.1% of explained variance). PA was another unique predictor of performance in word, pseudo-word and text reading fluency.

Visual attention span and PA contributed to explain a similar amount of variance in both pseudo-word (25 vs. 16%, $F_{(1, 108)} = 2.01$, $p = 0.160$) and word (7 vs. 5%, $F < 1$, ns) reading fluency. In contrast, the predictive power of VAS was stronger than that of PA in text reading fluency (60 vs. 6%, $F_{(1, 108)} = 54.96$, $p < 0.001$) and VAS was the sole predictor of text reading comprehension.

Discussion

The present study investigated VAS skills in native Arabic children to determine whether they uniquely influenced reading fluency and reading comprehension in Arabic. For this purpose, standard VAS tasks of whole and partial letter report were administered to Grade 4–5 native Arabic children; their reading skills were evaluated through tasks of single word, pseudo-word and text reading fluency, and a task of written text comprehension. The participants' ability to efficiently identify isolated letters was further estimated to control for potential effects of variations in single letter processing on the VAS-reading relationship. The overall findings argue for an independent influence of VAS in both reading fluency and reading comprehension. PA was an additional unique predictor of the reading fluency measures but did not influence reading comprehension.

The standard paradigms of whole and partial letter report were used to estimate VAS abilities but Latin letters were replaced by Arabic letters in the present study. In these tasks, performance primarily reflects the amount of visual attention available for multiletter parallel processing. Although standard paradigms require the verbal report of letter names, previous studies did not support a visual-to-phonological mapping account of VAS performance (for a review, see Valdois, 2022). Performance across VAS tasks is highly correlated either using verbal or non-verbal material (Lobier et al., 2012a; Chan and Yeung, 2020), and the same attentional brain regions are activated regardless of the verbal or non-verbal nature of the stimuli (Lobier et al., 2012b, 2014). Moreover, if phonologically-driven, VAS performance would likely relate to phonological skills, which was not previously reported (Valdois, 2022) and not found in the present study. Lexical effects on VAS performance are further prevented by the use of random consonant strings. In the VAS Arabic version, the strings did not include any existing root or pattern morpheme, so that letter identification did not benefit from lexical feedback but was mainly visually-driven. According to visual word recognition models, letter identification within string is modulated by visual acuity, crowding and the amount of visual attention available for processing. It is further dependent on letter discriminability (i.e., to what extent each target letter shares features with concurrent letters of the same alphabet). Inter-character spacing is systematically increased in VAS tasks to avoid crowding effects, so that inter-individual variations in performance cannot be attributed to differences in crowding. Visual acuity is expected to be constant, as far as strings do not vary in length and participants have normal or corrected vision. Thus, performance on VAS tasks mainly reflects how visual attention and letter discriminability interact for the accurate identification of letters within strings. Inter-individual differences in Arabic letter discriminability were estimated through the task of single letter identification threshold. Results showed high inter-individual variations in single letter processing skills. Furthermore, single letter identification efficiency correlated with performance on VAS tasks and text reading fluency. To zeroing on the impact of visual attention on reading, the VAS-reading relationship was studied while systematically controlling for inter-individual differences in single letter processing.

Current results showed that, beyond PA, VAS uniquely predicted Arabic word and pseudo-word reading fluency. This is well in line with evidence from European languages that VAS independently contributes to both word and pseudo-word reading (Bosse et al., 2007; Bosse and Valdois, 2009; Lallier et al., 2014; van den Boer et al., 2015; Valdois et al., 2019a, 2021a). An involvement of PA to Arabic word and pseudo-word reading was previously reported and PA is considered as a strong predictor of reading performance in Arabic (Saiegh-Haddad and Geva, 2008; Taibah and Haynes, 2011; Farran et al., 2012; Abu Ahmad et al., 2014; Tibi and Kirby, 2018, 2019). The present findings show that the contribution of VAS was equivalent to that of PA on the two measures of vowelized word and pseudo-word reading fluency. Reading single words and pseudo-words written in vowelized script relies on the mapping between sub-lexical orthographic and phonological units, in particular for pseudo-word processing that does not benefit from lexical feedback. Successful mapping is facilitated when sub-lexical phonological units are successfully identified within spoken words due to efficient PA skills. However, the contribution of VAS suggests that visual attention was involved in the successful identification of relevant orthographic units, in particular for pseudo-word processing. The processing of Arabic pseudo-words is particularly taxing for the visual system. In the absence of helpful lexical feedback, accurate letter identification almost exclusively relies on bottom-up sensory information. But extraction of letter identity sensory information is degraded due to high confusability between Arabic letters and increased crowding in the presence of diacritic marks. Moreover, efficient processing of the small superscripted marks that represent short vowels (i.e., the diacritics) is in particular critical for pseudo-word reading. The pronunciation of letters is ambiguous in the absence of diacritics, so that letters and diacritics have to be simultaneously processed for unambiguous orthography-to-phonology mapping. Visual attention is known to improve discriminability and accelerate information processing (Carrasco and McElree, 2001), two properties that would contribute to enhance letter and sublexical orthographic unit processing within strings. Previous findings suggested a contribution of VAS to graphemic parsing in European languages (Zoubrinetzky et al., 2014). More generally, VAS might be involved in the identification and segregation of relevant sub-lexical orthographic units for their mapping with phonology. It has been previously argued that individuals with higher visual attention resources would allocate more attention for the identification of visual characters (letters and diacritics) within letter strings. Assuming that a large amount of visual attention is required for in-depth identification of relevant information in visually complex and crowded environments, and assuming that a fixed amount of attention resources is available for processing, then available resources might only allow the accurate processing of a limited number of visual characters simultaneously, which would predict slow but accurate processing in vowelized script, as typically reported (Roman and Pavard, 1987; Abu-Rabia, 2001; Ibrahim, 2013; Saiegh-Haddad and Schiff, 2016).

The present study further revealed that VAS contributed to explain 60% of unique variance in text reading fluency while PA only moderately contributed. It is widely assumed that, in the absence of diacritics, reading is less reliant on phonological information but more on visual orthographic processing and whole-word recognition (Taouk and Coltheart, 2004; Hansen, 2014). Accurate and fast word recognition then implies fast processing of the consonants that form the root morpheme to favor matching with the corresponding orthographic word representation in long-term memory (Frost, 2005, 2012; Boudelaa, 2014; Perea et al., 2014; Shalhoub-Awwad and Leikin, 2016). One can easily infer that fast identification of root letters dispersed within the word letter-string requires deploying attention over the whole letter string to select relevant information. Individuals with higher visual attention resources (thus, higher VAS) are able to allocate enough attention to more letters within the word string. In non-vowelized Arabic script, this might contribute to accurate and fast identification of root letters among word patterns. Further, higher visual attention resources might favor letter information processing across multiple words in parallel in sentence reading (Snell and Grainger, 2019), which might trigger fast word recognition (Hermena et al., 2021; Khateb et al., 2022).

Last, the present findings argue for an exclusive influence of VAS on written text comprehension in Arabic, as previously reported for the English language (Chen et al., 2016). They are also in line with previous evidence for a non-significant influence of PA on text comprehension in the Arabic language (Elbeheri et al., 2011; Farran et al., 2012). We previously argued that word recognition in text reading was improved when a larger amount of visual attention was allocated to processing. Assuming that text reading comprehension is the product of word recognition and language comprehension (Gough and Tunmer, 1986; Duke and Cartwright, 2021), higher word recognition efficiency due to higher VAS might make more cognitive resources available to built-up and maintain a general model of text meaning. This would predict an indirect contribution of VAS to text reading comprehension. However, text reading comprehension mainly depends on high-level processing skills, like background knowledge and inferencing skills that were not considered in the present study.

Our main contribution in the current study was to provide first evidence that, above and beyond PA, VAS was a unique predictor of reading fluency in the Arabic language. We further argued that referring to theoretical models of word recognition is critical to disentangle the mechanisms involved in visuo-orthographic processing and that such models may be particularly relevant with respect to languages, like Arabic, that are particularly challenging for the visual system. The present findings also open new perspectives for future research. We found that VAS and PA equally accounted for single word and pseudo-word processing in vowelized script while VAS was a stronger predictor of reading fluency for texts written in non-vowelized script. Although some specific features of non-vowelized script may justify higher reliance on visual attention, strong conclusions would require a systematic manipulation of the two scripts. For this purpose, future studies should investigate the relative contribution of PA and VAS to reading performance for similar materials presented in either vowelized or non-vowelized script. The present study revealed only moderate contribution of PA to reading fluency after control of VAS in Grade 4–5 participants. However, PA may contribute more to reading in earlier grades. Investigation of the relative contribution of PA and VAS to reading on a large sample of grades would help better understanding the role of these two skills in reading development in Arabic. Last, the present study focused on PA and VAS as basic predictors of reading development. More research is required to better understanding how these two skills interact with the other predictors of the Arabic language, in particular morphological awareness and morphological processing skills.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Official authorizations from the Iraqi ministry. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

FA and SV contributed to the conception and design of the study. FA recruited the participants and collected the data. RZ organized the database. AZ performed the statistical analyses. FA, RZ, AZ, and SV wrote sections of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Handwriting fluency, latency, and kinematic in Portuguese writing system: Pilot study with school children from 3rd to 5th grade

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Studies have referred to the interaction between orthographic and motor aspects during the production of handwriting. However, studies with Brazilian Portuguese are still lacking. Hence, the aim of this study was to compare orthographic regularity, based on the Portuguese writing system, in high (HF) and low (LF) frequency words, in relation to latency and kinematic variables in students from the 3rd to the 5th grade of elementary school. This is a cross-sectional pilot study, with a convenience sample of 95 children participated in this study, from 3rd to 5th grade level attending a state elementary school. All were submitted to the following procedures of computerized evaluation of handwriting and submitted to the task of writing 15 HF and 15 LF words, selected according to the frequency criteria and classified according writing coding rule. Results indicated that for HF words, there was a decrease in writing and disfluencies production time, for all coding rules, from 3rd to 5th grade. However, for LF words, the more unpredictable orthographic affect production duration time, movement fluency, and students became more dependent on the use of gaze to check spelling aspects. This study revealed that lexical and sub-lexical activation affected motor production. For HF and LF words, lexical and sublexical process favored motor programming. However, for LF words, despite the maturation and school progression for the motor planes, there was an increase in latency time and in the need to search for word information, measured by the gaze variable for words with greater irregularity. This study has provided some evidence that linguistic variables such as orthographic regularity and word familiarity affect handwriting performance in Brazilian Portuguese written language.

KEYWORDS

learning, handwriting, academic competencies, evaluation, social vulnerability

1. Introduction

Learning to write is considered a linguistic skill that involves motor and orthographic aspects (Kandel and Perret, 2015a,b; Germano and Capellini, 2019). Recent models on the production of handwriting suggest that spelling processes modulate the timing of motor processes (Roux et al., 2013; Kandel and Perret, 2015a). Thus, for the authors, the central and peripheral processes interact during the production of handwriting, that is, there is a dynamic interaction between the processes, and the production of movement can be influenced by variables that regulate the orthographic process, such as frequency and lexicality (Roux et al., 2013). Ellis (1988) described that this is a cognitive neuropsychology approach, which central processes include semantic, syntactic and other sentence-level operations, along with those processes responsible for either retrieving from memory the spelling of a familiar word or assembling from sound a plausible spelling for an unfamiliar word or non-word. The end-product of these central processes is an abstract graphemic representation of words as letter strings. Peripheral writing processes translate that abstract graphemic representation into a range of possible output modes, including handwriting, typing, and spelling aloud.

In addition, central processes refer to spelling retrieval the activate information on the letter components of a word from orthographic long-term memory (Kandel et al., 2017). As mentioned by Purcell et al. (2011), spelling-specific central processes are usually identified as: orthographic long-term memory (the orthographic lexicon); phoneme–grapheme conversion; and orthographic working memory (the graphemic buffer). The authors also report that there is an interaction within the central processes, namely between the orthographic working and long-term memories and between the long-term orthographic memory and the phoneme-grapheme conversion.

The motor aspects of letter production are modulated by peripheral processes that regulate movement execution (Van Galen, 1991). However, Purcell et al. (2011) state that, in terms of peripheral processes, it is generally assumed that there are multiple stages involved in going from the abstract letter's representations in orthographic working memory to the correct ordering and execution of the effector-specific muscle movements required for expressing these letters. These peripheral processes generate written language in the major modalities of oral spelling, written spelling, or typing, i.e. peripheral processes of written language are involved in this spelling "format," including allographic or letter-shape conversion, motor plans for producing the letter forms, specifying size and ordering of the strokes (Ellis, 1988). These motor plans or graphic motor planning processes refer to an abstract representation of the movement that is then converted in motor commands that are specific for each end effector (for example, right or left hand, foot, etc.). As actions are encoded in the central nervous system in terms that are more abstract than commands to specific muscles, details of motor implementation, such as stroke size or speed, may be left unspecified until the effector is known. Once the effector is known, adjustment can then be made for effector-specific, indicating muscle activation patterns to accomplish letter size, and so on, given the specific writing context—are then generated and these, when executed, will result in the written trace (Wing, 2000). Furthermore, according with Marcelli et al. (2013), hypothesized that acquiring new motor skills requires two phases, in which two different processes occur, being during the early stage (spatial sequence is associated to the motor task in visual coordinates, i.e., the sequence of points to reach in order to generate the pencil trace) and during the late, i.e., automatic phase (sequence of motor commands in motor coordinates is acquired and comes to be executed as a single behavior).

Studies have demonstrated that writing can be produced by means of two separate routes, namely the lexical route and the sublexical route. In the lexical route, the orthographic form of the word is recovered as a whole from words stored in the long-term memory (Kandel and Valdois, 2006). Such lexical representations are influenced by the frequency of the words, in that the high-frequency words (HF) tend to be accessed with greater facility than the low-frequency words (LF; Bonin et al., 2016). The sublexical route applies the phonology-to-orthography conversion rules permitted by the language. This route is mostly used for the codification of non-familiar or non-words, although this route can also be used in parallel during the writing process (Coltheart and Rastle, 1994; Delattre et al., 2006; Afonso et al., 2018). It is important to highlight that both routes interact during the writing process, in that the information is manipulated and maintained in the orthographic working memory, in which the abstract graphemic units are maintained for subsequent production (Kandel et al., 2017; Afonso et al., 2020). In addition, Döhla et al. (2018) reported that during writing, working memory is important as it allows the maintaining and manipulating of phonological information in order to build orthographic representations of writing, from the establishment of the phoneme-grapheme conversion, linked with semantic information.

However, the interaction between spelling and motor processes can be restricted. Most grapho-motor gestures require extreme control and close sensory guidance (Mojet, 1991). Motor control is cognitively very demanding, as child concentrates on producing the correct shapes and connecting the letters between them. With practice there is a progressive learning of sensory-motor maps or motor programs (Teulings et al., 1983) that are stored in long-term memory. The use of this maps facilitates rapid access, diminishing use of sensory feedback and increases movement speed. This entails a long process that ends around 10–11 years old. At this period movement production is fast, implicit and automatic (Halsband and Lange, 2006). With neuro-motor maturation, grapho-motor skills become automatic (Van Galen et al., 1993) and children can use their cognitive resources for the other components of writing, such as spelling, sentence construction and text elaboration (Maggio et al., 2012; Pontart et al., 2013). The literature reports that the relation between the orthographic and motor aspects during the production of handwriting has been described in various languages with differing opacities and transparency; notably languages with greater opacity, such as French (Kandel and Perret, 2015a,b) and those with greater transparency such as Spanish (Afonso et al., 2015, 2018; Afonso and Álvarez, 2019). However, studies with Brazilian Portuguese are still lacking. The writing system for Brazilian Portuguese is characterized by orthography-to-phonology transparency for reading but is opaque in terms of writing (phonology-to-orthography opacity; Scliar-Cabral, 2003a,b). To be able to write the schoolchild needs to understand that the writing system comprises three types of relationships between the phonemes and graphemes of the alphabet. The first type of relationship is the biunivocal correspondence, consisting of the relationship between sounds and letters, or that is, the conversion of phonemes into graphemes independently from their context (regular words). The second type is the sound-letter relationship in which a letter represents various phonemes and also in which a phoneme can be represented by different graphemes according to their location within the word, or that is, there can be a certain predictability for conversion of phonemes into graphemes, depending on their position and/or their phonetic context (for example, the phoneme/k/can be written with the graphemes [c] or [qu]; irregular words). The third possibility for the type of relationship between phonemes and letters presents a situation of concurrence with a totally arbitrary relationship between the orthographic system and the phonological system, or that is, competing alternatives (for example, the phoneme/s/can be represented by the letters S/C/SS/SC/Ç/SÇ/XC). Regarding performance of children in coding writing, a greater difficulty is noted, since there are significant irregularities that need to be taught then systematized and memorized by children (irregular, and more unpredictable type of words; Scliar-Cabral, 2003a,b).

Roux et al. (2013) found that the syllabic position with the irregularity may affect triggering the production of writing, i.e., about the interaction between central and peripheral processing. The authors observed that if the orthographic irregularity is in the first syllable, the cascade effect is immediately performed. However, if it is second or final position of the word, the effect becomes permanent until the irregularity is achieved. In another words, Delattre et al. (2006) examined whether writing latencies and durations were affected by central processes at the lexical (word frequency) and sublexical levels (orthographic regularity). The cascaded view predicted that durations – which reflect peripheral processing – was affected by these variables because orthographic retrieval still operate after the initiation of the writing movements. The outputs are integrated either at the graphemic buffer, or at the grapheme level as claimed by recent implementations. With irregular words, if it is still not entirely solved when writing begins, it continues to be processed on-line, that is, until the irregular spelling conflict is resolved, regardless of syllable position in the word. This slows down the processing of the whole movement, increasing durations of irregular words with respect to regular ones. Thus, the authors concluded that both frequency and spelling regularity produce different effects of cascade, as verified by Roux et al. (2013). In this way, this study chose to verify kinematic variables and latency of HF and LF words, maintaining the activation of the same motor program (i.e., B). There was no comparation between HF and LF words because we would be talking about different activation processes, which was not the focus of this study.

In this way, it's expected that with automaticity, orthographic knowledge can be processed in parallel to movement production. Aspects such as frequency and orthographic regularity are related to the central process of writing production, since they can generate different kinematic processes [peripheral processes (Kandel and Perret, 2015a,b)].

Thus, this study is justified by the idea that writing fluency is an important aspect of writing development in the first grades so that other advanced skills can be achieved, such as text production. Kim et al. (2018) defined writing fluency as efficient and automatic writing connected texts, with accuracy, speed, and straightforwardness that is writing fluency is efficiency and automaticity in writing text. According to information processing theory (LaBerge and Samuels, 1974), fluency is a developmental phenomenon, spanning several stages, including sublexical, lexical, and text or speech levels, and lower-level fluency is necessary to achieve fluency at a higher level. Also, Berninger et al. (2008) emphasis the key role of handwriting automation in their Simple View of Writing model, highlighting the importance of efficient and fluent execution of lower-level processes in order to execute higher level metacognitive processes in composing a text. There are still no studies investigating this issue in Brazil, justifying this pilot study.

In this way, we seek to measure the latency time, related to the time the children needed to prepare the movements to start writing a word. We also tried to evaluate kinematic variables, such as movement duration and fluency. Thus, the aim of this study was to compare orthographic regularity, based on the Portuguese writing system, in HF and LF frequency words, in relation to latency and kinematic variables in students from the 3rd to the 5th grade of elementary school.

2. Materials and methods

This study was conducted following approval by the Research Ethics Committee of the Faculty of Philosophy and Sciences of São Paulo State University "Júlio de Mesquita Filho" (UNESP), Marilia, São Paulo, Brazil, under number CAAE: 87368618.4.0000.5406. All participants signed the Free and Informed Consent Form.

2.1. Participants

This is a cross-sectional pilot study carried out before the pandemic. A convenience sample of 95 children participated in this study, from 3rd to 5th grade level attending a state elementary school. There were 27 children attending 3rd grade (mean age: 8 years and 7 months; standard deviation: 2.54), 37 children attending 4th grade (mean age: 9 years and 3 months; standard deviation: 2.29) and 31 children attending 5th grade (mean age: 10 years and 9 months; standard deviation: 2.61). They were all right-handed, according to the motor assessment by Rosa Neto (2002) and native Brazilian speakers. The selection of participants for this study was realized by nonprobability convenience sampling, or that is, they were selected according to those who were available for the proposed evaluations twice per week. Participant recruitment and data collection took place over 2 months, in the second educational semester, from July and December 2018. After approval and consent by the school board, students were invited to participate in the study. Participation was confirmed after presentation of the Free and Informed Consent Form signed by the child's parent/guardian. The study protocol was approved by the Research Ethics Committee and all procedures followed the Helsinki Declaration. The inclusion criteria for the study were (a) ages 8–10 years-old and (b) teachers' observations of good academic performance. The exclusion criteria for the study were students (a) with sensory (auditory and/or visual), cognitive or physical deficits; (b) who did not complete at least 80% of the assessment; and (c) voluntary withdrawal.

2.2. Procedure

The children were evaluated individually, in 3 to 4 sessions, with a maximum duration of 30 min. Most students performed the writing of the HF word list in one session, and the LF list in another session, following that order. If there was any intercurrence, such as the student being called back to the classroom by the teacher, a new session (third or fourth) was used. The procedures were performed before the covid-19 pandemic, between July and December 2018. All were submitted to the following procedures of *Computerized evaluation of handwriting* (Ductus software®; Guinet and Kandel, 2010). To perform the procedures described below, a notebook computer was used (adapted version; Germano, 2018; Germano and Capellini, 2019) coupled to a digitizing table (Intuos Pro Wacom Pen and Touch Tablet). The stimuli were presented in the center of the notebook screen (written in capital letters – Times New Roman size 18). An auditory signal and a fixation point (duration of 100 ms) preceded the presentation of the stimuli. The stimulus remained on the screen until the student had finished writing the word. The student was instructed to write the word on the graphics tablet as soon as it appeared on the notebook screen. All student performance writing capital letters. This choice was made based on Brazilian Educational System, which is based on the current literacy curriculum approach, which is related to whole language. As mentioned by Germano and Capellini (2019) one aspect to be considered in the Brazilian context is the absence of systematic teaching of the movements of writing letters and the changes that occurred in the mid-1980s, when the teaching of the letter-writing movements was relegated to a secondary plane and the aspects of language were emphasized instead. They were submitted to the task of writing 15 HF (mean number of occurrences = 69; median = 58, range = 28–131) and 15 LF (mean number of occurrences = 1.0; median = 1, range = 1.0) frequency words, selected according to the frequency criteria (Germano, 2018; Table 1).

The words were taken from school vocabulary, composed of words extracted from Portuguese Language books from the 1st to the 5th grade level of Elementary Education of State of São Paulo (Germano and Capellini, 2011; Germano, 2018). Only disyllable nouns, of different syllabic complexities, regular and irregular words were included. The following classes of words were excluded: words in other languages, adverbs, adverbial phrases, prepositive phrases, adjectives, months of the year, numerals, augmentative or diminutive words, slang and words composed by juxtaposition words that present some diacritical signs and words with "ç." The list formed had words of different syllabic complexities, regular and irregular words, randomized by frequency. For both HF and LF words were classified according writing coding rule of, Scliar-Cabral (2003a,b), being 5 words classified as rule C1 (Conversion of phonemes to graphemes regardless of context – Phonographic conversion is not determined by position or phonetic context, that is, there is no restriction on the grapheme assignment in 12 phonemes – that is, each phoneme can be represented only by a single grapheme, being a univocal phoneme-grapheme correspondence, 5 words were classified as rule C2 (Conversion of phonemes to graphemes depending on position and/or phonetic context – Phonographic conversion, in these rules, depends on how the phonemes are pronounced, for the choice of letters or graphemes that will represent them) and 5 words as rule C3 (Competitive alternatives – there is competitiveness for the same phonetic context, it is necessary to

TABLE 1 Absolute number of occurrences of HF and LF words.

	HF	*N*	LF	*N*
C1	Pato/duck	109	Bolha/Bubble	1
	Olho/eye	58	Dama/lady	1
	Nome/Name	52	Mapa/map	1
	Velha/old	31	Moto/motorcycle	1
	Vida/life	33	Tipo/type	1
C2	Lobo/Wolf	131	Flora/flora	1
	Gato/cat	111	Regra/rule	1
	Tempo/time	60	Ruga/wrinkle	1
	Mundo/world	55	Saga/saga	1
	Cama/bed	51	Flanco/flank	1
C3	Casa/house	121	Chance/chance	1
	Coisa/thing	85	Classe/class	1
	Gente/people	76	Concha/shell	1
	Bruxa/witch	34	Xadrez/chess	1
	Bicho/animal	28	Chifre/horn	1
	Mean	69	Mean	1
	Median	58	Median	1
	N: absolute occurrence number			

have a metalinguistic knowledge, especially semantics and morphology, which can help in choosing the letter or grapheme that will represent it; words are dependent on orthographic lexical memory). We analyzed four measures, described below.

- Latency referred to the time between word presentation and the moment the child started to write (pen pressure > 0).
- A measure of "gaze" was used, that is, the moment when the child stop their handwriting to search/looks up at the screen to confirm the information about the words. The elevations of the gaze were considered as a "landmark of the event," being an option for the Researcher who can place a "mark" at any time on what the student produces. This marking was performed by the researcher by pressing the space key on the notebook keyboard, and later confirmed from the images recorded with a video camera, positioned so that it could capture eye movement.

Regarding information about kinematics aspects of motor production, we have measured movement duration and fluency:

- Writing word movement duration – referring the time the children took to write a complete word (summatory of each letter in a word, Movement duration – ms). The movement duration of a word was computed by summing up the time spent to draw each letter of the word, which was normalized with respect to the number of strokes that made up the letter, based on the criteria described in studies (Thibon, 2018; Thibon et al., 2018, 2019).
- Movement fluency is measured as the mean number of peaks of the absolute velocity profile per letter of a word. In particular, the total number of peaks is obtained by summing up the number of peaks counted in the absolute velocity profile of each letter of the word. For movement fluency, the sum was performed followed by the division of the number of letters, resulting in the average velocity of the word. It is noteworthy that the higher these values, the lower the movement fluency (disfluency; Lambert et al., 2011; Kandel and Perret, 2015a,b).

A stroke can be defined as a fundamental unit of handwriting movement, that is, a sequence of movement performed between two absolute velocity minima (Guinet and Kandel, 2010). For each letter, the calculation was considered from the contact of the pen on the digitizing table (pressure > 0), continuing until the end of the tracing (pressure = 0). We perform the calculation for each letter of each word, calculating the number of strokes presented in the segmentation of letters (Guinet and Kandel, 2010). So, we divided the values by the number of strokes in each letter, based on the criteria described in studies (Thibon, 2018; Thibon et al., 2018, 2019) for standardizing the difference in the types of strokes provided for in the different letters (for example the letter L has two strokes, while the letter B has five strokes).

2.3. Data analysis

We gathered, calculated, and presented descriptive statistics, including group means and standard deviations. Data analysis was performed with statistical analysis of the scores, using the SPSS (Statistical Package for Social Sciences) program. The ANOVA statistical test was used, verifying normal distribution with zero mean and constant variance per grade. A graphical analysis was also performed, and it was found that the data distribution of each measurement per grade is close to a normal distribution and that they have homoscedasticity. The value of $p < 0.05$ was considered significant and indicated by an asterisk (*).

3. Results

Table 2 shows the distribution of variables latency, movement duration, movement fluency and gaze in the comparison between groups for HF words.

Regarding the HF words, Table 2 indicated that there was a difference between the groups for the Latency variable in relation to the rule words C1 ("pato/duck," "velha/old," "vida/life"), C2 ("tempo/time" and "cama/bed") and C3 ("bruxa/witch" and "bicho/animal"). Regarding the movement duration, there was a difference between all the words from C1, to C2 (most, except the word "lobo/wolf"); and for C3 for the word "casa/house," "bruxa/witch" and "bicho/animal." Regarding the movement fluency, there was a difference for C1 for most words, except "pato/duck"; for C2 for all words; and for C3 for the word "casa/house," "gente/people," "bruxa/witch" and "bicho/animal." In relation to gaze, there was a difference for C1 ("velha/old") and C2 ("tempo/time"), with no difference for the words of C3. To better verify such differences, a comparison was made between the *p* values, in order to verify which groups presented the comparisons, based on Tukey's Multiple Comparison (*post hoc*; Table 3).

At Table 3, it was possible to observe that the difference was present in the comparison between 3rd and 5th grade students for the Latency variable, in relation to rules C1, C2 and C3. Regarding the movement duration, it was observed that there is a decrease in the duration time for the production of words, noticed between 3rd and 5th and 4th and 5th, for the words of C1, C2 and C3. For movement fluency, there is a decrease in disfluencies with the progression of schooling, especially for C1 words. Regarding the words C2 and C3, it was noted that there is a greater difference between 3rd and 5th grade students, suggesting that improved access to the motor and lexical plane for HF words occurs at the end of elementary school (5th grade level). Also, it is noted that the difference for the gaze variable occurred between students from 4th and 5th grade, as 4th grade students still needed to search for word's characteristic on the notebook's screen, suggesting that the orthographic lexicon was not formed for the words "velha/old" (C1) and "tempo/time" (C2). Despite being frequent words, the word "velha" (old) requires knowledge that a phoneme (/λ/) must be written by two letters (lh), while the word

TABLE 2 Comparison between the variables for groups for HF words.

Rule	Word	Group	Latency			Movement duration			Movement fluency			Gaze		
			Mean	SD	Value of *p*	Mean	SD	Value of *p*	Mean	SD	Value of *p*	Mean	SD	Value of *p*
C1	Pato/ duck	3rd	3,443	1916	0.005*	1,331	641	0.019*	8.13	4.44	0.085	0.148	0.362	0.066
		4th	2,249	848		1,283	449		7.48	2.53		0.054	0.229	
		5th	2,310	1760		983	453		6.2	3.15		0	0	
	Olho/eye	3rd	2,413	1,181	0.145	1,360	884	0.014*	8.76	6.14	0.002*	0.111	0.32	0.171
		4th	1988	703		1,216	390		7.5	2.36		0.054	0.229	
		5th	1977	989		931	324		5.31	1.83		0	0	
	Nome/ Name	3rd	2,360	1,372	0.13	1,160	593	0.002*	6.92	3.95	0.006*	0.111	0.32	0.171
		4th	1934	854		1,018	451		6.22	2.3		0.054	0.229	
		5th	1886	609		749	208		4.76	0.85		0	0	
	Velha/ old	3rd	2,590	936	0.012*	1,336	502	0.003*	7.13	2.54	0.005*	0.111	0.32	0.04*
		4th	2006	1,234		1.262	414		6.8	1.83		0.189	0.397	
		5th	1821	658		990	254		5.6	1.02		0	0	
	Vida/life	3rd	2,529	1,404	0.028*	1,405	814	0.009*	7.4	4.21	0.017*	0.037	0.192	0.287
		4th	1978	897		1,149	482		6.29	3.05		0	0	
		5th	1777	943		946	278		5.07	1.36		0	0	
C2	Lobo/ Wolf	3rd	3,398	2,199	0.417	9,695	4,843	0.46	9.36	1.44	0.001*	0.037	0.192	0.256
		4th	3,496	2,482		8,977	2,960		2.9	1.22		0.081	0.277	
		5th	2,854	1,320		8,451	3,597		2.37	1.62		0	0	
	Gato/cat	3rd	2099	762	0.191	1,417	591	<0.001*	8.64	3.4	<0.001*	0.037	0.192	0.287
		4th	1806	1,001		1,105	402		6.82	2.56		0	0	
		5th	1715	624		844	195		5.34	0.91		0	0	
	Tempo/ time	3rd	2,418	1,258	0.021*	1,313	618	0.004*	8.19	3.72	0.006*	0.222	0.424	0.022*
		4th	2008	1,196		1,161	406		6.88	1.53		0.108	0.315	
		5th	1,616	653		927	225		6.24	1.11		0	0	
	Mundo/ world	3rd	2,687	1,289	0.112	1,195	714	0.005*	7.53	5.16	0.029*	0.074	0.267	0.107
		4th	2004	1,108		1,130	535		6.96	2.96		0.135	0.347	
		5th	2,107	1,599		784	189		5.27	0.84		0	0	
	Cama/ bed	3rd	2,956	1,574	0.007*	925	427	0.001*	5.94	2.58	0.007*	0.074	0.267	0.275
		4th	2,387	1896		1,026	360		6.17	1.65		0.027	0.164	
		5th	1,643	926		710	176		4.81	0.89		0	0	
C3	Casa/ house	3rd	2,666	1798	0.995	1,067	567	0.007*	6.72	3.94	0.019*	0.037	0.192	0.595
		4th	2,676	1975		1.054	382		6.63	2.47		0.027	0.164	
		5th	2,712	1,600		770	246		4.96	1.35		0	0	
	Coisa/ thing	3rd	2024	1,304	0.998	1,358	717	0.082	8.3	4.44	0.248	0.185	0.396	0.095
		4th	2014	1,025		1,223	455		7.86	2.91		0.108	0.393	
		5th	2032	1,279		1,021	557		6.77	3.57		0	0	
	Gente/ people	3rd	1847	1,314	0.412	1,202	771	0.175	7.42	144.33	0.002*	0.222	0.424	0.064
		4th	2,216	1,207		1,145	469		7.18	1.9		0.054	0.229	
		5th	1921	1,051		939	475		6.39	2.56		0.065	0.25	
	Bruxa/ witch	3rd	2,374	857	0.012*	1,263	602	0.001*	7.84	3.47	0.001*	0.111	0.32	0.171
		4th	1946	948		1,118	388		6.71	1.68		0.054	0.229	
		5th	1,650	892		853	195		5.56	0.81		0	0	

(Continued)

TABLE 2 (Continued)

Rule	Word	Group	Latency			Movement duration			Movement fluency			Gaze		
			Mean	SD	Value of *p*	Mean	SD	Value of *p*	Mean	SD	Value of *p*	Mean	SD	Value of *p*
	Bicho/ animal	3rd	3,157	2,608	0.003*	1,369	747	0.012*	8.15	4.67	0.013*	0.148	0.362	0.101
		4th	2071	909		1,222	545		7.34	3.32		0.027	0.164	
		5th	1786	737		948	221		5.63	1.11		0.032	0.18	

Anova test (*$p < 0.05$).

TABLE 3 Comparison of *p* values for variables between groups for HF words.

Rule	Word	Group	Latency		Movement duration		Movement fluency		Gaze	
			3rd	4th	3rd	4th	3rd	4th	3rd	4th
C1	Pato/duck	4th	0.007*		0.925		0.728		0.273	
		5th	0.016*	0.985	0.03*	0.047*	0.08	0.265	0.055	0.626
	Olho/eye	4th	0.188		0.571		0.38		0.571	
		5th	0.196	0.999	0.013*	0.097	0.002*	0.047*	0.146	0.58
	Nome/Name	4th	0.196		0.413		0.542		0.571	
		5th	0.157	0.978	0.002*	0.036*	0.006*	0.057	0.146	0.58
	Velha/old	4th	0.057		0.742		0.757		0.563	
		5th	0.011*	0.725	0.004*	0.017*	0.006*	0.026*	0.344	0.03*
	Vida/life	4th	0.113		0.165		0.323		0.33	
		5th	0.026*	0.727	0.006*	0.287	0.013*	0.232	0.358	1
C2	Lobo/Wolf	4th	0.981		0.734		0.004*		0.663	
		5th	0.585	0.419	0.427	0.835	0.002*	0.958	0.764	0.228
	Gato/cat	4th	0.344		0.011*		0.012*		0.33	
		5th	0.187	0.894	<0.001*	0.032*	<0.001*	0.042*	0.358	1
	Tempo/time	4th	0.29		0.355		0.066		0.292	
		5th	0.015*	0.293	0.003*	0.075	0.005*	0.488	0.016	0.303
	Mundo/ world	4th	0.112		0.876		0.78		0.622	
		5th	0.23	0.946	0.009*	0.02*	0.032*	0.102	0.525	0.087
	Cama/bed	4th	0.318		0.459		0.867		0.541	
		5th	0.005*	0.123	0.044*	0.001*	0.049*	0.007*	0.248	0.802
C3	Casa/house	4th	1		0.992		0.989		0.96	
		5th	0.995	0.996	0.019*	0.015*	0.041*	0.036*	0.598	0.725
	Coisa/thing	4th	0.999		0.624		0.882		0.616	
		5th	1	0.998	0.07	0.319	0.248	0.433	0.081	0.36
	Gente/people	4th	0.441		0.918		0.004*		0.077	
		5th	0.97	0.566	0.192	0.304	0.006*	0.999	0.123	0.989
	Bruxa/witch	4th	0.153		0.356		0.103		0.571	
		5th	0.009*	0.375	0.001*	0.028*	<0.001*	0.082	0.146	0.58
	Bicho/animal	4th	0.019*		0.531		0.599		0.122	
		5th	0.003*	0.733	0.01*	0.097	0.013*	0.089	0.167	0.996

Anova test, Tukey's multiple comparison (*post hoc*; *$p < 0.05$).

"tempo" (time) requires knowledge of the rule code |C2.16.2|, which indicates that the use of m (before/p/and/b/) or the letter n (before other consonants) as nasalization marks in the conversion of nasalized vowels at the end of syllables internal. Brazilian study has indicated such difficulties present in schoolchildren due to the lack of systematic teaching of the phoneme-grapheme conversion mechanism and the explicit explanation of spelling rules at school (Chiaramonte and Capellini, 2022). Table 4 shows the distribution of latency variables, writing duration movement, writing fluency movement and gaze in the comparison between groups for LF.

In Table 4, regarding the LF words, we noticed that there was a difference between the groups for the variable Latency for the words of C1 ("bolha/bubble"; "tipo/type"); C2 ("flora/flora"; "ruga/wrinkle"; "saga/saga"; "flanco/flank"); and for C3 ("xadrez/chess"). There was also a difference for the movement duration variable for C1 words ("moto/motorcycle"; "tipo/type"); for all words in C2 and C3. For the variable movement fluency, there was no difference for the words of C1; there was a difference for most of the words in C2 (except "saga/saga "); and for all C3 words (except "xadrez/chess" and "chifre/horn"). For the gaze variable, there was no difference for words C1 and C2 words; and the words of C3 ("classe/class"; "concha/shell"; "chifre/horn "). To better verify such differences, a comparison was made between the *p* values, in order to verify which groups presented the comparisons, based on Tukey's Multiple Comparison (*post hoc*; Table 5).

Table 5 indicated that, for the latency variable, there was a difference between 3rd and 4th, and between 3rd and 5th grade for words from C1 and C2, suggesting improvement in the phoneme-grapheme conversion mechanism for words that are independent of the context – that is, regardless of the spelling context, there is only one phoneme-grapheme relationship (rule C1) and those dependent of context (rule C2). However, for words from C3, only the word "xadrez/chess" showed a difference between 3rd and 5th grade, while the other words do not present differences regarding latency time. These findings suggest that for C3, the opacity of words implies a failure in access to orthographic lexicon and, consequently, delay to start the motor act of handwriting. Regarding the movement duration and Movement fluency variables, for the words from C2, it was noted that there was a difference between the 3rd and 5th and between 4th and 5th grade, suggesting a decrease in writing production time and disfluency, according to the advance in the school grade levels. These findings indicated that for C2, reading and writing practices may have influenced the development of the orthographic lexicon. For the words of C3, there was a difference for the Movement Duration and Movement fluency variables in the comparison between 3rd and 5th grade. There was also a difference for gaze variable. These findings suggest that there was a difficulty in formation of the orthographic lexicon for C3 words, considering that the student performed pauses to seek visual information of the word through gaze.

A comparison was made between the HF and LF words considering each writing coding rule. Although, word activation can experiment with different motor programs, it was possible to observe that there is a difference between the values, indicating that the students had greater difficulties in the words of LF (Table 6).

In Table 6, we note that for the C1 rule words, there was a significant difference between the HF and LF words for comparisons of duration and fluency, with a lower value being observed for the HF words. It was also observed that there was no difference between HF and LF for the gaze and latency variables, suggesting that regularity (rule C1) favored access to the lexicon for both HF and LF words.

As for the C2 rule words, there was a significant difference for the comparisons of duration between the HF-LF pairs ("lobo/wolf"-"flora/flora"; "gato/cat"-"regra/rule"; "tempo/time"-"ruga/wrinkle") and for fluency between the HF-LF pairs ("lobo/wolf"-"flora/flora"; "gato/cat"; "mundo/world"-"saga/saga"), with a lower value being observed for the words of HF. It was also observed that there was a difference between HF and LF for gaze ("lobo/wolf"-"flora/flora") and latency ("gato/cat"-"regra/rule") variables. These findings suggest that both regularity and word frequency impacted movement. As for the C3 rule words, there was a significant difference for comparisons of duration between HF-LF pairs ("casa/house"- "chance/chance"; "bruxa/witch"-"xadrez/chess") and for fluency between HF-LF pairs ("casa/house"-"chance/chance"; "bruxa/witch"-"xadrez/chess"; "bicho/animal"-"chifre/horn"). It was also observed that there was a difference between HF and LF for gaze variables ("casa/house"-"chance/chance"; "coisa/thing"-"classe/class"; "bruxa/witch" –"xadrez/chess"; "bicho/animal"- "chifre/horn") and latency ("gato/cat"- "regra/rule"). There was no difference between latency values. These results suggest that increasing word complexity (C3 rules) impacted movement variables, but also increased the need to search for confirmation of how the word was spelled (gaze).

4. Discussion

This study presented an evaluation of the parameters of fluency and duration of movement, and latency time. There are no Brazilian studies with these measures, using technologies tool's assessment. We chose to evaluate the variables separately considering the frequency of words, being for HF and LF words. Comparisons were performed within each coding rule of the Brazilian Portuguese writing system. Such procedures were taken in order to avoid different types of cascaded effects, as mentioned by Roux et al. (2013). The findings of this study indicated that there was a decrease in movement duration and movement fluency from 3rd to 5th grade for HF and LF words. Although these processes did not occur in the same way. Orthographic aspects had influenced the performance of kinematic variables. This can be noticed when we observe the difference performance for coding rules for HF and LF.

For HF words, there was a decrease in movement duration and movement fluency, for all coding rule (C1, C2 and C3), suggesting an improvement in the use of motor planes combined with the formation of orthographic lexicon. We can say that there was an influence of effect for HF words, which influenced performance, as they improved progressively from 3rd to 5th, since the increased exposure to words favored the establishment of the phoneme-grapheme relationship. International studies of

TABLE 4 Comparison between the variables for groups for LF words.

Rule	Word	group	Latency (ms)			Movement duration			Movement fluency			Gaze		
			Mean	SD	Value of *p*	Mean	SD	Value of *p*	Mean	SD	Value of *p*	Mean	SD	Value of *p*
C1	Bolha/ Bubble	3rd	3,707	2025	<0.001*	1,206	607	0.493	7.38	2.76	0.318	0.148	0.362	0.209
		4th	2,285	1,355		1,149	342		6.98	1.27		0.054	0.229	
		5th	1987	918		1,066	405		6.55	2.19		0.032	0.18	
	Dama/lady	3rd	2004	1,113	0.441	869	437	0.073	5.27	1.73	0.299	0.074	0.267	0.275
		4th	2,266	1754		879	367		5.28	1.51		0.027	0.164	
		5th	1829	1,168		702	173		4.79	0.86		0	0	
	Mapa/map	3rd	2,364	1,406	0.062	883	376	0.093	5.44	1.8	0.282	0.111	0.32	0.088
		4th	1919	909		889	338		5.51	1.59		0	0	
		5th	1728	746		728	264		4.96	1.04		0.032	0.18	
	Moto/ motorcycle	3rd	2,168	951	0.271	1,016	538	0.035*	6.45	2.87	0.055	0.074	0.267	0.077
		4th	2011	958		1,015	593		6.62	3.27		0	0	
		5th	1785	784		738	184		5.16	1		0	0	
	Tipo/type	3rd	2,749	1,364	<0.001*	1,011	347	0.187	2.54	2.38	0.218	0	0	0.124
		4th	1700	736		971	215		2.54	1.21		0	0	
		5th	1700	820		892	188		2.54	1.19		0.065	0.25	
C2	Flora/flora	3rd	3,465	2,251	<0.001*	1,104	437	0.006*	7.08	2.08	0.006*	0.222	0.506	0.096
		4th	1961	768		1,178	493		7.3	2.25		0.243	0.495	
		5th	2077	1,279		865	193		5.87	0.94		0.032	0.18	
	Regra/rule	3rd	2,533	1703	0.233	1,080	494	0.002*	7.03	2.48	0.013*	0.074	0.267	0.186
		4th	2,155	951		1,080	381		6.94	2.01		0.108	0.315	
		5th	1989	1,003		792	161		5.72	0.99		0	0	
	Ruga/ wrinkle	3rd	3,060	2,269	0.001*	974	450	0.034*	6.21	2.53	0.02*	0.074	0.267	0.104
		4th	2,110	1,099		932	379		5.89	2.2		0.162	0.442	
		5th	1,560	630		745	216		4.8	1.01		0	0	
	Saga/saga	3rd	2,494	1,180	0.019*	820	249	0.01*	5.3	1.38	0.073	0.037	0.192	0.595
		4th	1922	681		877	325		5.48	1.49		0.027	0.164	
		5th	1891	833		685	143		4.77	0.81		0	0	
	Flanco/ flank	3rd	3,649	2,312	0.032*	1,398	558	0.021*	8.4	2.92	0.038*	0.556	0.698	0.908
		4th	2,793	2058		1,389	492		8.17	2.06		0.486	0.768	
		5th	2,324	1,150		1,098	360		7.05	1.35		0.484	0.626	
C3	Chance/ chance	3rd	2,680	1,488	0.217	1,429	761	0.005*	9.22	4.76	0.005*	0.667	0.62	0.053
		4th	2,304	1,147		1,228	471		7.77	2.47		0.324	0.475	
		5th	2,144	883		976	227		6.5	1.27		0.484	0.57	
	Classe/ class	3rd	2,752	1,512	0.139	1,361	804	0.003*	8.81	4.47	0.002*	0.63	0.492	0.004*
		4th	2061	1,013		1,110	255		7.32	1.24		0.324	0.475	
		5th	2,298	1,586		927	234		6.32	1.25		0.226	0.425	
	Concha/ shell	3rd	2,420	1,682	0.216	1,379	804	0.012*	8.62	4.7	0.045*	0.481	0.509	0.002*
		4th	2,714	1784		1,129	301		7.64	1.9		0.162	0.442	
		5th	2040	1,125		991	239		6.69	1.53		0.097	0.301	
	Xadrez/ chess	3rd	2,928	2,563	0.043*	1,356	582	0.013*	8.2	3.6	0.065	0.778	0.641	0.056
		4th	2,165	935		1,176	466		7.79	2.57		0.541	0.558	
		5th	1917	842		1,008	189		6.69	0.9		0.419	0.502	

(Continued)

TABLE 4 (Continued)

Rule	Word	group	Latency (ms)			Movement duration			Movement fluency			Gaze		
			Mean	SD	Value of *p*	Mean	SD	Value of *p*	Mean	SD	Value of *p*	Mean	SD	Value of *p*
	Chifre/ horn	3rd	2,341	1,496	0.648	1,535	717	0.047*	9.06	3.79	0.086	0.63	0.688	0.014*
		4th	2065	970		1,355	490		7.77	1.72		0.216	0.479	
		5th	2,243	1,175		1,188	331		7.78	1.84		0.355	0.486	

Anova test (*$p < 0.05$).

TABLE 5 Comparison of *p* values for variables between groups for LF words.

	Word	Group	Latency		Movement duration		Movement fluency		Gaze	
			3rd	4th	3rd	4th	3rd	4th	3rd	4th
C1	Bolha/Bubble	4th	0.001*		0.869		0.736		0.333	
		5th	<0.001*	0.684	0.468	0.734	0.287	0.663	0.216	0.937
	Tipo/type	4th	<0.001*		0.807		0.323		1	
		5th	<0.001*	1	0.177	0.404	0.234	0.96	0.204	0.157
C2	Flora/flora	4th	<0.001*		0.744		0.89		0.979	
		5th	0.002*	0.945	0.066	0.005*	0.043*	0.007*	0.208	0.106
	Regra/rule	4th	0.445		1		0.979		0.845	
		5th	0.215	0.843	0.01*	0.005*	0.029*	0.028*	0.48	0.166
	Ruga/wrinkle	4th	0.028*		0.892		0.812		0.504	
		5th	<0.001*	0.263	0.045*	0.086	0.024*	0.07	0.638	0.087
	Saga/saga	4th	0.035*		0.656		0.84		0.96	
		5th	0.032*	0.989	0.118	0.008*	0.268	0.065	0.598	0.725
	Flanco/flank	4th	0.181		0.997		0.901		0.921	
		5th	0.025*	0.57	0.048*	0.036*	0.05	0.091	0.921	1
C3	Chance/ chance	4th	0.422		0.28		0.153		0.042*	
		5th	0.202	0.844	0.004*	0.118	0.003*	0.208	0.42	0.462
	Classe/class	4th	0.118		0.098		0.064		0.029*	
		5th	0.421	0.756	0.002*	0.259	0.001*	0.261	0.004*	0.659
	Concha/shell	4th	0.741		0.111		0.377		0.01*	
		5th	0.628	0.187	0.009*	0.476	0.035*	0.377	0.002*	0.801
	Xadrez/chess	4th	0.135		0.241		0.8		0.227	
		5th	0.041*	0.792	0.009*	0.263	0.068	0.184	0.047*	0.654
	Chifre/horn	4th	0.639		0.369		0.112		0.01*	
		5th	0.949	0.817	0.036*	0.393	0.137	1	0.143	0.555

Anova test, Tukey's multiple comparison (*post hoc*; *$p < 0.05$).

writing motor development have indicated that movement duration and disfluency decrease between the ages of 8 and 9 years and become relatively stable by age 10 years (Meulenbroek and van Galen, 1990; Mojet, 1991; Zesiger et al., 1993). The decrease is mainly due to maturation and motor practice. In the same way, for Brazilian students, it was possible to notice that the decrease in the cognitive load of the writing movement favored the writing of HF words, indicating that writing practices favored the formation of long-term orthographic memory, suggesting an effect of lexicality for HF words. According with Shibata and Omura (2018), cognitive load is the amount of working memory in use to perform the task. As mentioned by Bonin et al. (2016), and Purcell et al. (2011), although there was a reduced spelling regularity effect. As mentioned by Kandel and Perret (2015a), when writing movements are fast and smooth, they require less sensory control and working memory. This results in a decrease in cognitive load. The consequence is that writing movements become automatized between ages 9 and 10.

TABLE 6 Comparison of variables between HF and LF words.

				3rd grade			4th grade			5th grade		
				Mean	SD	Value of *p*	Mean	SD	Value of *p*	Mean	SD	Value of *p*
C1	Movement duration	Olho/eye	HF	1,360	884	0.012*	1,216	390	0.000*	931	324	0.001*
		Dama/lady	LF	869	437		879	367		702	173	
	Movement fluency	Olho/eye	HF	9	6	0.006*	8	2	0.000*	5	2	0.156
		Dama/lady	LF	5	2		5	2		5	1	
	Movement duration	Nome/Name	HF	1,160	593	0.045*	1,018	451	0.168	749	208	0.725
		Mapa/map	LF	883	376		889	338		728	264	
	Movement duration	Velha/old	HF	1,336	502	0.027*	1,262	414	0.042*	990	254	0.000*
		Moto/ motorcycle	LF	1,016	538		1,015	593		738	184	
	Movement duration	Vida/life	HF	1,405	814	0.024*	1,149	482	0.044*	946	278	0.375
		Tipo/type	LF	1,011	347		971	215		892	188	
	Movement disfluency	Vida/life	HF	7	4	0.000*	6	3	0.000*	5	1	0.000*
		Tipo/type	LF	2	2		2	1		2	1	
C2	Movement duration	Lobo/Wolf	HF	9,695	4,843	0.000*	8,977	2,960	0.000*	8,451	3,597	0.000*
		Flora/flora	LF	1,398	558		1,389	492		1,098	360	
	Movement disfluency	Lobo/Wolf	HF	9.36	1.44	0.000*	2.90	1.22	0.000*	2.37	1.62	0.000*
		Flora/flora	LF	8	3		8	2		7	1	
	Gaze	Lobo/Wolf	HF	0.04	0.192	0.000*	0.08	0.277	0.003*	0.00	0.000	0.000*
		Flora/flora	LF	0.56	0.698		0.49	0.768		0.48	0.626	
	Latency	Gato/cat	HF	2099	762	0.004*	1806	1,001	0.455	1715	624	0.161
		Regra/rule	LF	3,465	2,251		1961	768		2077	1,279	
	Movement duration	Gato/cat	HF	1,417	591	0.031*	1,105	402	0.483	844	195	0.674
		Regra/rule	LF	1,104	437		1,178	493		865	193	
	Movement disfluency	Gato/cat	HF	9	3	0.047*	7	3	0.399	5	1	0.028
		Regra/rule	LF	7	2		7	2		6	1	
	Movement duration	Tempo/time	HF	1,313	618	0.133	1,161	406	0.380	927	225	0.008*
		Ruga/wrinkle	LF	1,080	494		1,080	381		792	161	
	Movement disfluency	Mundo/ world	HF	8	5	0.238	7	3	0.083	5	1	0.047*
		Saga/saga	LF	6	3		6	2		5	1	
C3	Movement duration	Casa/house	HF	1,067	567	0.053	1,054	382	0.087	770	246	0.001*
		Chance/ chance	LF	1,429	761		1,228	471		976	227	
	Movement disfluency	Casa/house	HF	7	4	0.041*	7	2	0.050	5	1	0.000*
		Chance/ chance	LF	9	5		8	2		7	1	
	Gaze	Casa/house	HF	0.04	0.192	0.000*	0.03	0.164	0.001*	0.00	0.000	0.000*
		Chance/ chance	LF	0.67	0.620		0.32	0.475		0.48	0.570	
	Gaze	Coisa/thing	HF	0.19	0.396	0.001*	0.11	0.393	0.036	0.00	0.000	0.004*
		Classe/class	LF	0.63	0.492		0.32	0.475		0.23	0.425	

(Continued)

TABLE 6 (Continued)

				3rd grade			4th grade			5th grade		
				Mean	SD	Value of *p*	Mean	SD	Value of *p*	Mean	SD	Value of *p*
	Movement duration	Bruxa/witch	HF	1,263	602	0.567	1,118	388	0.564	853	195	0.002*
		Xadrez/chess	LF	1,356	582		1,176	466		1,008	189	
	Movement disfluency	Bruxa/witch_V	HF	8	3	0.707	7	2	0.034*	6	1	0.000*
		Xadrez/chess	LF	8	4		8	3		7	1	
	Gaze	Bruxa/witch	HF	0.11	0.320	0.000*	0.05	0.229	0.000*	0.00	0.000	0.000*
		Xadrez/chess	LF	0.78	0.641		0.54	0.558		0.42	0.502	
	Movement duration	Bicho/animal	HF	1,369	747	0.409	1,222	545	0.274	948	221	0.001*
		Chifre/horn	LF	1,535	717		1,355	490		1,188	331	
	Movement disfluency	Bicho/animal	HF	8	5	0.436	7	3	0.489	6	1	0.000*
		Chifre/horn	LF	9	4		8	2		8	2	
	Gaze	Bicho/animal	HF	0.15	0.362	0.002*	0.03	0.164	0.026*	0.03	0.180	0.001*
		Chifre/horn	LF	0.63	0.688		0.22	0.479		0.35	0.486	

T-test, (*$p < 0.05$).

Regarding LF words, the effect of orthographic regularity could be noticed. The students had improved progressively from 3rd to 5th grade fluency and duration of movement for words with coding rules of type C1 and C2. The same cannot be observed for C3. These findings suggest that the movements became automatic from the 3rd to the 5th grade, suggesting the impact of the effect of orthographic regularity and lexicality. This study revealed that lexical and sub-lexical activation affected motor production. For HF and LF words, lexical and sublexical process favored motor programming.

Still, the results of the comparison between HF and LF words indicated that the regularity of the words played an important role in lexical access, and the HF words could be accessed through the lexical route, especially for the C1 rule words, as highlighted by Caramazza (1988) and Afonso et al. (2018) lexical route gives access to the spelling of whole words from long-term memory so it would be used when spelling familiar words.

However, the results of the comparison between HF and LF words indicated that the regularity of the words played an important role in lexical access, and the HF words could be accessed through the lexical route, especially for the C1 rule words, which do not showed no difference between latency times and neither the need to use the gaze.

Still in the comparison between HF-LF words, in relation to the C2 rule words, we noticed that there is still a need to use lexical and sublexical routes, since for some words, it was necessary to use the eye to check the spelling of the word. This finding corroborates studies, which have already indicated that the lack of teaching based on the reflection of spelling rules, on the part of students, makes it difficult to appropriate spelling rules (Scliar-Cabral, 2003b; Germano and Capellini, 2011, 2019; Chiaramonte and Capellini, 2022).

Nonetheless, for the words of C3, the motor improvement did not prevent the cognitive overload resulting from the spelling conflict, related to central process. Collaborating with Olive and Kellogg (2002), unless automatic, the transcription processes can place so many demands on working memory that they interfere with other higher-order processes required for writing, such as planning and reviewing. That is, we noticed that there was a progression in the decrease in duration and disfluency for LF, however, such words require more systematic instruction from the school, that is, these effects were noticed due to the greater unpredictability of phoneme-grapheme correspondences, rule knowledge spelling and less opportunity to be exposed to these words impacted the students' performance.

Döhla et al. (2018) also refers to the importance of working memory for the maintenance and manipulation of phonological information in order to access orthographic representations of writing, thus allowing the automation of handwriting, and the release of cognitive resources.

Combined with this, the students used the gaze as a support feature for checking the spelling of the word, that is, they became more dependent on visual clues from the word. These aspects suggest that there was an effect of orthographic regularity, and that the complexity and unpredictability of the C3 rule was not yet fully automatic, suggesting failure of long-term orthographic lexicon formation. When words are unfamiliar, such as those with LF of C3 rules, we can infer that students have not formed their orthographic representations (Perfetti et al., 1992; Share, 1999). Thus, to write this type of word, the student must memorize the spelling of the entire word and remember that there is a part of the word, such as the syllable that contains the spelling conflict, which will require more attention. (Kandel and Valdois, 2006). Therefore, the student must use strategies to be able to write the word without error, such as process letters separately, aiming to identify and locate letters that contain irregularities; or to write the word applying graphophonological conversion rules.

Nevertheless, irrespective the strategy used, students have made pauses while writing, verified in this study by the increased number of gaze, constituting additional cognitive loads that consume time and result in increased processing time. Kandel and Valdois (2006) have shown that children program their handwriting movements according to the syllabic structure of the word, as orthographic syllabification for irregular words is not so easy as regular words. This could be the next step for research for Brazilian Portuguese language.

As pointed out by Kandel and Perret (2015a,b), and in accordance with our results, orthographically irregular words (C2 and C3 coding rules) required more processing demands than regular words (C1 coding rule), suggesting that handwriting movements were affected by central processes. This "regularity effect" has been documented in previous research in other language (Delattre et al., 2006; Roux et al., 2013), but still has not been documented in Brazilian Portuguese language.

Regarding latency, which refers to lexical access, we noticed that for the HF words, there was a decrease in latency, according to the progression from the 3rd to the 5th year, for the three coding rules. This finding suggests that the HF of the word favored the recovery and access of the phoneme-grapheme conversion mechanism, indicating that there was a long-term memorization of words in the orthographic lexicon (Kandel and Valdois, 2006).

Conversely, for LF words, it was possible to notice that the lexical process and orthographic regularity influenced the students' performance. For the latency of the words of C1 and C2, there was a decrease in the access time for students, with the progression from 3rd to 5th grade. However, for C3 words, most words did not differ in latency time. This finding suggests failure in the formation of the long-term orthographic lexicon, especially for words with LF and greater unpredictability (C3), and subsequent need of longer time to start the writing movement. In the case of words with C3 rules, in the comparison between pairs of HF-LF words, the students possibly had to access the word through the phonological route that is, looking for possible phoneme-grapheme relationships in Brazilian Portuguese, being verified by the difference between the kinematic variables. Thus, due to the use of the sublexical route, and the spelling uncertainty (Central Processes), the students relied even more on visual feedback, increasing the need to look for spelling information on the screen (greater number of gaze in the comparison between the words of LF and HF). As mentioned by Caramazza (1988), the sublexical route or assembled route makes use of knowledge about the links between phonology and orthography and provides a phonologically plausible spelling for non-words or low-frequency words. Moreover, in accordance with Afonso et al. (2015), our findings had showed that phonology-to-orthography influenced word spelling.

Going further, we can infer that there was a regularity effect, regarding the importance of phoneme-grapheme mappings, as manifested by shorter latencies and writing durations for HF words. It is emphasized that, in situations where there is competition for the same phonetic context (rule C3), it is necessary to have metalinguistic knowledge, especially semantic and morphological knowledge, which can help in choosing the letter or grapheme that will represent it. Nonetheless, these rules are dependent on spelling lexical memory (Scliar-Cabral, 2003a). These findings indicate that the students had difficulties in the formation of the orthographic mental lexicon, which were aggravated by the lack of systematic teaching of conversion and by the lack of strategies aimed at the visual memorization of these words. (Germano and Capellini, 2019; Chiaramonte and Capellini, 2022).

We can also infer that the students maintained activated the central and peripheral process for these words, because they needed more time to access orthographic information and to program motor planes for handwriting. We also noticed a greater need to search for the word on the notebook screen, in order to confirm spellings aspects of the word. As mentioned in a study, typically developing children also showed that writing, pausing, and spelling are closely linked and that word writing can be influenced by word-level pause effects related to frequency and morphological complexity (Kandel et al., 2011).

We can also assume that the spelling of the words was processed before the beginning of the movement and during the production of the words, mainly for the words of LF and of greater irregularity (coding rule C3). It's possible to assure this by observing the increase in latency and writing pauses (greater number of gaze). Unfortunately, as we do not perform letter-by-letter analysis – related with local aspects of movements – but of the entire word analysis, we can only infer that such motor programming of words may also have occurred in HF and regular words. In this way, this was a limitation of this study.

5. Conclusion

Despite being a pilot study, this one brought us many reflections and collaborations on the production of writing for Brazilian Portuguese. This study revealed that lexical and sub-lexical activation affected motor production. For HF words, we noticed that the lexical and sublexical process favored motor programming, that is, the central orthographic lexical memory cascaded the motor programs (peripheral processes), indicating an interaction between the central and peripheral processes, as in which maturation and school progression occurs. For LF words, we noticed that the lexical and sublexical process also impacted motor programming (peripheral processes). However, despite the maturation and school progression for the motor planes, there was an increase in latency time and in the need to search for word information, measured by the Gaze variable for words with greater irregularity (C3). Hence, LF and less predictable words demanded greater cognitive overload and, thus, a greater need for interaction between central and peripheral processes. Finally, this study provides further evidence that linguistic variables such as orthographic regularity and word familiarity affect in Brazilian Portuguese written language for handwriting performance.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Research Ethics Committee of the Faculty of Philosophy and Sciences of São Paulo State University "Júlio de Mesquita Filho" (UNESP), Marilia, São Paulo, Brazil, under number CAAE: 87368618.4.0000.5406. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

GG designed the experiment and project, collected, and interpreted data. SC provided technical support and conceptual advice. All authors discussed the results and implications, contributed to writing the main manuscript, and approved the submitted version.

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Conflict of interest

The authors declare that the present research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Translation and cultural adaptation of the HELPS Reading Fluency Program into Brazilian Portuguese: A report of systematic adaptation processes and initial evidence of efficacy

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Introduction: Across multiples languages, research demonstrates the important relationship between reading fluency and comprehension. Put simply, a fluent reader has greater attention and memory resources to use higher-order functions in reading, resulting in better comprehension of text. Some reading fluency interventions have shown positive results in improving students' text reading fluency and comprehension; however, this research has predominantly been conducted with English-speaking students. For instance, until this report, a comprehensive search revealed only one prior study that evaluated an intervention strategy designed to improve students' reading fluency in Brazilian Portuguese and no prior studies evaluated an intervention *program* with that population of students.

Methods: The main goals of this two-part project were to (a) systematically translate, culturally adapt, and pilot test the Helping Early Literacy with Practice Strategies (HELPS) reading fluency program for use in Brazilian Portuguese (referred to as, *HELPS-PB*); and (b) conduct a preliminary quasi-experimental study of the HELPS-PB program with 23 students in grades 3 to 5 who needed a reading fluency intervention.

Results and Discussion: This report documents the processes and successful adaptation of existing English- and Spanish-versions of HELPS into a new HELPS-PB program. It also offers preliminary evidence showing that students receiving HELPS-PB significantly improved their text reading fluency comparted to students in a control group. Implications for research, practice, and the adaptation of reading fluency programs into other languages are discussed.

KEYWORDS

reading fluency, intervention, reading development, automaticity, visual word recognition, HELPS program, language adaptation

Introduction

Of the various key components that are activated in the reading process (e.g., decoding words, understanding vocabulary, comprehending words on the page), reading fluency is equally important and is a multidimensional concept involving reading rate, accuracy, and prosody (Puliezi and Maluf, 2014; Hudson et al., 2020).

One of the earliest models used to explain the importance of reading fluency was proposed by LaBerge and Samuels (1974) and is called the information processing model. With exposure to the visual code (letters, spelling patterns, frequent words, and subsequent practice), the sets of letters of a word come to be recognized as a single unit, making the process increasingly automatic. Thus, attention resources for the visual decoding processes decrease, allowing focus to shift to other areas, such as the semantics (meanings) of the text being read and critical thought or analysis of the text.

As the reader acquires and improves text reading fluency skills, this frees attention and memory resources for the use of higher-order functions in reading, resulting in better comprehension (Laberge and Samuels, 1974; Hudson et al., 2020). Higher-order functions are related to cognitive abilities necessary for strong comprehension. For example, a reader must integrate the meaning of words and phrases into a meaningful whole, make inferences, monitor one's own comprehension of text, and seek to build a coherent representation of the text in memory in order to integrate it with previous knowledge (Rapp et al., 2007; Oakhill et al., 2017; Pacheco and Santos, 2017).

Despite the advancement of research on instruction in reading (e.g., research on how to develop students' fluency and improve reading comprehension), a large percentage of students around the world continue to struggle with basic reading proficiency. The Programme for International Student Assessment (PISA) represents just one well-known source for this global crisis in literacy development (OECD, 2019b). Reading difficulties affect students of all ages and demographic characteristics, but those who grow up with economic disadvantages are particularly at risk for significant difficulties in reading (e.g., OECD, 2019b; Soares and Bergmann, 2020; National Center for Education Statistics, 2022). Although a widespread lack of reading proficiency calls for global action, we next highlight some data and information about literacy in Brazil because this is the geographic location of the student participants discussed later in this paper.

Reading proficiency in Brazil

The Brazilian National Common Curriculum Base states that literacy is a priority in the first two grades of elementary school so children can learn "the alphabetic writing system in an articulated way [along] with the development of other reading and writing skills [while involved] in diversified literacy practices" (Brasil, 2018, p. 59). However, multiple sources of evidence suggest that many students in Brazil do not develop proficient reading skills.

For example, one recent UNESCO report highlighted significant gaps in Brazilian students' reading proficiency, showing, for instance, that only 3.6% of public-school students in Brazil complete elementary school with advanced reading skills (UNESCO, 2017). Additionally, data analyzed from PISA within Brazil—which included 597 public and private schools and 10,961 students—indicate that 50% of Brazilian students aged 15 years old had low reading proficiency (Araújo and Andriola, 2019; OECD, 2019a). This percentage is also highly consistent with national assessments of literacy in Brazil that included primary grade students (Brasil, 2013, 2021; Soares and Bergmann, 2020).

Overall, assessments of students' reading performance in Brazil (Brasil, 2013, 2021), as well as international assessments (e.g., OECD, 2019a), suggest a critical need to improve students' reading. This is extremely important in the early grades because it appears that most students identified as having reading difficulties continue to have them all the way into secondary school (Brasil, 2013, 2021; UNESCO, 2017).

Reading fluency and related research in Brazil

Although reading proficiency involves developing a handful of essential foundational skills (e.g., phonemic awareness, vocabulary, and comprehension), reading fluency is one of those essential skills (Hudson et al., 2020; Rupley et al., 2020; Meggiato et al., 2021; Silvano and Godoy, 2022). Reading fluency is often defined as the ability to read aloud quickly, accurately, and with proper expression (e.g., Rasinski, 2006; Kuhn et al., 2010; Pinto and Navas, 2011). As we discuss in greater detail later, students' development of reading fluency involves using evidence-based practice and motivational strategies, including strategies such as having students repeatedly read ability-appropriate text for a prescribed frequency and duration, having a proficient reader model fluent reading for a student developing fluency, using systematic error-correction procedures with words a student reads aloud incorrectly, and integrating motivational strategies such as goal-setting and structured praise (e.g., Therrien, 2004; Morgan and Sideridis, 2006; Lee and Yoon, 2017; Stevens et al., 2017; Padeliadu et al., 2021).

Given the importance of text reading fluency as an essential foundational literacy skill, as well as existing research validating a small number of intervention programs that improve students' fluency, there is a critical need to utilize evidence-based intervention for the millions of Brazilian students who have not yet developed reading fluency (Puliezi and Maluf, 2014; Meggiato et al., 2021; Silvano and Godoy, 2022). To date, and after a comprehensive search for relevant literature, we identified only one existing study designed to evaluate intervention strategies to support Brazilian students' reading fluency.

In that study, Pinto and Navas (2011) used fluency-based instructional strategies in an effort to improve fourth-grade students' reading rate. During the five instructional sessions with each student (15 min per session), they used silent reading, modeling, and repeated reading strategies, as well as a prosody-based strategy in the first session. The results showed small but statistically significant improvements from pre- to-post-test in students' reading prosody and error-rate, whereas the small growth in students' number of words read correctly per minute (reading rate) was not statistically significant. In what appears to be the very first study designed to evaluate and improve Brazilian students' text reading fluency, this study was important in emphasizing the need to strengthen students' fluency and it offered an initial evaluation of a few basic instructional strategies that studies outside of Brazil have shown to be effective (Lee and Yoon, 2017). However, this study was also limited in several important ways. For example, applying only a few fluency-based instructional strategies in a more "basic" manner is unlikely to support students as much as using several evidence-based strategies that are implemented in the most empirically supported ways (Therrien, 2004; Morgan and Sideridis, 2006; Begeny, 2009; Stevens et al., 2017). Similarly, evaluations of comprehensive instructional *programs* (e.g., programs that provide all needed implementation materials, training, guidance, etc. that educators can access outside of a journal article) have important implications for usability and feasibility of such interventions outside of a research context. Methodologically, the study also had some important limitations, such as no inclusion of a control group and only involving students who did not appear to have reading difficulties.

Purpose of this two-part study

Our discussion thus far emphasizes two key ideas. First, there is critical need to support students' reading development, including development of fluency as a foundational skill. This fact is true in Brazil and in most countries around the world (e.g., Therrien, 2004; Pinto and Navas, 2011; Lee and Yoon, 2017; OECD, 2019b; Brasil, 2021). Second, there is a substantial gap in programming and research around reading fluency for students learning to read in Brazilian Portuguese. These two main facts served as the impetuses for this 5-year project that involved two main studies.

Study 1 sought to systematically translate, culturally adapt, and pilot test an existing reading program that (a) has the target goal of improving students' reading fluency and confidence as readers, (b) has more than a decade of research supporting its effectiveness on students' reading fluency and comprehension, (c) has been used with students in more than 60 countries, and (d) was available in English in Spanish at the beginning of this project. Specifically, we sought to systematically adapt and develop a Brazilian Portuguese version of the Helping Early Literacy with Practice Strategies (HELPS) program—which was originally developed in English (Begeny, 2009) and later adapted into Spanish, with the name of *Leamos para Avanzar* (Begeny, 2012). Systematic adaptation and development work for the Brazilian Portuguese version of HELPS also required translation, adaptation, and pilot testing of the reading passages (i.e., the HELPS curriculum of passages) that accompany the intervention program in English (Begeny et al., 2009) and Spanish (Begeny et al., 2012a). Collectively, Study 1 sought to document the systematic process of creating the Brazilian Portuguese version of HELPS (i.e., HELPS-PB), including documentation of the necessary pilot data needed to appropriately adapt and sequence the HELPS-PB curriculum of passages and related implementation materials. Study 1 sought to answer the following two questions: (a) will our empirically and theoretically based approach to translation and adaptation lead to successful development of HELPS-PB (as defined by data collected throughout the process and implementation observations occurring during pilot implementation) and (b) what key aspects of our development process were learned that may influence similar development processes in future work?

Study 2 was designed to build upon the development work from Study 1 by conducting an initial quasi-experimental study of HELPS-PB with students in grades 3 to 5 who lacked proficient reading fluency and needed a targeted reading fluency intervention. As a preliminary evaluation of the efficacy of HELPS-PB and the first known study to evaluate a reading fluency intervention program with students learning to read in Brazilian Portuguese, Study 2 sought to answer one main research question: do participants who receive HELPS-PB significantly outperform wait-list control group participants in text reading fluency, as measured by a standardized reading fluency assessment?

This research project was submitted to the Research Ethics Committee of the School of Philosophy and Sciences-CEP/FFC/UNESP-Marília-SP and approved under number 1.299.842, CAAE 50201915.9.0000.5406. The project approved by this CEP refers to all stages of the work, including Study 1 and Study 2.

Study 1: Cross-cultural translation and adaptation of HELPS materials into Brazilian Portuguese

Overview and context

HELPS is a structured, evidence-based program designed to improve students' oral reading fluency (ORF) and confidence in reading. Several published studies (e.g., Begeny et al., 2010, 2011; Malouf et al., 2014; Mitchell and Begeny, 2014; Vess et al., 2018) and more than 10 consecutive years of comprehensive program evaluations have evidenced the effectiveness of HELPS in improving reading fluency and/or comprehension for a broad and diverse group of students, including but not limited to students in elementary and middle school, students for whom English is or is not the student's first language, students with and without disabilities, and students who live in economically disadvantaged households. Based on several meta-analyses and systematic reviews of the available research on interventions designed to improve reading fluency and (as a result) reading comprehension (e.g., Chard et al., 2002; Therrien, 2004; Morgan and Sideridis, 2006; Lee and Yoon, 2017), HELPS includes each of the known evidence-based strategies for building reading fluency. This includes strategies such as repeated reading, systematic error correction, model reading, performance feedback, goal setting, and structured motivation systems (Begeny, 2009). HELPS instructional sessions last approximately 15–20 min, it is recommended that students receive at least three sessions per week for at least 30–50 sessions, the program can be implemented effectively in a one-on-one or small group context, and HELPS can be used effectively in-person or virtually (Begeny, 2009, 2018b; Vess et al., 2018; Richardson, 2019; Musti-Rao et al., in press).

In an effort to promote educational equity and a more just society, all HELPS program implementation and training materials are made available for free by the program's lead developer and are disseminated by Helps Education Fund, a United Stated 501(c)(3) non-profit organization that provides more than a dozen research-validated programs and services for free or low cost. As part of this work, efforts are made to work with educators, researchers, and program developers around the globe who have interest in translating and adapting any of Helps Education Fund's programs and materials into additional languages. Consistent with all other programs and services offered by Helps Education Fund, any newly adapted or translated Helps Education Fund programs, such as HELPS, must (a) be comprehensively developed, (b) evidence some level of effectiveness with the intended beneficiaries (e.g., students), and (c) be made available from Helps Education Fund for free or low cost.

This overall context served as the foundation for the collaborative partnership that sought to facilitate Study 1 of this report. To conduct Study 1, a translation and adaptation license agreement was requested and granted by the lead developer of HELPS. Directed by the first author of this report, Study 1 involved approximately 4 years of collaborative development and pilot-testing work before Study 2 of this report could be initiated.

Finally, because the goal of Study 1 was to complete a translation and adaptation of HELPS materials into Brazilian Portuguese, it is important to highlight that the appropriateness of reading intervention programs that are applied and adapted to different languages can be influenced by the orthographic transparency of each alphabetic language system. As described in detail by others (e.g., Cardoso-Martins and Navas, 2016; Borleffs et al., 2017), Portuguese is at an intermediate level of orthographic transparency compared to English (which is more opaque) and Spanish (which is more consistent). The more that grapheme and phoneme correspondences are consistent for the learner, the better they will be able to learn decoding skills at the beginning stages of literacy development. As such, reading difficulties for Brazilian students that occur during or after grade 1 or 2 have a relatively high likelihood of being influenced by fluency difficulties, due to the relatively consistent or "transparent" nature of Portuguese (Borleffs et al., 2019). In fact, research with Brazilian students confirms this idea, with evidence suggesting that difficulties in reading fluency play an important role in reading comprehension from the beginning of learning to read, such as for grade 1 students (Cardoso-Martins and Navas, 2016).

Method

The cultural adaptation of the HELPS program included the translation of (a) a comprehensive instructor's manual (Begeny, 2009), which included 152 pages of all the needed implementation materials, answers to frequently asked implementation questions, a brief summary of relevant research and context for using HELPS, as well as overall guidance for teachers on how to most effectively use the program; and (b) a curriculum of 100 passages (narrative and expository text) for the students to read as part of program implementation. Henceforth we will simply refer to these two documents as the "instructor's manual" and "curriculum." In addition to the translation and back-translation of these materials, the curriculum passages were adapted for cultural fit and student data were systematically collected to level the passages of the curriculum for Brazilian students, adapt the HELPS goal-setting procedure according to norms for students to read in Brazilian Portuguese, and adapt the HELPS program's Placement Assessment that specifies where a student should start in the curriculum of passages.

At its foundation, the methodology for translation and adaptation of this program was based on methods described by Cassepp-Borges et al. (2010) and Alexandre and Coluci (2011), as well as studies that used these authors' techniques (e.g., Manzi-Oliveira et al., 2011; Constant et al., 2014; Holst et al., 2016; Brito and Faro, 2017). For example, we followed guidance from Cassepp-Borges et al. (2010), who presented techniques for adapting psychological instruments from one culture to another in ways that aim to reduce cultural bias. Based on work by Alexandre and Coluci (2011) regarding standardized, international guidelines to help ensure the quality of adapted materials, we utilized steps proposed by these authors that were described as essential for this type of work: initial translation, synthesis, translation back to the original language, review by a committee, and performance of a pre-test (pilot study).

We also used geographic and localized contexts, based on conceptual and practical models of internationalization in psychology and education (e.g., Arfken, 2012; Begeny, 2018a, 2019; Begeny et al., 2021). Finally, adaptation procedures involved collaborative work among all authors of this paper to account for specific program-related guidelines that are unique to using and developing the HELPS program. What follows is a summary of the primary steps we used for Study 1: (a) translation of HELPS materials, (b) cultural adaptation of the HELPS curriculum, (c) systematically sequencing the HELPS-PB curriculum of passages based on text complexity, (d) developing an updated HELPS Placement Assessment for specific use with HELPS-PB, and (e) pilot testing of the newly developed HELPS-PB program. Figure 1 also presents a visual depiction of the primary stages and activities of Study 1.

Translation and back-translation of the HELPS manual and curriculum of passages

To prepare for translation, the Spanish version of the HELPS curriculum of passages (Begeny et al., 2012a) and the English version of the HELPS instructor's manual (Begeny, 2009) were selected as the two key sources of text to translate. These were selected because a translation of the HELPS curriculum from Spanish to Brazilian Portuguese (both Latin languages) would likely be easier compared to translating the English version of the curriculum to Brazilian Portuguese. However, the Spanish version of the HELPS Instructor's manual is not a fully comprehensive version (e.g., it excludes summaries of relevant research about the instructional strategies used in HELPS), so the English (and fully comprehensive) instructor's manual was used for translation. For concision, unless otherwise stated, we will subsequently use *Portuguese* to refer to *Brazilian Portuguese,* though we acknowledge that written and spoken Portuguese outside of Brazil (e.g., in Portugal) is sometimes different.

The choice to translate the HELPS curriculum from Spanish to Portuguese was also done because of Latin American cultural constructs and relative similarities. For example, there are corresponding elements between the Brazilian and the Castilian cultures, which facilitates translation because it decreases the probability of idiomatic and grammatical incompatibilities (Cassepp-Borges et al., 2010). The person selected to translate the HELPS curriculum was a native Portuguese speaker who is also fluent in Spanish. The person selected to translate the HELPS manual was a native Portuguese speaker who is fluent in English. Following the instructions of Cassepp-Borges et al. (2010) and others (e.g., Herdman et al., 1998; Reichenheim and Moraes, 2007; Almeida et al., 2013) to ensure a valid and independent reverse translation, the translated versions of the manual and curriculum were translated back into the original language by professionals who did not participate in the first stage translations and did not know about the HELPS curriculum or manual.

To unify a preliminary version of the curriculum and manual, a committee then met to assist in the consolidation of the translations, minimizing possible linguistic, psychological, cultural, and comprehension biases found in the simple and reverse translations (Cassepp-Borges et al., 2010). The committee included one of the translators of the original in English into Portuguese (also fluent in the Spanish language), a researcher connected to this project, and a member external to this project but an expert in the area of pedagogy. In one meeting, all questions divergent from the original HELPS materials were analyzed, suggestions were discussed, and then modifications were made through the process of dynamic equivalence, including revisions to address any linguistic or conceptual issues.

Finally, the orthographic and grammatical revisions of all content was completed by two additional professionals who were highly qualified for this work: a retired teacher who taught school-aged students literacy and grammar for 30 years in Brazil, and a Portuguese language teacher with 47 years of experience revising the Portuguese language (through grammar and spelling reviews). The reviews were performed in sequence, that is, initially by one of these professionals and then independently reviewed by the second teacher. After all translation steps were completed and we had our initial HELPS-PB curriculum of passages, that curriculum was now ready for cultural adaptation.

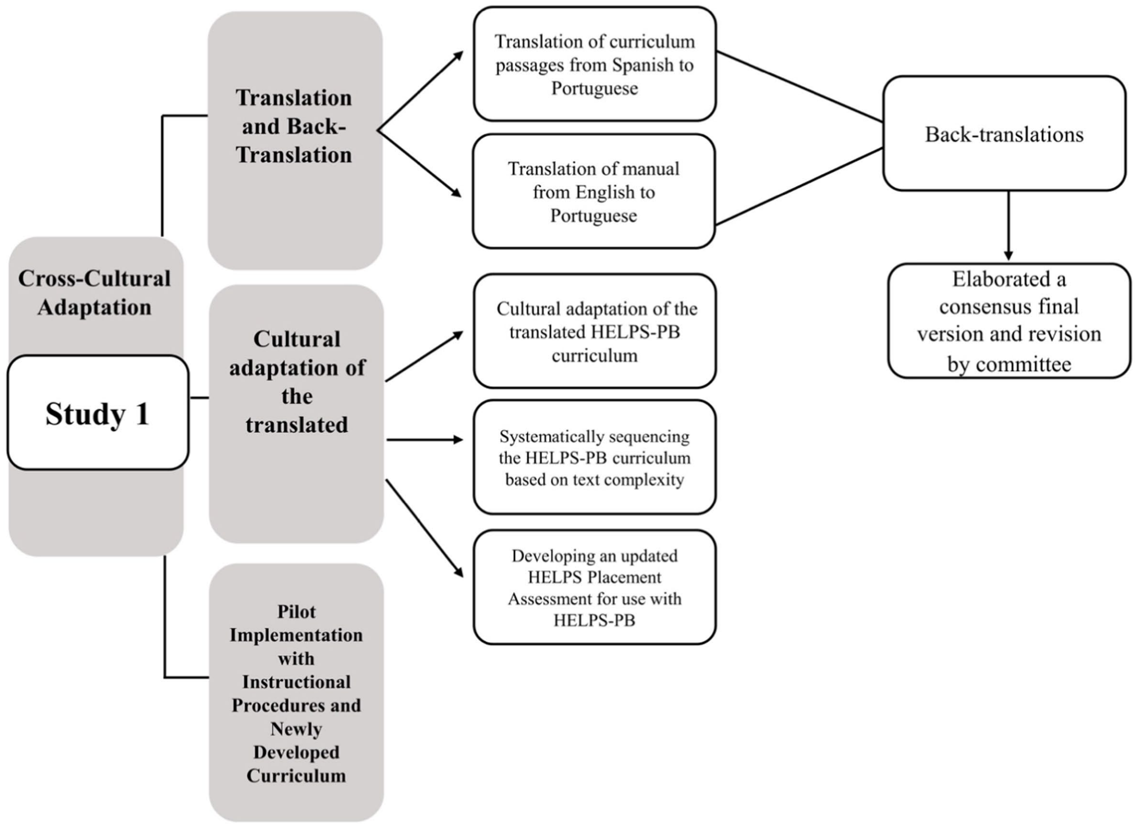

FIGURE 1
Diagram for the primary stages and activities of Study 1.

Cultural adaptation of the translated HELPS-PB curriculum

The original HELPS curriculum was developed with the overall goal of creating a large set of reading passages that could be used effectively in English with students who are working to strengthen their text reading fluency—and in particular, the passages were developed for use with the HELPS program. The authors who developed the original HELPS curriculum in English (Begeny et al., 2009) considered more than a dozen passage characteristics and parameters that would be used in the curriculum development process. Chapter 3 of Begeny's (2009) HELPS Manual summarizes the key considerations and characteristics of the HELPS curriculum, but examples of considerations included intentional creation of passages that: (a) have a complete story/passage in approximately 150–200 total words; (b) cover a variety of topics that would likely be of interest to a wide range of students, particularly primary school students; (c) incorporate themes and character names that collectively reflect cultural diversity and at least some global relevance; (d) offer both narrative and expository text, with the latter type of text being particularly age-appropriate for learners of all ages; and (e) across all 100 passages, collectively integrate 100% of the words from the Dolch High Frequency Word Lists (Dolch, 1948, 2007). The authors who translated and adapted the HELPS curriculum into Spanish (Begeny et al., 2012a) likewise attended to the considerations and parameters used in developing the original curriculum, as applicable for Spanish-language text.

With development of the HELPS-PB curriculum, these considerations were also used and therefore required intentional cultural adaptation of several passages. For example, the names used in passages and the themes of each passage were carefully examined by the curriculum developers to determine whether any passages should be modified or completely excluded from the HELPS-PB curriculum. This process included ongoing discussion about appropriate adaptations of the passages until there was full agreement among the HELPS-PB authors. After the curriculum adaptation process, and consistent with the development process for HELPS in English and Spanish, the HELPS-PB passages were ready to be systematically sequenced based on the text complexity of each passage—as measured by students' ORF scores.

Systematically sequencing the HELPS-PB curriculum based on text complexity

The original HELPS curriculum was systematically sequenced from the least difficult to the most difficult passages. For this purpose, the developers used the mean oral reading rate (i.e., words read correctly per minute; WCPM) from hundreds of students in grades 1–4 to identify and sequence 100 usable passages that met the goals of curriculum development. More than 100 passages were originally written in the development process and standard deviations of students' WCPM were used to exclude any passage that resulted in too much variability (i.e., any passage that was difficult for some readers and easy for other readers was not used because it reflected too much variability in text difficulty level). This overall approach was used for both practical and empirical reasons, and passage sequencing did not rely on applying readability formulas to each passage because there are still many criticisms and limitations of using such formulas to predict text that will be more or less difficult for a student to read with fluency or comprehension (for an extended discussion, see Begeny and Greene, 2014).

In considering the HELPS-PB curriculum, scholars suggest that English-language works translated into Portuguese tend to generate more complex texts than the original English version (e.g., Pasqualini et al., 2014). Considering this and the need to level the HELPS-PB passages from the least difficult to the most difficult for Brazilian students learning in Portuguese, it was therefore necessary to empirically assess the linguistic complexity of the adapted HELPS-PB passages by assessing Brazilian students' oral reading rate and accuracy with each passage (i.e., their WCPM). Accordingly, a sample of students was selected and we engaged in a four-step process to determine the appropriate sequence of the HELPS-PB passages from least to most difficult, when read for purposes of fluency.

Participants and overview of assessment procedures. Prior to the beginning the passage sequencing process, parents or guardians of the participating students signed an informed consent form to authorize the study, which was in compliance with the resolutions of Brazil's National Health Council CNS 466/12. In total, 72 third-grade students participated, 37 boys (51.4%) and 35 girls (48.6%), all students were 8 or 9 years old, $M = 8.72$, $SD = 0.44$. All students attended a public elementary school in the Midwest region of São Paulo. The participating school was the same for all stages of Study 1 and the same school participated in Study 2. The inclusion criteria for students to participate were (a) parental consent; (b) visual and auditory acuity within the normal range, as described in the school records and teachers' reports; (c) no presence of a neurological, behavioral, or cognitive disorder.

The process of sequencing the HELPS-PB passages included the five main steps summarized below. When a step involved obtaining a student's WCPM score, this was done by a trained assessor administering the standardized ORF assessment procedure (e.g., providing brief, specific directions for the student, timing the student's reading for 1 min, and recording specified errors in reading). See Chapter 4 of Begeny (2009) for specific administration directions and scoring rules.

Step 1. A sub-sample of students and passages were selected to help us identify three HELPS-PB passages that are highly similar in difficulty level so that those three passages could later be used to identify our "homogenous-reader assessment pool" (i.e., a group of students from the 72 who have roughly the same level of ORF). To achieve this, we first selected HELPS-PB 10 passages. These 10 were the passages that Begeny (2009) reported as representing distinct levels of difficulty within the English version of the passages. There were two passages at each distinct level of difficulty, resulting in 10 total passages.

Although translation and adaptation of these passages into Portuguese undoubtedly changes the level of difficulty compared to the English-version passages, a goal of Step 1 in this process was simply to estimate roughly different difficulty levels of 10 total passages so that we could then identify (in Step 2) three passages that appear to be highly consistent in difficulty level. Also part of Step 1, we identified a reasonably sized sub-sample of students to read the 10 aforementioned passages. Specifically, of the 72 total participants, we had teachers nominate students who they reported as having grade-level reading skills (i.e., not with below average or advanced skills, but those with skills expected of third grade) and then randomly selected 12 of those students to participate in Step 2.

Step 2. The 12 aforementioned students read the 10 passages described in Step 1, and from that we averaged each student's WCPM score for each passage. Of the 10 passages and based on average WCPM scores, we then identified three passages that showed roughly the same level of difficulty. These three passages served as the "screening passages" to determine (of the 72 total students) which of those students would be appropriate as participants in the *homogenous-reader assessment pool*.

Step 3. Of the three passages with roughly the same difficulty level identified in Step 2, we then administered those three passages to all 72 participants and each student's median WCPM score represented their overall ORF score for the purpose of our sequencing process. Using the median WCPM score across three passage with similar difficulty level is well-substantiated and commonly used as best-practice in determining a student's ORF. From this score, we identified 29 total students (15 female, 14 male, mean age = 8.51, SD = 0.49) who had highly similar levels of ORF [$M = 64.75$ WCPM; approximately the 35th percentile based on norms from Martins and Capellini, 2021] and this sample of participants served as our *homogenous-reader assessment pool.*

Step 4. Of the 29 students in the homogenous-reader assessment pool, each student read all 100 passages of the HELPS-PB curriculum over approximately a 2-week period. Each passage was printed on one A4 size sheet of paper and in a font size that was easy for students to read. The passages were presented in a binder-type folder so that each passage was presented in a uniformly straight manner and so that the student did not have access to the next passage before the reading began.

Data collection for this step involved the trained assessor administering 10 passages per day to individual students. The student always read each passage for only 1 min and the assessor obtained a WCPM score per passage. Consistent with the development of the original HELPS curriculum, a maximum of 10 passages were read daily (requiring approximately 12 total min for the day's entire assessment session) so that students would be less likely to experience fatigue, inattention, or challenges with working memory—and thereby providing a context to obtain valid reading assessment data. Also, each assessment session took place at the student's school, during the school day, and in a quiet room provided by the school principal.

The sequence of texts used in the assessment followed the sequential order of the passages (from 1 to 100) in the Leamos para Avanzar curriculum. The assessment process began with the same text for all children and followed with the same sequence of 10 passages presented per day to all children.

Step 5. Based on the sample of 29 students reading all 100 passages, we then calculated the mean and standard deviation of each passage. For the purposes of the HELPS instructional program and its ability to improve students' fluency, passages in the curriculum should have relatively low variability. Thus, a passage (from the data collected in Step 4) was included within the final HELPS-PB curriculum if the passage showed reasonable variability across students' performance (i.e., it was included if the standard deviation was less than 15.5 WCPM). Of the included passages ($N = 95$), these were sequenced from the highest to the lowest WCPM averages (with higher WCPM scores reflecting relatively easier passages) and HELPS-PB passages were sequenced accordingly. Table 1 shows the final sequence of each HELPS-PB passages as well as the respective WCPM and standard deviation. More details on the process of adapting the texts and their sequencing can be found in the Results of Study 1.

Developing an updated HELPS placement assessment for use with HELPS-PB

According to the HELPS Instructor's Manual, "the ideal starting point for a student in the HELPS curriculum is one in which the student will regularly meet his reading goal" (Begeny, 2009, p. 53). Research and program evaluations with HELPS also shows that an ideal starting point in the curriculum passages is the point at which the student reads a passage with approximately 20–30 WCPM less than the student's specific Reading Goal and it is usually the case that a student's WCPM score on

TABLE 1 Sequence of HELPS-PB passages based Study 1 WCPM averages.

Passage # for HELPS-PB curriculum	Average WCPM	Standard deviation	Passage # for HELPS-PB curriculum	Average WCPM	Standard deviation
Excluded	78.3	15.8	47	66.8	12.5
Excluded	77.5	15.6	48	66.8	10.0
1	77.2	11.7	Excluded	66.7	15.5
2	77.1	10.6	49	66.6	13.9
3	76.6	13.6	50	66.5	13.1
4	76.2	13.2	51	66.1	14.2
5	75.7	12.8	52	65.7	11.1
6	75.7	12.3	53	65.6	11.1
7	75.2	10.4	54	65.6	11.7
8	74.9	15.1	55	65.2	9.7
9	74.8	14.4	56	64.9	13.7
10	74.8	12.6	57	64.8	9.1
11	74.5	11.1	58	64.7	9.5
12	74.4	13.0	59	64.6	13.1
13	73.8	11.7	60	64.6	14.7
14	73.8	12.9	61	64.2	10.7
15	73.4	11.0	62	63.6	13.1
16	73.3	13.0	63	63.6	12.5
Excluded	73.3	15.5	64	63.4	13.7
17	72.9	13.4	65	63.1	14.4
18	72.4	14.4	66	62.3	13.9
19	72.1	11.7	67	62.0	13.2
20	71.8	13.5	68	61.8	13.7
21	71.7	11.2	69	61.7	11.4
22	71.3	10.4	70	60.8	8.6
23	71.1	9.9	71	60.7	10.5
24	70.2	11.0	72	59.2	11.7
25	70.1	10.3	73	59.0	10.8
26	70.0	14.7	74	58.7	10.9
27	70.0	14.0	75	58.6	12.8
28	69.7	12.0	76	58.5	10.3
29	69.5	15.2	77	57.9	10.8
30	69.4	12.9	78	56.4	12.4
31	69.2	11.7	79	56.2	9.9
32	69.1	12.6	80	55.6	10.7
33	69.1	13.3	81	55.4	11.8
34	69.0	11.8	82	55.2	7.8
35	68.8	11.3	83	55.0	13.2
Excluded	68.6	15.5	84	54.9	10.8
36	68.5	13.1	85	53.9	12.9
37	68.3	13.0	86	53.7	11.3
38	68.3	12.7	87	53.4	10.6
39	68.2	9.4	88	52.3	12.4
40	67.9	12.3	89	51.3	10.6
41	67.9	10.1	90	49.2	12.0
42	67.9	14.3	91	44.9	10.9
43	67.7	13.3	92	44.6	8.5
44	67.4	12.7	93	43.8	8.7
45	67.4	10.3	94	38.4	8.4
46	67.1	13.8	95	35.2	6.1

WCPM, words read correctly per minute.

each passage improves by approximately 20–30 words after 1–3 HELPS sessions (Begeny, 2009). With this, by starting a student in the curriculum at a passage where they will read approximately 20–30 WCPM less than the Reading Goal, this generally allows the student to regularly achieve the Reading Goal after 1–3 HELPS sessions and this logic is strategically designed to increase students' reading fluency, motivation for the program, and reading confidence. However, when considering the large number of students who may receive HELPS, it is neither beneficial nor time-efficient for educators to have each student read every single passage in the curriculum to determine the optimal starting point per individual student. Rather, a data-based and time-efficient system must be in place to determine exactly where in the curriculum a student should begin once the HELPS instructional sessions commence.

That data-based system was developed for the English and Spanish versions of HELPS and is referred to as the HELPS Placement Assessment. More specifically, before a student begins receiving HELPS instructional sessions, a brief (usually 4–12 min) and structured assessment allows the educator to determine exactly what passage number in the curriculum a student should start with simply by having the student read a small number of pre-selected passages in the curriculum. Begeny (2009) describes the exact steps and rationale for the Placement Assessment, and the steps are likewise used for HELPS-PB.

It is beyond the scope of this paper to detail all the steps to administering the HELPS Placement Assessment, but because the HELPS-PB curriculum has its own sequence of passages (as shown in Table 1), it is necessary for this report to summarize how Study 1 completed the Placement Assessment decision-making rules for specific use with HELPS-PB. First, our decision-making rules followed the same logic and criteria used to develop the original HELPS Placement Assessment (e.g., the WCPM criterion table for the starting point in the curriculum was made with an interval of 20–30 words less than the student's reading target, and this was calibrated appropriately for each grade level). Second, we needed to identify 10 appropriate passages that would represent each of the five "Levels" that are integrated in the Placement Assessment. The term *Level* is simply used to describe some Placement Assessment procedures and does not reflect the level of education, grade level, or the ability of the student.

Consistent with past procedures for developing the HELPS Placement Assessment, two passages should be selected for each of the five levels, with each level reflecting meaningfully different difficulty of the passages. For example, Level 1 passages are meaningfully easier than Level 2 passages; Level 2 passages are meaningfully easier than Level 3 passages, and so forth. Also, passages with lower standard deviations are best to select for the Placement Assessment procedures. Based on these and related rules for passage selection, the passages selected for the HELPS-PB placement assessment are as follows: Level 1 (passages 2 and 7); Level 2 (passages 23 and 25); Level 3 (passages 48 and 55); Level 4 (passages 61 and 70); and Level 5 (passages 79 and 82).

HELPS-PB pilot implementation with instructional procedures and newly developed curriculum

With each of the earlier procedures in Study 1 completed, this allowed us to then pilot HELPS-PB implementation with students. This pilot involved using both the newly translated HELPS-PB instructional procedures and materials (all available in the HELPS-PB Instructor's Manual; Begeny et al., 2018a) as well as the now-finalized HELPS-PB curriculum of passages (Begeny et al., 2018b). This piloting of all HELPS-PB procedures and materials sought to verify whether the procedures (e.g., instructional steps, directions for students) used during the intervention are understandable by the target audience and to determine if students and teachers show responsiveness that is generally similar to what happens when HELPS is used in English or Spanish (based on past implementation of HELPS in these languages).

Participants

For the HELPS-PB pilot implementation, standard HELPS screening procedures (described next and within Begeny, 2009) were performed using Brazilian Portuguese ORF norms (see Martins and Capellini, 2021) to select students who could benefit from the HELPS-PB program. More specifically, to select the students who would participate in the pilot implementation, ORF scores were obtained from a sample of third to fifth grade students ($N = 174$) from one elementary school in the region of São Paulo. Prior to obtaining ORF scores, a parent or guardian of each student provided consent for participation. To participate, students also had visual and auditory acuity within the normal range and no presence of a neurological, behavioral, or cognitive disorder.

After administration of the ORF assessment with the 174 students (52 from third grade, 60 from fourth grade, and 62 from fifth grade), only students with reading difficulties were eligible to participate, as reflected by an ORF score between the 25th–50th percentile for the student's respective grade level. Given the main purpose of this pilot (i.e., to understand whether the HELPS-PB procedures and materials were usable for students and instructors and whether sessions appeared to have the same general "feel" and benefits as HELPS when used in English or Spanish), we selected 6 students to participate (two each from the third, fourth, and fifth grades). Important to highlight, the participants involved with this pilot were not eligible to participate in the quasi-experimental study (i.e., Study 2 of this report, described later) and did not participate in any other stage of this study.

Materials and procedures

The newly translated and adapted HELPS-PB materials were used in the pilot. Intervention procedures followed each of the overall HELPS implementation steps that were originally developed (see Begeny, 2009), but all directions to students and corresponding materials were in Portuguese. For this pilot, six intervention sessions were conducted with each student and took place at each student's school. Sessions were provided individually (interventionist and student only) and in a space provided by the school coordinator. Consistent with HELPS implementation recommendations, each student received three session per week. The duration of each session was approximately 15 min.

The lead researcher served as the interventionist during pilot implementation. In preparation for Study 1, she received the most intensive approach to HELPS training, which included 12 h of face-to-face training and structured practice activities that were facilitated by the program's developer. At the beginning of training, a workshop was provided by the program's developer to (a) address relevant instructional and theoretical questions, (b) teach workshop attendees how to implement the program, and (c) offer attendees structured practice opportunities with feedback. After additional practice, the lead researcher was eventually observed and verified by the program developer to be able to consistently implement the program with 100% fidelity.

To observe the overall usability of the program during the pilot implementation, we sought to gather information about some key questions. These questions were consistent with similar work of other researchers (e.g., Canhota, 2008) and guided by our interest in ensuring that HELPS-PB would be ready for Study 2. For example, we sought to understand: (a) the feasibility of implementing HELPS-PB three times per week in the participating school, and with sessions aimed to last approximately 15 min (which is important to assess because past research with HELPS had not taken place in Brazilian schools); (b) whether all HELPS-PB procedures and instructions were equally understood by all participating teachers and students; (c) whether students generally increased their WCPM on the passage practiced during each HELPS-PB session (which would be expected, based on past work with HELPS); and (d) whether students generally seemed motivated and engaged during each session.

Study 1 results

Given the goals of Study 1, we sometimes integrated data or related information about "results" in the prior sections if doing that could enhance understanding and readability of this report. This section, however, summarizes some key results of Study 1 that have not yet been specified.

Translation and back-translation of the original versions of HELPS

There are three main results to report of the translation process. First, based on conversations among those involved with translating HELPS-PB, it was decided to keep the version of the American name of the Program: *"Helping Early Literacy with Practice Strategies* (HELPS)" and adding "Brazilian Portuguese (PB)." As such, the finalized program name was determined to be HELPS-PB. Second, unlike the various modifications and the use of the semantic equivalence process used in the translation of the Leamos para Avanzar curriculum passages to HELPS-PB passages (e.g., searching for another word that best describes the meaning in a sentence), the translation of the Instructor's Manual from English into Portuguese typically did not require semantic equivalence processes because most of the language used in the manual is considered more technical-scientific. As such, translation of the manual allowed for a more rigid translation, referred to as word-word translation by Barbosa (2004). Third, from the back-translation and observations of the professionals trained by the translation committee, we observed that the translated part of the *HELPS* Manual was very similar to the retranslated or linguistically faithful material, demonstrating that this version closely approximated the original, maintaining a conceptual equivalence.

Adaptation of the HELPS-PB curriculum passages

It was possible that none of the themes of passages within the Leamos para Avanzar curriculum (Begeny et al., 2012a) would be analyzed in Study 1 as having content directly related to Brazilian culture. To discuss the possible need for exclusion and/or replacement of the passages, a meeting was held with the author of the original HELPS program, who encouraged and authorized replacement of any passages if that would help enhance the HELPS-PB curriculum's themes to be more familiar and applicable to Brazilian students. When the Leamos para Avanzar curriculum was adapted from English into Spanish, three passages from the original HELPS program were excluded due to insufficient fit of culturally appropriate themes. Those three passages were replaced with three new passages that were developed to have themes and content closer to the reality of many students in Latin American. After analyses of passage content in the adaptation of HELPS-PB, it was decided to keep all the passages from the Leamos para Avanzar curriculum, and new themes generally seemed appropriate for Brazilian students.

During the adaptation analysis, words of foreign origin that had been incorporated into the vocabulary of the Portuguese language were retained within the curriculum. In a meeting with the committee, and in consultation with the Michaelis Modern Portuguese Language Dictionary (online version)[1], it was decided to keep these "borrowed words," called anglicisms, due to their common use. In fact, many of the words can already be found in Brazilian Portuguese dictionaries, are part of the Brazilian culture, and have been systematically incorporated into daily life of Brazilians. Some examples of words maintained in the translation process of the curriculum passages are: milkshake, pizza, video game, picnic, laser, kart, and guacamole.

Unlike Anglicisms, other foreign words were retained from the original translation even though they were not incorporated into Portuguese, as they describe words and foreign behaviors that were the subject of the passages and reflected cultural diversity of different countries. This included words such as *plátano banano, cambur, guineo, avocato, and oonch neech*. To mark the distinction of foreign words or expressions that are not included in the dictionary, they were written in italics within the HELPS-PB curriculum, thus highlighting them as foreign words. If the students did not read these words correctly, they were not considered errors.

HELPS-PB pilot implementation

In seeking to understand program usability of HELPS-PB during pilot implementation, we observed the following. First, the 15 min allotted for implementation was adequate to use all program steps with fidelity and it was likewise observed that students' school routine allowed for three sessions per week. Classroom teachers knew when and how each student would be met by the interventionist to receive intervention and teachers reported feeling comfortable with the process.

Pilot implementation also revealed that all students, regardless of grade, easily understood the commands and instructions used during each HELPS-PB session. These observations suggested that although some of the fluency-based activities may have been somewhat unfamiliar with students' typical school-day experience, they understood how to engage in the activities and showed no signs of disliking the activities. Rather, students showed and verbalized that they enjoyed the sessions, maintained age-appropriate engagement throughout each session, and liked the praise and systematic motivational system integrated within the program. Based on these observations, the program development team did not see a need to modify any of the procedures, directions for students, or methods for gathering reading data during each session.

The pilot also showed that students routinely increased their WCPM on passages from the beginning to end of the session, which is what would be expected and evidenced if the activities were, in fact, helping students improve their fluency on the passage practiced in each respective session. This was also important to find because the six students who participated in the pilot had started on different passages and each read multiple passages (range = 3–5) across the six pilot sessions. Additionally, the interventionist had no difficulty completing the student's Progress Tracking Form or using the graph or motivational Star Chart.

1 Available at: http://michaelis.uol.com.br/moderno-portugues/

Study 2: Quasi-experimental evaluation of the *Helping Early Literacy with Practice Strategies* program in Brazilian Portuguese (HELPS-PB)

Method

Participants

As described previously, the pilot implementation (conducted as part of Study 1 of this report) involved an ORF screening assessment with 174 students in grades 3–5. This process sought to identify students who could benefit from the HELPS-PB program as an intervention targeting students with difficulties in text reading fluency. Specifically, Martins and Capellini (2021) established ORF norms in Brazilian Portuguese and recommended that students in need of targeted fluency intervention are those students who fall within the 25th–50th percentile. Accordingly, Study 2 included students within that sample of 174 who (a) fell within the 25th–50th percentile range; (b) did not participate in the pilot implementation summarized in Study 1; (c) had visual and auditory acuity within the normal range; and (d) had no presence of a neurological, behavioral, or cognitive disorder. A total of 23 students met these inclusion criteria. Intervention staffing at the time of the study allowed for up to 15 students to receive approximately 30 sessions of HELPS-PB, so 15 students were randomly selected to receive HELPS-PB (i.e., experimental group students) and all remaining students ($n = 8$) were randomly assigned to a wait-list control condition.

Of the 15 students in the experimental group, five were in third grade, five in fourth grade, and five in fifth grade. Of the eight control group students, two were in third grade, four were in fourth grade, and two were in fifth grade. All control-group students received the HELPS-PB intervention after Study 2 was completed, as suggested in the National Code of Ethics in Human Research.

Materials and procedures

Assessment of oral reading fluency

All participants in Study 2 received an ORF assessment at the very beginning (pre-test) and end (post-test) of the study. All assessments were completed within an approximately 1-week period at pre-test and again during post-test. Each student's WCPM and words read incorrectly per minute (WIPM) were evaluated. The passage selected for the pretest was "The Umbrella" and for the posttest the passage "The Secret of the Locker," both passages are within the narrative genre and published within the Reading Comprehension Assessment Protocol (RCAP; Cunha and Capellini, 2014). The RCAP is appropriate for students from the third to fifth grade and the user's manual suggests providing these two passages at pre-test and post-test like we did in Study 2. The choice to use narrative passages was because students are frequently exposed to narrative text during childhood and throughout the educational process.

Intervention procedures with the HELPS-PB program

The intervention was performed one-on-one (adult-student) in spaces provided by the school coordinator. The implementation period of HELPS-PB was 2 months and 25 days, beginning in August and ending in November. The HELPS-PB program was implemented approximately three times per week (every Monday, Wednesday, and Friday) for 12–14 min per session. All students received 30 intervention sessions.

The procedures of the HELPS-PB program are the same as those in the originally developed HELPS program in English (Begeny, 2009) and the subsequent Spanish version (Begeny, 2012). As a brief summary, implementation procedures include each of the evidence-based instructional and motivational strategies that past research (e.g., Therrien, 2004; Morgan and Sideridis, 2006; Lee and Yoon, 2017; Stevens et al., 2017) has found to improve students' fluency: repeated timed readings of ability-appropriate text, modeling, phrase-drill error correction, verbal cues for the student to read with fluency and comprehension, goal setting, feedback about the student's performance, and a structured motivational reward system {see Begeny (2009) [English] or Begeny et al. (2018a) [Portuguese] for details}. Additionally, HELPS implementation (regardless of language) incorporates 31 quality characteristics that help to ensure the most effective use of the core procedures (see instructor's manual for details).

To find the ideal passage for each student to begin the HELPS-PB intervention, we followed the HELPS-PB Placement Assessment that was summarized in Study 1. In each intervention session, the instructor had the implementation flowchart and specified student directions, which were followed in each HELPS-PB session. Figure 2 presents a visual depiction of the primary stages and activities of Study 2.

Intervention fidelity and training

HELPS-PB was implemented by the lead researcher. At the time of the study, she had almost 10 years of experience implementing intervention programs for children with special educational needs. The Method section of Study 1 describes the extensive training this interventionist received prior to beginning Study 1.

In addition to comprehensive training in HELPS-PB, intervention fidelity was recorded at the end of each HELPS-PB session since this is a required procedure within the HELPS-PB program. That is, the final step of program requires that the instructor systematically reviews each step of the implementation sequence (i.e., of the 13 steps summarized on the one-page implementation flowchart) and then records the fidelity on the progress sheet if any of the steps were forgotten or implemented incorrectly. A previous study with this methodology demonstrated that self-recording is a reliable and valid method of assessing the implementation integrity of HELPS program procedures (Begeny et al.,

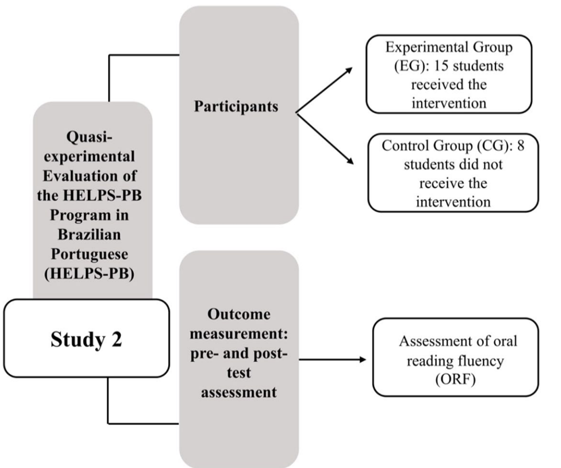

FIGURE 2
Diagram for the primary stages and activities of Study 2.

TABLE 2 Mean, standard deviation, and range WCPM and WIPM scores at pre-and post-test by group.

Group	*n*	Score	WCPM at pre-test	WCPM at post-test	Change in WCPM[1]	WIPM at pre-test	WIPM at post-test	Change in WIPM[1]
Experimental	15	Mean	83.7	93.5	9.8[a]	3.1	2.7	−0.5
		SD	(15.2)	(13.3)	(7.4)	(2.3)	(1.5)	(2.6)
		Range	61–106	65–115	3–28	0–7	1–6	−6–4
Wait-list control	8	Mean	90.8	93.0	2.3	4.0	4.1	0.1
		SD	(11.9)	(13.8)	(7.1)	(2.5)	(3.3)	(2.4)
		Range	73–106	70–108	−9–10	1–8	0–9	−4–4

[1]Change score refers to the change between pre-and post-test. [a]Denotes a statistically significant difference between the groups. WCPM, words read correctly per minute. WIPM, words read incorrectly per minute. SD, standard deviation (with scores shown in parentheses). Score ranges reflect students in third, fourth, and fifth grades, which helps to explain wider ranges for WCPM. Negative values in the last column reflect an improvement in reading during the post-test. The Experimental Group received HELPS-PB between the pre-and post-test period. Whereas the wait-list control group did not.

2013). Thus, based on data from each student's progress sheet, 99% of the total sessions were conducted with 100% fidelity of the core HELPS-PB procedures. That is, all 13 core steps were completed correctly.

Statistical analyses

To analyze possible differences in reading between the students in the experimental and control group, Mann–Whitney *U* tests (two-tailed) were used to examine possible difference in students' WCPM and WIPM scores. This non-parametric test was the most appropriate analysis because of our relatively small sample size and because the Mann–Whitney *U* is designed for two independent (versus dependent) samples. Prior to analyses, we set our *value of p* at 0.05., and to perform these analyses, we used the *Statistical Package for Social Sciences* (SPSS-version 28.0) software.

Study 2 results

Table 2 summarizes the average WCPM (words read correctly per minute) and WIPM (words read incorrectly per minute) scores at pre-and post-test for both the experimental and wait-list control group. As shown, students in the experimental group had, on average, somewhat lower scores at pre-test, but this difference was not statistically significant (Mann–Whitney $U = 48.0$, $n_1 = 15$; $n_2 = 8$, $p = 0.44$, two-tailed). Also, as stated previously, all participants were in the qualifying range for being able to benefit from a text-reading fluency intervention based on their pre-test score that was below average and generally within approximately the 30th-40th percentile based on ORF norms published by Martins and Capellini (2021).

At post-test, the experimental group increased nearly 10 WCPM whereas the control group made very little improvement over time (with a mean increase of only 2.3 WCPM). This difference in improvement (i.e., the gains made by those in the intervention group compared to gains made by those in the control group) was statistically significant (Mann–Whitney $U = 29.5$, $n_1 = 15$; $n_2 = 8$, $p < 0.05$, two-tailed). Using an effect size calculation for the Mann–Whitney *U* test,[2] this revealed found a large effect size: Cohen's $d = 0.9$; Eta squared $(n^2) = 0.17$.

With WIPM, the average score for the students in the experimental group improved somewhat between pre-and post-test whereas the average WIPM for students in the control group actually increased slightly during post-test. However, the differences were not statistically significant and, in general, both groups stayed relatively similar in their average WIPM between pre-and post-test.

Finally, although it was not a specific research question for Study 2, it is useful to note that some data from Study 2 helped to substantiate the passage sequencing and program adaptation process in Study 1. For example, the 15 participants in the experimental group had varied Placement Assessment scores, which is what would be expected if the Placement Assessment was developed well and the curriculum of passages were logically sequenced. Specifically, five students began on Passage 5; three began on Passage 25; two began on Passage 50; four began on Passage 66; and one began on Passage 75. Further, after identifying each student's proper starting point from the Placement Assessment, successful passage development and sequencing would allow students to improve their reading in each session and ultimately meet the Reading Goal fairly regularly (e.g., usually within 1–3 sessions of practicing that passage). Data from Study 2 showed that 100% of the students who received HELPS-PB regularly met the Reading Goal in ways we would hope; thus, all 15 students practiced several new passages during the 30 sessions they received in Study 2. Across all students, with a possible maximum of practicing 29 different passages within the 30 total sessions received, the median number of passages practiced was 24 (range = 14–29). These patterns of data are highly consistent with known data for HELPS when implemented in English (e.g., Begeny et al., in press).

Discussion of Study 1 and Study 2

National data in Brazil (e.g., OECD, 2019a; Brasil, 2021) and other countries (e.g., OECD, 2019b; National Center for Education Statistics, 2022) make it clear that millions of individuals have not yet established foundational literacy skills—which many argue is a violation of both human rights and equitable pathways to economic and quality-of-life opportunities. Reading fluency is a foundational literacy skill in most, if not all, alphabetic language systems, and evidence-based intervention programs targeting students' text reading fluency have the capacity to improve literacy development for millions of students (e.g., Therrien, 2004; Hudson et al., 2020). Cross-cultural collaboration and possible adaptation of existing literacy programs—especially when using values and processes of internationalization in education and psychology—offer a potentially promising approach to effectively and efficiently developing high-impact instructional programs that can meet global literacy needs (Arfken, 2012; Begeny et al., 2021).

2 https://www.psychometrica.de/effect_size.html

This two-part study was designed to (a) systematically translate, culturally adapt, and pilot test an existing evidence-based reading fluency program (Begeny, 2009) in order to create a version of that program (i.e., HELPS-PB) that can be used to support students learning to read in Brazilian Portuguese; and then (b) conduct an initial evaluation of HELPS-PB by using a randomized control-group quasi-experimental design. In Study 1, the systematic processes that were used (e.g., translation and back-translation, cultural adaptation, data-based curriculum sequencing, pilot implementation) ultimately led to the successful development of HELPS-PB materials and procedures. Given the systems and rigor employed in this process, it was not totally surprising to achieve successful development of HELPS-PB, as this outcome is consistent with similarly rigorous work that is often designed to translate and/or adapt other materials (often for assessment purposes) relevant to psychology and/or education (e.g., Cassepp-Borges et al., 2010; Almeida et al., 2013; Pasqualini et al., 2014). However, one should not assume such processes will lead to successful development of an adapted program, and Study 1 offers a comprehensive "blueprint" for how to achieve this with a structured literacy program such as HELPS.

Study 1 also revealed some interesting findings during the process. For instance, the translation and adaptation process led to retaining all passages adapted from the Leamos para Avanzar curriculum (Begeny et al., 2012a) and retaining several "borrowed words" from those passages. Considering that the translation of the curriculum passages sought to make the stories appropriate for most students living in Brazil, our most optimal translation and adaptation process—which sought high fidelity to the context and semantic meanings of words—did not benefit as much from following a process commonly described in the literature as word-for-word translation, which according to Barbosa (2004) reflects a literal translation. Our translation process considered the morphosyntactic changes necessary to produce the most acceptable passage in Brazilian Portuguese. This included attention to textual comprehension (Barbosa, 2004) and relevance for most Brazilian readers, while simultaneously wanting to minimize deviations from the original passage. Overall, due to the type of translation performed and its purpose, we found that there was no need to perform back translation of the HELPS curriculum passages, as this step was mainly necessary only for the HELPS instructor's manual. This approach was also appropriate because, after the adaptation process, we gathered and analyzed data from the HELPS-PB passages to systematically sequence the passages in order of difficulty and we then developed an updated Placement Assessment and appropriate grade-level goals for HELPS-PB implementation. From this, we then validated the work even further by using pilot implementation procedures.

In Study 2 (our quasi-experimental evaluation of HELPS-PB), we found that the students randomly assigned to the experimental group significantly outperformed students in the control group on WCPM, which is the measure of reading fluency that is considered by most fluency researchers to be one of the most important, studied, and valid measures of fluency (e.g., Hasbrouck and Tindal, 2006; Lee and Yoon, 2017). Furthermore, the difference between the groups on the change/improvement of WCPM from pre-to post-test resulted in a large effect size ($d = 0.9$). This finding is very important as a promising indicator of efficacy for the newly developed HELPS-PB program. The finding is consistent with past studies on HELPS in English and Spanish (e.g., Begeny et al., 2010, 2012b; Begeny, 2011, 2019; Malouf et al., 2014) and consistent with other empirical and theoretical work in text reading fluency (e.g., Laberge and Samuels, 1974; Therrien, 2004; Stevens et al., 2017; Hudson et al., 2020). Despite this empirical consistency, this is an important preliminary finding for HELPS-PB because (a) any newly adapted intervention program should be directly evaluated for effectiveness; and (b) to our knowledge, HELPS-PB is the first and only widely available program specifically designed to target and improve text reading fluency in Brazilian Portuguese.

In Study 2 we also found that students in the experimental group lowered their WIPM from pre-to post-test, whereas students in the control group somewhat increased in WIPM. Although this is a positive direction of reducing WIPM for students who received HELPS-PB, the difference between groups was not large or statistically significant. However, this finding is not necessarily surprising because students needing support with reading fluency usually have generally good accuracy (i.e., not a lot of WIPM). Thus, with (a) a low average WIPM score to begin with (e.g., average of 3 WIPM); (b) a low opportunity for variance among the groups and thus a fairly "restricted range" in scores (e.g., 0–3); and (c) a relatively small sample size in the study—we would not expect to see statistically significant differences between the groups on WIPM even if there was some relative improvement for those receiving HELPS-PB. In this study, we felt it would be relevant to at least report the WIPM data, but we also note that in many fluency intervention studies, WIPM does not even get reported or analyzed for the reasons above (e.g., Begeny et al., 2010, 2011; Mitchell and Begeny, 2014).

Implications

We believe our studies reported in this paper have meaningful implications for research, practice, and adapting reading fluency programs into other languages. Examples of such implications are as follows. First, Study 1 should assist reading researchers with understanding some key concepts and steps necessary in developing materials and research protocols that are essential for translating and adapting a reading intervention program in a comprehensive way and thereby preparing it to ultimately be evaluated in an experimental or quasi-experimental study (or optimally, a series of studies). We also encourage such researchers to consider adaptation and collaboration based on values and processes associated with internationalization (Arfken, 2012; van de Vijver, 2013; Begeny, 2018a), which should help to avoid the all-too-common "over-Westernization" of programming in non-Western contexts where that may be harmful (see, for example, Bernardo et al., 2018; Begeny et al., 2021). Indeed, a great deal of past work has used cross-cultural translations and adaptations, particularly when considering methods of assessment in psychology and/or education (van de Vijver, 2013); but much less appears to be written about comprehensive cross-cultural adaptation of targeted academic interventions that may have applicability to improve students' learning on a global scale. Thus, the present report offers one example that researchers can consider in this regard.

Another implication of our work and dissemination model for HELPS-PB allows easier opportunity for interested researchers to conduct additional efficacy or effectiveness studies on HELPS-PB—which is greatly needed at this time because multiple studies are needed to strengthen confidence and understanding about a program's impact. With HELPS-PB now fully developed and freely available for download, along with Study 2 showing initial indicators of efficacy for HELPS-PB, we encourage interested researchers to continue evaluating the impact of this program so that there is greater understanding about the contexts where it is effective and the variables (e.g., student grade level, type of interventionist) that may influence effectiveness. This model of dissemination was used with the original HELPS program and, to date, has assisted in better understanding the impact of HELPS in a range of different contexts.

In terms of examples of implications for practice, we first highlight that, as result of our studies, educators in Brazil now have an intervention program (HELPS-PB) to use with the many students in Brazil who struggle with reading fluency. Again, the free access to HELPS-PB, including all implementation materials and the do-it-yourself training materials (including freely accessible video demonstrations), may make this program appealing to teachers who need to better support students' reading fluency and are looking for a program to accomplish that. Indeed, just by having the program available online, the initial year has already resulted in hundreds of downloads by Brazilian educators. Additionally, our team, in collaboration with Helps Education Fund, aims to make video-based (e.g., with Zoom) or in-person training for HELPS-PB free or low cost for Brazilian educators who prefer that approach to training over the do-it-yourself model.

With this, we recognize the time-based limitation of using a one-on-one (adult-student) intervention program, but there are numerous ways in which the versatility of this intervention has made it widely usable and feasible for educators at the classroom, school, or district level (Begeny, 2009; Begeny et al., in press). Examples of what can make HELPS-PB versatile include (a) options to train non-education experts (e.g., community volunteers or university students preparing to be an educator) to implement the program with fidelity; (b) the feasible "dosage" needed for effectiveness (e.g., 15 min per session, three times per week); and (c) the ability for the program to be easily used by multiple interventionists with the same student. Also, a small-group version of the program can be implemented with multiple students at once, and our team is already in the process of translating the HELPS-SG instructor's manual (Begeny, 2018b) so that educators in Brazil have the additional option of using HELPS-PB with multiple students at once. Fortunately, the same HELPS-PB curriculum of passages developed in Study 1 is the curriculum needed for a forthcoming small-group version of HELPS-PB.

Finally, we believe another implication of this report is that Study 1 and 2 provide a relatively clear blueprint for other researchers, educators, or education administrators to consider if they are specifically interested in adapting the HELPS intervention program into other languages—in addition to what is currently available in English, Spanish, and Brazilian Portuguese. Such work may allow greater opportunity to support students around the globe who have not yet developed proficient text reading fluency in their native language.

Limitations and directions for future research

Both of our studies reported in this paper are not without limitations. For example, Study 1 ultimately allowed for an appropriate data collection process for purposes of sequencing the curriculum and developing implementation tools (i.e., the Placement Assessment) and guidelines (i.e., the Reading Goal levels for Brazilian Portuguese). However, this process could have been strengthened if it had included students in grades 2–4 and involved a larger number of students per grade level who could all read the initial set of HELPS-PB passages. For example, including 30–50 students across students in grade 2, 3, and 4—all of whom share similar grade-level oral reading fluency—would strengthen the process. Fortunately, the pilot implementation (Study 1) and subsequent quasi-experimental study helped to validate decisions on curriculum sequencing; but this limitation should still be considered as efficacy and effectiveness studies continue over time with HELPS-PB.

Pilot implementation and experimental work could also be improved in future research. For example, researchers are encouraged to collect acceptability and usability data (collected systematically through surveys and/or interviews) from (a) students who receive HELPS-PB; (b) interventionists who deliver it; and (c) classroom teachers of students who receive the program, if those teachers do not serve as the interventionist. Similar to current research with HELPS in English and Spanish, future research with HELPS-PB should also include different types of interventionists (e.g., classroom teachers, other school staff, teachers in training, community volunteers, etc.). Past studies with HELPS show that all types of interventionists can be equally effective as long as they receive proper training and implement with fidelity, but this type of research specifically with HELPS-PB would be beneficial.

Furthermore, future studies of HELPS-PB would benefit from including larger sample sizes for experimental and control groups, as well as using additional measures of student performance (e.g., multiple measures of oral reading fluency; robust measures of reading comprehension and/or prosody that are psychometrically supported and do not restrict variability in scored performance). These types of directions for future research are common for nearly all intervention research (especially newly developed programs), so we readily acknowledge that such work will greatly enhance the existing research-base of HELPS-PB. Such research with larger samples will also minimize Type 2 error. For example, in Study 2, the very small sample size significantly increased the probability of not finding a statistically significant effect. The fact that we still observed a statistically significant difference between the groups in students' improvement of WCPM suggests there was a strong and promising effect; but future studies should aim to minimize Type 2 error by having a sample size that supports a beta level of 0.20 or lower (i.e., having statistical power at 0.80 or higher).

Additional research should also systematically evaluate training and coaching procedures for educators and other interventionists who want to use HELPS-PB in their educational contexts. Such research will complement usability and acceptability studies of the HELPS-PB program by specifically examining the variables, challenges, and successes that come with training and coaching interventionists to use HELPS-PB in a variety of educational contexts. Similarly, future research should consider completing and reporting even more comprehensive evaluations of intervention fidelity. The present study monitored and reported fidelity in one way that has been supported by past HELPS research (e.g., Begeny et al., 2013), but most of the past research with HELPS also includes a report of intervention fidelity as determined by an independent observer who documents the fidelity of at least 20–35% of each interventionist's HELPS sessions with students—and we encourage this added level of fidelity reporting in future studies.

Conclusion

This report summarizes a 5-year project that ultimately achieved a fully adapted version of an evidence-based reading fluency intervention into Brazilian Portuguese and the first quasi-experimental evaluation of the program. HELPS-PB is now available for researchers and educators to potentially use and/or further research, and such work will hopefully allow for an expanded knowledge-base for HELPS-PB usability and effectiveness. HELPS-PB is simply one potentially promising tool to assist the millions of students in Brazil who have not developed proficient reading skills; but such a program and/or its iterations that may come from additional research and development, offers promise for providing students with a more equitable and effective learning experience—one that results in proficient reading skills and the opportunities that come from being a confident, proficient reader.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by UNESP—Faculdade de Filosofia e Ciências—Campus de Marília. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

MM designed and executed the study, performed the data collection, and wrote the manuscript and final revision of the manuscript. JB and SC designed the study, assisted with the data analyses, critically reviewed the theoretical content, and revised the manuscript. All authors have read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Reading comprehension performance of elementary and senior high school students

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Introduction: In Brazil, reading has been widely discussed, mainly due to the published results of national and international performance exams of Brazilian schoolchildren. Learning to read is therefore a continuous process, and the ability to make inferences while reading a text develops with age. The textual complexity involving the syntactic structuring, vocabulary and types of text progressively increases from the initial years of elementary school to high school students, also increasing the cognitive demand of the students; this occurs in parallel to their development and school advancement, which allows improvements in their teaching/learning processes. Based on the above, the following questions were raised: (1) How is the semantic process of reading established among elementary school students in elementary school (cycle II) and high school? Aim: to characterize the performance of elementary and senior high school students on semantic process tests from the Brazilian adaptation of the evaluation of reading processes (PROLEC-SE-R).

Methods: A total of 436 students of both sexes, aged between 11 and 18 years, participated. They were evaluated with Assessment of Reading Processes-PROLEC-SE-R.

Results and discussion: The results indicated that the semantic process was equally established among high school students, with a higher average performance compared with that of elementary school students. Among elementary school students, there was progression in the average correct answers with advancement in schooling. In the two levels of education, narrative texts allowed a greater number of correct answers, followed by multiple-choice and literal questions. The PROLEC-SE-R semantic process tests proved to be effective for assessing reading comprehension in elementary and high school students and reflected the Brazilian reality with regard to the gaps and weaknesses in the educational system.

KEYWORDS

reading, reading comprehension, adolescence, middle school, high school, assessment, education in Brazil

1. Introduction

In Brazil, reading has been widely discussed, mainly due to the published results of national and international performance exams of Brazilian schoolchildren. The most recent results of the International Student Evaluation Program (PISA), coordinated in Brazil by the National Institute of Studies and Educational Research Anísio Teixeira (INEP), applied in 2018, were released in 2019 (Brasil, 2019; OECD, 2019).

From a proficiency scale of one to six, 24.5% of Brazilian schoolchildren reached level two (minimum for reading proficiency). These students can identify the main idea of moderate-sized texts, can find information based on explicit criteria and can reflect on the purpose and form of texts if explicitly instructed to do so. Thus, students begin to demonstrate the ability to use their reading skills to acquire knowledge and solve a wide variety of practical problems (Brasil, 2019; OECD, 2019).

Those who do not achieve proficiency at level two – i.e., 50% of the schoolchildren - usually have difficulty with material that is unfamiliar to them or that is of moderate length and complexity. These students can understand the literal meaning of sentences or short passages, identify simple connections between the information provided and rely on their own prior knowledge (Brasil, 2019; OECD, 2019).

Approximately 2% of students reached levels five and six; they are able to understand long texts, deal with abstract or counterintuitive concepts and make distinctions between fact and opinion based on implicit clues regarding the content or source of the information. The INEP assumes that these results hinder or even prevent these students from advancing in their studies, have better job opportunities and become active citizens (Brasil, 2019). This is because reading is the main tool for students to acquire new concepts (both in academia and in situations of daily life and participation in society) and can also influence their health and their future generations, being one of the greatest challenges of schools today (Sánchez et al., 2012; Norton et al., 2014; Azizifar et al., 2015; Denton et al., 2015; Oliveira and Capellini, 2016; Okkinga et al., 2018; ter Beek et al., 2018; Hjetland et al., 2020).

One of the models used to explain reading is the "Simple View of Reading" by Hoover and Gough (1990), which states that decoding and listening are fundamental predictors of reading comprehension. These two components are independent and may be altered separately. This means that it is possible to have a good ability to understand oral language and not to decode words efficiently but that it is not possible to have adequate reading comprehension without efficient decoding and listening (Hoover and Gough, 1990; Massonnié et al., 2019).

Decoding is the process of converting graphemes into phonemes, from which the reader is expected to achieve automaticity, i.e., speed, accuracy and efficiency in the conversion of these segments (Coltheart et al., 2001; Cunningham et al., 2002; Cuetos, 2010; Sánchez et al., 2012; Navas, 2017; Oliveira, 2017; Clemens et al., 2018, 2020). Share (1995) states that word decoding is the starting point for reading comprehension. Conversely, oral comprehension is defined as the ability to obtain semantic information at the word level and thereby assist in the understanding of both oral and written discourse (Hoover and Gough, 1990; Massonnié et al., 2019).

Upon recognizing a word, the word must be used in a sentence so that a message can be extracted and integrated into a student's knowledge. Every time a student transfers what he or she reads to what he or she already knows (his or her knowledge of the world and his or her prior knowledge), thus constructing meaning from reading a text, the student acquires new ideas, enabling cognitive development (Cuetos, 2010; Sánchez et al., 2012; Kintsch and Rawson, 2013; Nation, 2013; Perfetti et al., 2013; Capellini et al., 2014; Perfetti and Stafura, 2014; Azizifar et al., 2015; Tiffin-Richards and Schroeder, 2015; Hjetland et al., 2020).

Inference, in turn, is to go beyond what is explicit in a text or discourse to infer the intended message. Even in very clear texts, inferences are necessary (Nation, 2013). Inferences occur when two terms, apparently unrelated in a text, are related, making implicit knowledge explicit. Inference allows readers to connect the information in the text with their knowledge and to complete the information that is not present in the text but that the reader must know to understand the text (Cuetos, 2010).

Learning to read is therefore a continuous process, and the ability to make inferences while reading a text develops with age and varies depending on the nature of the inferential information requested (Spinillo and Mahon, 2007; Carvalho et al., 2009). The ability to construct inferences is determinant in the differentiation of individuals regarding reading comprehension.

Based on the above, the following questions were raised: (1) How is the semantic process of reading established among elementary school students in elementary school (cycle II) and high school?

The aim of this study was to characterize the performance of 6th to the 9th grade (elementary school cycle II) student and of 1st to 3rd grade high school students on tests of the semantic process of reading of the Brazilian adaptation of the evaluation of reading processes- PROLEC-SE-R.

2. Materials and methods

A cross-sectional quantitative study was conducted to characterize the performance of students on tests of the semantic process of reading in public and private schools in a city in Midwest São Paulo.

2.1. Participants

A total of 436 students were evaluated, among whom 221 (51%) were enrolled in state public education institutions and 215 (49%) were enrolled in private education institutions; of these, 263 (60%) were female, and 173 (40%) were male (Table 1):

The sample size was designed to ensure that the tests to be applied (Wilcoxon rank sum test, Mann–Whitney test, and Kruskal–Wallis test) obtained a minimum power of 80%, for a maximum deviation (standard deviation) of 0.2, at a significance level of 5%, for each of the three groups.

TABLE 1 Sample distribution per school year and mean age.

Group	School year	Mean age	*n*
G1	6th year Elementary School	11.19	61
G2	7th grade Elementary School	11.98	64
G3	8th grade Elementary School	12.83	65
G4	9th grade Elementary School	13.93	62
G5	1st grade High School	14.91	62
G6	2nd grade High School	16.09	61
G7	3rd grade High School	17.22	61
		Total	436

The criteria for the selection of students were as follows:

Inclusion criteria: (1) parents or guardians signed an informed consent form; (2) signature of the Terms of Assent; (3) regularly enrolled in elementary school cycle II or high school of the participating schools.

Exclusion criteria: (1) students who refused to participate, although the parents or guardians signed an informed consent form; (2) students with an interdisciplinary diagnosis of learning disorder, dyslexia or attention deficit hyperactivity disorder; (4) learning complaints (average score less than five); (5) alteration of language or speech; (6) refractive errors identified in school screening that were not corrected, severe reduction in visual acuity, low vision and/or visual impairment diagnosis; (7) diagnosis of hearing impairment; (8) diagnosis of genetic or neurological syndromes; (9) history of repetition; and (10) intellectual demeaning.

These criteria, with the exception of the consent and assent forms, were assessed by consulting the school records of the participants and/or reported by the teachers and school coordinators. All information related to learning complaints and diagnoses are included in academic records with a reference to the ICD or DSM-V. The learning complaints reported by teachers when not accompanied by documentation were compared with school grades. Students with a mean of less than five in the overall calculation of subjects were excluded.

Some students were excluded from the sample after data collection because language and speech changes were detected during the application of the tests. All students who returned a signed consent form and signed an assent form were evaluated, despite the detected changes, so as to not make any student feel excluded from his or her classmates; however, such individuals were not included in the study sample.

2.2. Instruments

Assessment of Reading Processes-PROLEC-SE-R (Oliveira, 2017; Oliveira et al., 2020).

The Brazilian adaptation of the assessment of reading processes (PROLEC-SE-R) (Oliveira, 2017; Oliveira et al., 2020) aims to evaluate the lexical, syntactic and semantic processes of reading. It consists of 13 tests, the first six of which are screening versions that can be applied collectively. The materials included in the battery are two test notebooks, i.e., (1) screening versions of exams 1 to 6 (which the student has access to during the evaluation) and (2) tests 7 to 13, which are applied individually, and the answer sheet. For this study, the semantic process of the two test books was used:

- Expositional comprehension (EC): In this test, the task consists of evaluating the ability of the student to extract information from the expository text and remember it. It includes literal and multiple-choice questions, with four answer options (A, B, C, or D).
- Narrative comprehension (NC): This test includes narrative-type text, with the objective of evaluating the student's ability to form a mental representation of the narrative-type text. It contains ten multiple-choice questions, with four answer options (A, B, C, or D), with consultation;
- Pure reading comprehension (PRC): The aim of this test is to evaluate the student's ability to understand expository text without the interference of memory. The student can consult the text to answer questions. Reading is performed aloud, and the time to complete the test is recorded;
- Mnemonic reading comprehension (MRC): This test evaluates the student's ability to understand expository texts with memory interference, with open questions; and
- Oral comprehension (OC): In this test, the examiner reads a text to the student twice, aloud. Then, one by one, ten questions are asked.

2.3. Procedures

1. The free and informed consent form was signed by the guardians of the students.
2. The terms of assent form was signed by the evaluated students.
3. The screening versions of the semantic process tests were applied collectively.
4. The remaining semantic process tests were applied individually.

Collective application: The students were collectively evaluated by the researcher in a private environment at the school. Groups were formed with ten students to minimize disruptions during the procedure. The order of application was as follows: (1) EC and (2) NC.

Individual application: The students were individually evaluated. The order of application was as follows: PRC, MRC and OC.

The application of the PROLEC-SE-R was performed in two sessions, i.e., collective and individual, performed on alternate days. Data collection was performed by seven professionals, all duly trained by the researcher to apply the PROLEC-SE-R. The information was recorded in a response sheet, which was identical for the collective and individual application sessions.

For the group session, the students were provided with a test book and a pencil with eraser to fill in the data and answers during the evaluation; average duration of the evaluation was 25 min. Groups were formed with ten students to minimize disruptions during the procedure. In the individual session, the answer sheet was kept by the evaluator, along with a stopwatch and pencil for notes; the average duration was 20 min.

The tests were applied in a classroom provided by the school or in the reading classroom during the reading period of school. Regarding the removal of students from class, permission was granted by the teacher in advance. Therefore, the removal of students was conditional on authorization by the responsible teacher and the content that was being taught at the time.

2.4. Data analysis

A database was created in a Microsoft Excel spreadsheet and transferred to STATA/SE (version 13.1) for statistical analysis.

Descriptive statistical tools were used to characterize the sample. Student's t test was performed to determine whether one average was higher than the other with respect to the variables time per education level and average age. Confidence intervals, with Student's t distributions, were calculated to determine the 95% confidence intervals for estimates of the means.

The Wilcoxon rank sum test (Mann–Whitney test) was used to compare the performance of students (correct answers) on the PROLEC-SE-R by level of education (elementary and secondary).

Kruskal–Wallis analysis of variance was used to compare the performance of schoolchildren per year of primary and secondary school, adopting a significance level of $\alpha = 0.05$. When it was necessary to identify which school years differed significantly from each other, contrast analysis was used.

2.5. Statement of ethics

This study is registered in the Brazil Platform (CAAE: 45464915.4.0000.5406) and was approved by the educational institution (opinion no. 1,125,746).

3. Results

Student's *t* test and the confidence interval (95% CI) were used to compare the mean age per school year and public and private schools. Student's *t* test was used to analyze whether one mean was greater than the other, and the 95% CI indicated how much variability in the estimates was concentrated around the estimated value.

The Student's t test results indicated that for the 1st grade of high school, one average was higher than the other. When analyzing the mean value obtained, private school students had a mean age higher than that of public school students. Despite this indication, when analyzing the 95% CI, the confidence intervals overlap, indicating equality between the means if the test were two-tailed ($p = 0.038$, 95% CI 1st public education: 14.51–15.05/95% CI 1st private education: 14.89–15.23).

When comparing the students by level of education (elementary and secondary), regarding the variable time and the collective version and individual version, by Student's t test, there was no evidence that one average was lower than the other, in relation to the time in minutes, for the execution of the tests (collective version $p = 0.999$, 95% CI: 40.04; 41.43/95% CI: 38.37; 39.50) and (individual version $p = 0.999$, 95% CI EF: 33.83; 35.37/95% CI ME: 31.95; 33.39).

To characterize the performance of elementary school students (PE) and high school students (ME) on the PROLEC-SE-R tests, the semantic processes of reading were assessed using Kruskal–Wallis analysis of variance, and when necessary, contrast analysis was performed to verify which groups differed from each other.

For the PE students, the Kruskal–Wallis test did not indicate evidence of a difference in EC ($p = 0.202$) and PRC-A (correct variable: $p = 0.136$), which are the tests that evaluate the comprehension of expository texts, one with memory interference (CE) and the other without (PRC-A). When analyzing the mean score and the median of the PRC test, all students of all years obtained a median value of 4 to 5, i.e., half of the correct answers.

In the narrative comprehension (NC) test, the Kruskal–Wallis test revealed differences ($p < 0.001$). The performance of multiple comparisons (contrasts) suggested that the differences occurred between students in the 6th and 8th grades, 6th and 9th grades and 7th and 9th grades (Table 2).

Evidence of a difference between the means was indicated in the timed reading comprehension test (PRC-T) ($p < 0.001$), MRC ($p = 0.002$) and OC (CO) ($p = 0.005$). The performance of multiple comparisons (contrast) suggested differences between students in the 6th and 7th grades, 6th and 8th grades, and 6th and 9th grades for the PRC-T, indicating longer reading times for 6th graders than for students in other grades. In the MRC test, the differences between the 6th and 8th graders, the 6th and 9th graders and, finally, the 6th and 8th graders in OC indicated inferior performance by the 6th graders in such tests.

In the timed PRC test (PRC-T), the median values corresponding to the time in seconds reading the expository text decreased with the advancement of education, as did the dispersion of the answers and the discrepant values.

For ME students, Kruskal–Wallis analysis of variance revealed differences between school years in the MRC test ($p = 0.041$). Despite the evidence of differences, differences were not identified in the contrasts (multiple comparisons: 1st grade and 2nd grade, 1st grade and 3rd grade, and 2nd grade and 3rd grade) (Table 3).

In the PROLEC-SE-R semantic process tests, there was no indication of evidence of differences for ME students (CE: $p = 0.262$; CN: $p = 0.221$; PRC-A: $p = 0.527$, PRC-T: $p = 0.065$ and CO: $p = 0.078$) (Table 2).

The Wilcoxon test was used to compare the test performance of PE students with ME students. There was evidence of differences between the groups, and the ME students had a mean score higher than that of PE students. Regarding the time variable (PRC-T), the PE students had times that were longer than those for ME students (Table 4).

4. Discussion

By characterizing the semantic reading process levels of elementary school (ES) and high school (HS) students, it was possible to observe that the mean performance of HS students was higher than that of ES students. As mentioned in the National Curriculum Common Base (BNCC, acronym in Portuguese) (2018), the textual complexity involving the syntactic structuring, vocabulary and types of text progressively increases from the initial years of PE to ME, also increasing the cognitive demand of the students; this occurs in parallel to their development and school advancement, which allows improvements in their teaching/learning processes (ter Beek et al., 2018, 2019; Brasil, 2019).

By characterizing the level of education, year by year, in PE, 6th and 7th graders are adapting to the new curricular structure. This finding is in agreement with what was proposed in the Common National Curriculum Base (BNCC) and in the National Curriculum Guidelines for Nine-Year Elementary Education (Resolution CNE/CEB no. 7/2010). PE is the longest stage of basic education, covering children between 6 and 14 years old, and for this reason, it is divided into two phases, initial years and final years. The transition between the initial and final years involves, in many cases, a change in school and is marked by changes in educational, curricular and faculty structures, in which there is a change from generalist teachers to specialists in different areas of education (Brasil, 2018).

Regarding the semantic process tests, pairwise comparisons indicated that HS students did not differ from each other, a finding that may lead to the inference that the semantic process is consolidated among these students; however, for these tests, the mean performance

TABLE 2 Description and comparison of the performance of elementary school students on the PROLEC-SE-R semantic tests.

	Mean (SD)	Median	Minimum	Maximum	*p* value	Difference between groups
Collective version						
EC						
6th year	6.36 (1.97)	7.00	2.00	10.00	0.202	
7th year	6.53 (1.99)	6.00	2.00	10.00		
8th grade	7.06 (1.84)	7.00	3.00	10.00		
9th year	6.79 (1.92)	7.00	3.00	10.00		
NC						
6th year	4.70 (2.00)	5.00	0.00	6.00	<0.001*	6° < 8°
7th year	4.90 (1.87)	5.00	0.00	6.00		6° < 9°
8th grade	5.86 (1.86)	6.00	2.00	7.00		7° < 9°
9th year	5.98 (1.63)	6.00	2.00	7.00		
Individual version						
PRC-A						
6th year	3.60 (2.11)	4.00	0.00	8.00	0.136	
7th year	4.29 (2.01)	4.00	0.00	9.00		
8th grade	4.41 (1.95)	5.00	0.00	9.00		
9th year	4.32 (2.05)	4.00	1.00	8.00		
PRC-T						
6th year	263.39 (92.03)	240.00	150.00	540.00	<0.001*	6° > 7°
7th year	217.45 (66.64)	200.50	109.00	428.00		6° > 8°
8th grade	199.06 (51.01)	191.00	130.00	380.00		6° > 9°
9th year	196.83 (39.18)	194.50	132.00	300.00		
MRC						
6th year	3.65 (2.50)	3.00	0.00	9.00	0.002*	6° < 8°
7th year	4.64 (2.41)	4.00	0.00	10.00		6° < 9°
8th grade	5.21 (2.29)	5.00	0.00	10.00		
9th year	5.33 (2.96)	5.50	0.00	10.00		
OC						
6th year	3.55 (2.42)	3.00	0.00	9.00	0.005*	6° < 8°
7th year	4.51 (2.59)	4.00	0.00	9.00		
8th grade	5.23 (2.71)	6.00	0.00	10.00		
9th year	4.77 (2.63)	5.00	0.00	10.00		

Kruskal–Wallis test. *Evidence of statistical association ($p < 0.05$). SD, standard deviation; EC, expository comprehension; NC, narrative comprehension; PRC-A, pure reading comprehension-correct answers; PRC-T, pure reading comprehension-time in seconds; MRC, mnemonic reading comprehension; OC, oral comprehension.

score was below the ceiling range. This result is consistent with the Spanish PROLEC-SE-R results (Cuetos et al., 2016); however, the average number of correct answers by these students was higher than that by Brazilian students, and the heterogeneity of the answers was lower. This result can be justified by the classification of Brazilian schoolchildren in the 2015 PISA, in which 51% were at level one, compared with 17% of Spanish schoolchildren (OECD, 2016).

The EC and MRC tests are mnemonic tests, with expository texts that require the use of memory. In the EC test, the questions are multiple choice, whereas MRC open questions require a greater linguistic demand by the student. In the EC test, the student reads the text silently; in the MRC test, the student reads aloud. For both ES and HS students, the average performance on the multiple-choice version (EC) was higher. This finding can be justified by the fact that tests with open questions require a greater linguistic demand than do tests with multiple-choice answers (Guimarães and Mousinho, 2019; Gentilini et al., 2020). However, in a recent study of a theoretical and empirical survey of international studies of reading comprehension tests, the authors found that many of the differences between tests with multiple-choice and open-ended questions may be related to the length of the text and the development of the reader (Guimarães and Mousinho, 2019).

Another important aspect is decoding. In the collective version of the EC test, reading was performed silently; in contrast, in the

TABLE 3 Description and comparison of the performance of high school students on the PROLEC-SE-R semantic tests.

	Mean (SD)	Median	Minimum	Maximum	*p* value
Collective version					
EC					
1st grade	7.25 (1.92)	8.00	3.00	10.00	0.262
2nd grade	7.81 (1.73)	8.00	2.00	10.00	
3rd grade	7.68 (1.84)	8.00	3.00	10.00	
NC					
1st grade	5.93 (1.99)	6.00	1.00	10.00	0.221
2nd grade	6.45 (1.63)	7.00	0.00	9.00	
3rd grade	6.55 (1.91)	7.00	2.00	10.00	
PRC-A					
1st grade	4.66 (2.20)	4.00	0.00	10.00	0.527
2nd grade	5.04 (1.87)	5.00	1.00	9.00	
3rd grade	4.91 (1.87)	5.00	0.00	9.00	
PRC-T					
1st grade	184.61 (36.31)	179.50	120.00	291.00	0.064
2nd grade	172.00 (31.31)	167.00	90.00	265.00	
3rd grade	179.34 (27.64)	176.00	120.00	305.00	
MRC					
1st grade	5.41 (2.73)	6.00	0.00	10.00	0.041*
2nd grade	6.31 (2.55)	7.00	0.00	10.00	
3rd grade	6.54 (2.58)	7.00	0.00	10.00	
OC					
1st grade	5.01 (2.53)	5.00	0.00	10.00	0.077
2nd grade	5.73 (2.70)	6.00	0.00	10.00	
3rd grade	6.01 (2.14)	6.00	1.00	10.00	

Kruskal–Wallis test. *Evidence of statistical association ($p < 0.05$). However, the contrasts did not indicate which groups differed individually from the others. SD, standard deviation; EC, expository comprehension; NC, narrative comprehension; PRC-A, pure reading comprehension-correct answers; PRC-T, pure reading comprehension-time in seconds; MRC, mnemonic reading comprehension; OC, oral comprehension.

MRC test, the text is read orally by the student. Reading aloud demands the activation of the phonological codes of words, while in silent reading, the orthographic forms of words directly activate meaning. Studies indicate that the identification of misspelled words is identified more frequently in oral reading than in silent reading, indicating that orthographic and phonological characteristics at the word level may affect oral reading more than silent reading (van den Boer et al., 2014).

The NC and PRC tests are structured in the same way as the EC and MRC tests; however, the evaluation is based on the inferential processing of a narrative (NC) and expository (PRC) text. The superior performance of both PE and ME students on the NC test may have been influenced by the linguistic decrease that multiple-choice tests offer. However, in addition to the multiple-choice answers and open questions factor, there are also types of narrative and expository texts. Narrative texts are more common in the early years of PE, potentially hindering the adaptation of students when entering PE II to expository texts. In addition, with school progression, expository texts increase in syntactic complexity, and the content becomes denser, with unknown vocabulary and no previous reference to the subject, requiring the student to monitor his or her reading and knowledge of strategies for understanding (Ahmed et al., 2016; Okkinga et al., 2018; Cockerill et al., 2019; Guimarães and Mousinho, 2019; ter Beek et al., 2019; Gentilini et al., 2020).

When comparing the EC and MRC tests (mnemonic) with the CN and PRC tests (without interference of memory with inferential questions), at all levels of education, the inferential questions generated more difficulties for the students to answer than did the literal questions. The students showed superior performance on the tests with literal questions, both in the collective and individual versions.

The best performance in literal-type questions indicates that the students acquired only general textual representations and details directly related to the topic; that is, the students built the macrostructure of the text, which is nothing more than the relationship of the ideas of the text, known as global understanding (Azizifar et al., 2015; Cunha and Capellini, 2016; Hjetland et al., 2020). The findings of this study agree with the latest PISA evaluations conducted in 2015 and 2018. Brazilian students have greater ease answering questions that involve the skills of locating and retrieving information (textual macrostructure). These skills are involved in the basic and elementary levels of reading development (Brasil, 2016, 2019; OECD, 2016, 2019).

As occurred in this study, in the PISA evaluation, the questions involving integration and interpretation skills were the most difficult.

TABLE 4 Description and comparison of the performance of elementary and high school students on the PROLEC-SE-R semantic tests.

	Mean (SD)	Median	Minimum	Maximum	*P*-value	Difference between groups
Collective version						
EC						
PEII	6.69 (1.94)	7.00	2.00	10.00	<0.001*	PEII < HS
HS	7.58 (1.84)	8.00	2.00	10.00		
Total	7.06 (1.94)	7.00	2.00	10.00		
NC						
PEII	5.36 (1.92)	5.00	0.00	10.00	<0.001*	PEII < HS
HS	6.31 (1.86)	7.00	0.00	10.00		
Total	5.76 (1.95)	6.00	0.00	10.00		
Individual version						
PRC-A						
PEII	4.16 (2.04)	4.00	0.00	9.00	<0.001*	PEII < HS
HS	4.87 (1.98)	5.00	0.00	10.00		
TOTAL	4.46 (2.05)	4.00	0.00	10.00		
PRC-T						
PEII	218.39 (69.85)	200.00	109.00	540.00	0.000*	PEII > HS
HS	178.68 (32.22)	175.00	90.00	305.00		
Total	201.84 (60.37)	186.50	90.00	540.00		
MRC***						
PEII	4.72 (2.62)	5.00	0.00	10.00	0.000*	PEII < HS
HS	6.08 (2.65)	7.00	0.00	10.00		
Total	5.29 (2.71)	6.00	0.00	10.00		
OC						
PEII	4.53 (2.65)	4.00	0.00	10.00	0.000*	PEII < HS
HS	5.58 (2.49)	6.00	0.00	10.00		
Total	4.97 (2.63)	5.00	0.00	10.00		

Wilcoxon test. *Evidence of statistical association ($p < 0.05$). EC, expository comprehension; NC, narrative comprehension; PRC-A, pure reading comprehension-correct answers; PRC-T, pure reading comprehension-time in seconds; MRC, mnemonic reading comprehension; OC, oral comprehension; PEII, elementary school II; HS, high school.

These skills involve the formulation of inferences, an understanding of gender, linguistic style, knowledge of the world and prior knowledge, the ability to think about the structure of a text and how it is organized and the relationships of grammatical structures (Brasil, 2016; OECD, 2016). Inferential questions can only be answered with a full understanding of the text, with the integration of information in the memory and with the completion of corresponding inferences. As stated in the PISA report (Brasil, 2019; OECD, 2019), Brazilian students are able to easily identify the function of specific textual sequences for the objectives and purposes of different texts and to understand their global meaning; however, they have difficulty inferring information on the same subject.

When analyzing the reading time of the expository text in the PRC test, there is evidence of a difference between the means, indicating that with the advancement of schooling, there is a decrease in the time in seconds of reading from ES to HS. By decreasing the reading time, there is a consequent increase in words read per minute. This finding is contrary to the studies by Hasbrouck and Tindal (2017) and Washburn (2022); according to the data presented by those authors, the number of words read correctly per minute increases with the progression of schooling but only until the sixth school year, when the number of words read per minute remains the same, even with advancement of schooling.

In a Brazilian study conducted by Gentilini et al. (2020), the average silent reading time for a narrative text was recorded for 6th and 7th graders grouped in a single group and 8th and 9th graders in another group. No statistically significant difference was found, indicating a possible stabilization of textual fluency in adolescence.

One of the differentials of the PROLEC-SE-R is the evaluation of the OC of texts. The main reason for the evaluation of OC is that difficulties in reading comprehension may originate in oral language, in decoding and/or in the lack of automatic identification of written words.

The progression in the performance of students, with the advancement of education, supports results reported in the literature, i.e., OC increases throughout development and has a reciprocal relationship with the development of reading comprehension. Lexical knowledge, knowledge of the world, syntactic processing and the making of inferences develop as these skills advance (Perfetti et al., 2013).

The poor reading performance of Brazilian schoolchildren may be due to difficulty in the development of oral language as well as a lack of knowledge of the subject and vocabulary, which develop with age and reading practice and experience, fundamental factors for a thorough understanding of texts (Cuetos, 2010; Sánchez et al., 2012; Nation, 2013; Perfetti et al., 2013). The authors state that reading comprehension and OC originate from the same neural circuit. The general ability to understand text increases with reading experience and experience with spoken language (Cuetos, 2010; Perfetti et al., 2013).

The results from this study provide speech-language pathologists and other health and education professionals with elements for understanding the reading profile of students in PE II and Brazilian high schools. The PROLEC-SE-R semantic process tests proved to be efficient for the evaluation of reading comprehension in elementary and high school students and reflected the Brazilian reality with regard to the gaps and weaknesses in the educational system. With this knowledge, professionals can both evaluate reading with adequate parameters and contribute to the planning of both clinical and educational interventions.

4.1. Study limitations

The sample size was calculated on the basis of the statistics used. Inferences from the sample can be made for students from schools and municipalities similar to the study population because there is no evidence that the phenomena studied are different in other schools and cities. However, when generalizing the population data, different types of teaching materials used in the country, teaching methods, socioeconomic-cultural conditions and regionalism should be taken into account.

5. Conclusion

Reading processes are established equally among HS students, and in ES, there is a progression in the average performance (correct answers) as schooling advances, especially in those from the 6th year to other years of ESII.

There is evidence that compared with that of ES students, the average performance of HS students on the PROLEC-SE-R semantic process tests is superior.

For both primary and secondary education, narrative texts allow a greater number of correct answers, as do texts that offer questions with multiple-choice answers. Inferential questions generate more difficulties for students to answer than do literal questions. The OC of expository texts by students is low, which may reflect difficulty in language development, low vocabulary, a lack of knowledge of the subject, among other factors that can affect OC.

The PROLEC-SE-R semantic process tests proved to be effective for assessing reading comprehension in elementary and high school students and reflected the Brazilian reality with regard to the gaps and weaknesses in the educational system.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Research Ethics Committee of the School of Philosophy and Sciences of the São Paulo State University "Júlio de Mesquita Filho" (UNESP), Marilia, São Paulo, Brazil (opinion no. 1.125.746). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

AO: contributions to the conception and planning of the study, data analysis, interpretation, drafting and revision, final approval, and agreement to be accountable for all aspects of the work. JS: substantial contribution to the study design, statistics, data analysis, revision, final approval, and agreement to be accountable for all aspects of the work. SC: contributions to the conception of the study, planning and guidance of the research project, substantial revising, final approval, and agreement to be accountable for all aspects of the work. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Reading-to-Writing Mediation model of higher-order literacy

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Introduction: Writing difficulties frequently manifest comorbidly with reading challenges, and reading is implicated in particular acts of writing, such as reviewing and editing. Despite what is known, however, there remain significant barriers to understanding the nature of reading-writing relations, as few studies are comprehensive in the number and types of literacy skills evaluated. This study consists of a secondary data analysis of two studies employing structural equation modeling (SEM) to evaluate relations among reading and writing components skills independently, using the Direct and Inferential Mediation Model (DIME) of reading comprehension and Not-so-Simple View of Writing (NSVW) as theoretical frameworks.

Methods: We examine relations between reading and writing components from these models with a sample of upper elementary students with/at-risk for learning disabilities (n = 405). Lower-order components included word reading, vocabulary, handwriting and spelling. Higher-order components included background knowledge, reading strategies, inferencing, planning, editing, and revision. The literacy outcomes were oral and silent reading fluency, reading comprehension, and writing quality and productivity. We systematically build a Reading-to-Writing Mediation (RWM) model by first merging the DIME and NSVW components in a direct effects model (Aim 1), expanding the joint model to include reading and writing fluency (Aim 2), evaluating indirect effects between DIME and NSVW component skills (Aim 3), and finally, evaluating indirect effects with reading and writing fluency (Aim 4).

Results: The findings suggest that higher order fluency and comprehension skills are differentially related to writing activities and products.

Discussion: The pattern of results helps elucidate the mechanisms of how various reading and writing skills transfer and relate. The results have implications for targeted and implicit instruction in multicomponent interventions and the use of screeners to identify areas of risk.

KEYWORDS

written expression, text writing, compositional fluency, reading comprehension, text reading fluency, learning disabilities

Introduction

National data on student performance in the United States indicates that reading and writing (R-W) continue to be areas of concern, particularly for children with or at-risk for learning difficulties. Just over one-third of the nation's students in grades 4, 8, and 12 demonstrated proficient reading comprehension in the latest National Assessment of Educational Progress (NAEP; McFarland et al., 2019). The NAEP Oral Reading Study (White et al., 2021) showed that reading fluency is also a concern for grade 4 students with reading difficulties; specifically, students who performed at the basic or below basic level on the NAEP reading assessment performed significantly lower on measures of passage fluency, accuracy, and expression in comparison to students at the proficient and advanced reading levels. Students at the lowest level of performance averaged just 71 words read correct per minute and 82% accuracy. Historically, an even lower percentage (~25%) of students have attained proficiency in writing (Aud et al., 2012). Beyond the K-12 setting, writing serves as a gatekeeper to college access for underrepresented students. Of note, 58% of employers rated recent graduates as not proficient in writing, and proficiency in written communication skills was considered essential by nearly 96% of employers, who report often considering writing skills when making decisions about hiring and promotions (National Association of Colleges and Employers, 2017). The National Commission on Writing (2004, 2005) estimated that $3.1 billion are spent annually remediating writing skills in the private sector and $250 million in the public sector.

Many individuals who have difficulty with reading also have challenges in the area of writing, highlighting the established connection across these skill areas; however, there is limited research on the relationships among R-W component skills. One group of students particularly likely to demonstrate lower performance in R-W are those with learning difficulties (LD; Fletcher et al., 2018). The most commonly occurring difficulties for students with LDs are word reading, fluency, and comprehension. Students with word-level reading difficulties, such as those with dyslexia, exhibit difficulties not only with handwriting and spelling but also demonstrate deficits with composition skills such as editing (e.g., Berninger et al., 2008; Carretti et al., 2016; Hebert et al., 2018). Difficulty with reading comprehension has been linked to difficulty with composition quality (Cragg and Nation, 2006; Re and Carretti, 2016). Given this reality, and the need to better understand the R-W connection in this group, the primary purpose of this study was to conduct an exhaustive examination of the associations among R-W skills to better inform research and practice. Theoretical and empirical accounts of literacy (described below) suggest that multiple skills contribute to the inter-connectedness of R-W. In an era when multiple interventions are available and easily accessible, it is important for researchers and practitioners alike to understand the complex patterns in which literacy skills interact with each other and how reading skills can be leveraged to explicitly teach skills in the academic domain of writing (and vice versa). Understanding the connections across these skill areas is critical given not only the opportunities for better conceptual or theoretical understanding of the relationships but also the potential for direction regarding the provision of literacy supports broadly.

Reading-to-Writing directionality

The instructional context in which R-W skills are taught can significantly impact the connection between reading and writing, as writing is both shaped and constrained by socio-cultural factors (Graham, 2018). Research has demonstrated that when R-W skills are integrated and taught together, rather than in isolation, students develop stronger R-W skills (Hebert et al., 2018). For example, writing-to-learn approaches emphasize using writing as a tool for understanding and learning new information through activities like summarizing or creating concept maps, which can help students organize and make sense of texts, which in turn can improve reading comprehension. R-W instruction can also be integrated through reading-to-write approaches, which emphasize using reading as a tool for developing writing skills. When students read a wide range of texts, they are exposed to a variety of text genres and structures, which can improve their own writing skills. We focus on the Reading-to-Writing directionality because the instructional context of this study was business-as-usual (i.e., reading instruction was more easily and frequently implemented than writing instruction; see Ahmed et al., 2022a). While we acknowledge that directionality of influence between R-W is not necessarily unidirectional, we emphasize the need for careful consideration of contextual factors, such as the nature of R-W instruction, orthography, and other relevant factors, in determining the directionality of the influence of one set of skills on another. In this study, we present an alternative Writing-to-Reading model in Supplementary Appendix B to acknowledge the potential for bidirectional influence, noting that the current study is limited in its capacity to establish causal connections because doing so necessitates an experimental research design. In the next sections, we start by presenting piecemeal evidence of R-W associations from experimental and correlational studies and end with component skills models that incorporate multiple skills and their interrelations.

Word-, sentence-, and text-level reading-writing

Robust relations between word reading and transcription skills (handwriting and spelling) have been demonstrated (e.g., Berninger et al., 2002; Abbott et al., 2010; Georgiou et al., 2020), and word-level literacy has been established as an important precursor of production and quality of writing. In addition, there is ample evidence for the relation between reading comprehension and writing skills, including word-level skills like spelling (Berninger et al., 2002) and text-level writing outcomes (e.g., Cragg and Nation, 2006; Carretti et al., 2016). There is little evidence, however, of the relationship between oral and silent reading fluency and the various levels of writing performance at the letter/word, sentence, and discourse levels.

Automaticity in R-W is a general issue affecting children with LDs, although little is known about whether rate-subtypes of disability can be reliably identified as separate subgroups of LD (Fletcher et al., 2018). Compromised accuracy and automaticity of word-level skills result in problems of automaticity at the sentence and discourse level of R-W fluency by reducing access to processes required for constructing meaning (e.g., inferencing or revision), as conscious attention to decoding or spelling makes R-W slow and laborious (Fletcher et al., 2018). Consequently, children with LDs are limited to proofreading texts for mechanics but not substance or content (MacArthur, 2016).

Oral reading fluency (ORF)—the ability to read aloud with speed, accuracy, and proper expression— is heavily used both in research and practice as an overall indicator of performance in reading because it is highly predictive of reading problems in children with LD (Deno, 2003). ORF is an overall indicator of reading performance in early elementary grades where the number of words read correctly in 1 min is the outcome observed. Measures of ORF are used as part of screening efforts in the context of multi-tiered systems of support (MTSS) where performance in reading is measured periodically and used to identify those students at-risk for poor performance as well as to monitor progress in response to instruction or intervention.

Limited studies investigate the relationship between reading fluency and writing —specifically, planning, translating, and revising—in typically developing and children with LDs (Graham and Hebert, 2011) despite the clear correlations of reading fluency with writing outcomes and the regular use of ORF in practice (e.g., Shinn et al., 1992; Fewster and MacMillan, 2002; Cragg and Nation, 2006; Berninger et al., 2008; Codding et al., 2015). There is support for the notion that the rate, accuracy, and prosody in ORF may relate to spelling at the word-level (Bear, 1991; Lefly and Pennington, 1991; Ritchey and Coker, 2014), although other researchers have found that ORF did not relate to spelling after controlling for other foundational reading skills (Morris et al., 2017). Two studies found that ORF was related to the total number of words written at the text-level for children in elementary grades (Ahmed et al., 2014; Tortorelli and Truckenmiller, 2023), but these studies did not explore the relations of ORF with sentence-level writing or text-level writing quality. Bear (1991) hypothesized that ORF may play a role in one writing process (planning) because word- and phrase/sentence-level planning are especially evident in oral expression (e.g., phrasal intonation and placement of accent in reading unfamiliar words). However, von Koss Torkildsen et al. (2016) found that ORF was *not* related to another writing process (revision) after controlling for executive function (working memory and attention) and spelling. To better understand individual differences in R-W, a more complete understanding of the role of ORF is necessary, when individuals engage in foundational writing skills at the word-level (e.g., spelling), self-monitoring during writing processes at the sentence-level (e.g., editing), and general writing outcomes at the text-level (quality and productivity).

Silent reading fluency (SRF) —the ability to read silently with speed and comprehension—emerges as a more important skill as students progress to higher grade levels, and ultimately adulthood, because SRF is required for more advanced texts. It is possible that SRF plays a more critical role in written expression when children are in the transitional phase from ORF to SRF and when the focus of instruction shifts from sentence- to text-level (Bear, 1991; Berninger et al., 2013; van den Boer et al., 2022). Notably, children with LD exhibit deficits in SRF that are commensurate with, or more pronounced than, their deficits in ORF (van den Boer et al., 2022). Research shows that SRF training results in better spelling for children with dyslexia (Berninger et al., 2013). Further, SRF contributes to children's ability to revise sentences, and revision also impacts SRF (Ahmed et al., 2014). To our knowledge no studies have systematically examined the contributions of both ORF and SRF to higher-order writing processes (Shanahan, 2012). We propose that when evaluating sentence level R-W together with word- and text-level R-W, sentence level skills will have greater predictive power for text level writing quality and fluency than word level literacy.

Higher-order reading-writing connections

Reading skills are needed when individuals engage in self-monitoring during the planning, revision, and reviewing states of writing. That is, one's ability to accurately and efficiently decode, scan, and comprehend what has been written are pre-requisite skills for revising the composition (McCutchen, 1996). Fitzgerald and Shanahan (2000) outline four areas of shared knowledge: (a) content or domain knowledge; (b) meta-knowledge about written language (i.e., functions and purposes); (c) pragmatic knowledge of text attributes (e.g., words, syntax, and usage); and (d) procedural knowledge for accessing information purposively, setting goals, analyzing, etc. For example, text is extended according to background knowledge and the writer's hypotheses about the readers' knowledge (Flower and Hayes, 1980), particularly in later grades, when students are required to write about topics outside of themselves (Davis and Winek, 1989). Knowledge of text structures help students understand the purpose for presenting information, the organization of ideas, and the use of similar schema across texts. A meta-analysis of 45 studies (Hebert et al., 2016), showed that text structure instruction (measured as strategies, such as evaluation of text) improved expository reading comprehension, particularly when including writing in that instruction. Furthermore, it has long been recognized that vocabulary plays a key role in writing development (Olinghouse and Wilson, 2013) with significant relationships evident for vocabulary to spelling and to planning before writing (Vanderberg and Swanson, 2006). Vocabulary knowledge is also related to individuals' written production and text quality (e.g., Carretti et al., 2016; Kim and Schatschneider, 2017). Finally, planning involves goal-setting and knowledge mobilization, requiring students to evaluate their own knowledge of the topic, and narrow their topics and goals (Tierney and Shanahan, 1991).

Older theoretical models devoted solely to the interaction among R-W processes (Pearson and Tierney, 1984; Langer, 1986) and broader frameworks of writing in adults also specify various mechanisms of co-development (Bereiter and Scardamalia, 1987; Tierney and Shanahan, 1991; Fitzgerald and Shanahan, 2000; Deane et al., 2008). For example, inferencing allows writers to elaborate a new representation from a former one and is related to writing for children in first grade (Kim and Schatschneider, 2017) and in college (Connelly et al., 2006). Overall, higher-order reading skills (background knowledge, inferencing, strategies for reading) predict writing-specific processes such as planning, editing, and revising (e.g., Tierney and Pearson, 1983; Kirby et al., 1986; Singer and Bashir, 2004; Weston-Sementelli et al., 2018). These reading skills are also related to the quality of written composition (e.g., Fitzgerald and Shanahan, 2000; Decker et al., 2016; Kim and Schatschneider, 2017; Weston-Sementelli et al., 2018). The important conclusion from the theoretical literature is that higher-order reasoning processes of R-W are text-based (i.e., require interaction with text).

Component-skills models of reading and writing

To examine the above-mentioned R-W relationships, it is important to situate the study within the specific component models of R-W focused on in the present study. Although several models exist in both areas, there is significant overlap in the component skills represented in each. For the current study, we chose to frame our examination of the R-W relationship using the Direct and Inferential Mediation Model (DIME; Cromley and Azevedo, 2007) and the Not-so-Simple View of Writing (NSVW; Berninger and Winn, 2006) because they are well aligned with cognitive theories of reading and writing, respectively.

Direct and Inferential Mediation model of reading comprehension

The DIME model posits that the several components work together for the end goal of comprehension, and account for virtually all the variance in reading comprehension (Cromley and Azevedo, 2007; Ahmed et al., 2016). The elements of the DIME model include: (1) *Decoding* and (2) *Vocabulary*, because students who have adequate word reading skills and word knowledge can better understand text (Hoover and Gough, 1990), (3) *Background knowledge*, because readers who possess high levels of general knowledge perform better on reading comprehension and retain the information for longer periods of time (Chiesi et al., 1979; Kintsch, 1988), (4) *Inferences* (knowledge-to-text and text-to-text integration) are automatically generated when students understand what is implied by the text without explicitly being stated (Cain and Oakhill, 1999; Barnes and Dennis, 2001), and (5) *Reading strategies*, refers to engagement in cognitive and meta-cognitive strategies, such as summarizing, structuring, drawing conclusions, and evaluating text (O'Reilly and McNamara, 2007). The DIME model can be seen as an extension of the Simple View of Reading (SVR; Gough and Tunmer, 1986). While the SVR conceptualized comprehension as a product of word reading/decoding and oral language/linguistic comprehension, in the DIME model, the components of linguistic comprehension are further specified as lower (i.e., word reading, vocabulary) and higher-level (background knowledge, strategies for reading, inferencing) component skills; reading comprehension is thought to be influenced directly and indirectly via these skills. To enhance understanding of relations among the DIME components, four studies included silent reading fluency (SRF) or efficiency as an additional predictor (Smith, 2013; Oslund et al., 2016, 2018; Völlinger et al., 2018). In general, SRF was a strong predictor of reading comprehension for children in upper elementary or middle school, but vocabulary had the largest direct effect, followed by inferences. The relation of SRF and comprehension was dependent on reader proficiency.

Not-so-Simple View of Writing

An early component skill model of writing was the simple view of writing, which posited that transcription and ideation (i.e., text generation) together were necessary for writing (see Juel et al., 1986; Berninger et al., 2002). As a follow-up and extension, the NSVW holds that transcription skills (e.g., spelling and handwriting fluency), along with ideation, interact with higher-order, executive, and self-regulatory functions to produce writing through planning, composing, and revision. That is, proficient writers possess linguistic knowledge of grammar and syntax to create coherent and well-structured sentences and also engage in multiple cycles of reviewing, revising, and editing their work to improve their content, organization, and language use. Further, working memory is intrinsic and is responsible for storing and manipulating information needed during planning, composing, and revision processes. Our recent study (Ahmed et al., 2022a) using structural equation modeling (SEM) showed the NSVW can be deconstructed into key correlates (cognitive resources: self-efficacy and executive function), components (lower-order writing: handwriting and spelling; higher-order writing: planning, editing, and revising), and attributes of writing (productivity, quality, complexity, etc.) with multiple relations within and across the model. Similar to Ahmed et al. (2022a), the present study operationally defines the editing component of the NSVW as a broad construct that includes the knowledge of grammar, spelling, punctuation, and capitalization rules, as well as the ability to effectively apply these rules during the writing process. Likewise, in our study, we operationalized the concept of revision as a comprehensive construct that involves an understanding of syntax and structure, such as the development and organization of sentences and paragraphs, and the effective integration of this knowledge into the child's written work. These definitions emphasize that the NSVW considers planning, editing, and revising as executive functions that necessitate the manipulation of information during the writing process beyond a mere understanding of grammar and syntax in oral language. The significance of these definitions lies in their recognition of the critical role played by higher-order cognitive processes in the writing process, such as the capacity to plan and organize ideas, pay attention to details, and revise written work for clarity and coherence. Consequently, the NSVW places equal emphasis on both declarative and procedural linguistic knowledge, highlighting the importance of not only understanding the rules of language but also applying them effectively in written expression.

Joint models of reading-writing

An early component skills model linking R-W development is the Simple View of Reading and Writing (SVRW; Juel et al., 1986), which specified common predictors of word recognition and spelling (e.g., lexical knowledge) but did not find support for connections among spelling and word recognition or among reading comprehension and writing. In the SVRW, oral language and IQ were exogenous factors which indirectly influenced spelling through their effect on phonemic awareness (i.e., the effect of oral language on spelling was completely mediated by phonemic awareness). More recently, Kim (2020) developed the Interactive Dynamic Literacy Model (IDL) and the Direct and Indirect Effects Model of Writing (DIEW; Kim and Graham, 2022). The premise of the IDL and DIEW is that several related, yet separate, systems support R-W and include oral language, knowledge, domain-general and higher-order cognition, and sociocultural systems. The IDL model is situated within a levels of language framework, including discourse (text reading fluency, text writing or composition fluency), sentence level (sentence comprehension and sentence writing fluency), lexical (word reading fluency, spelling fluency), and sub-lexical (phoneme-grapheme correspondence, transcription fluency) levels. Interactive relations are highlighted in both models with R-W skills developing interdependently within and across a hierarchy. For example, reading comprehension influences composition and the experience of generating compositions can enhance comprehension through promoting awareness of structure and meaning of text. Reading comprehension is also expected to vary as a function of dimension of written composition (e.g., writing quality, productivity, correctness in writing, syntax, story structure, etc.; Shanahan and Lomax, 1986).

The IDL and DIEW models are broad frameworks that build on older R-W models described above. The empirically tested versions of the IDL and DIEW models are narrower in the number and types of components included and the associations among them. The models

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do not specify direct relations among higher-order R-W (e.g., vocabulary or inferencing to written expression) because the tested models postulated a complete mediation of higher-order skills through their effects on oral language. In the DIME model described above, higher-order skills (vocabulary, background knowledge, inferencing, and strategies) are pre-requisite reading skills, and collectively replace the linguistic comprehension component of the Simple View of Reading. In contrast, in the empirically tested IDL and DIEW, oral language plays a central role. The same higher-order skills (vocabulary, background knowledge, inferencing, and strategies) are specified as pre-requisite oral language skills, such that higher-order skills only influence reading comprehension (and writing) indirectly through their effect on oral language. Additional research is needed to better understand the nature of the indirect *and* direct relations between higher-order R-W processes to provide critical information that informs interventions for students with LDs.

Current study

The purpose of this study is to examine the relationships between multiple component skills of R-W in a sample of children with LD, focusing on two areas of research that have received the least attention: (1) connections among higher-order component skills of R-W (e.g., inferencing and revision); (2) connections among reading fluency and higher-order R-W. Our central research question was: What are the direct (Aims 1 and 2) and mediated (Aims 3 and 4) relations among R-W skills in comprehensive component-skills models? With the above-mentioned theoretical models and existing evidence as our foundation for understanding component skills involved in the R-W connection, the following four aims guided this question:

Aim 1: To build and test a Reading-to-Writing Skills (RWS) model of literacy by joining the DIME and NSVW component skills (Model 1, Figure 1). As shown in Figure 1, this model evaluates direct effects only, with lower- and higher-order DIME skills on the left-hand side and lower- and higher-order NSVW skills on the right-hand side.

1.1. We hypothesized *word- and text-level connections* among word reading and transcription skill (spelling and handwriting), and reading comprehension and written expression (e.g., Juel et al., 1986; Berninger et al., 2002; Abbott et al., 2010). Although decoding contributes to writing quality and productivity (Connelly et al., 2006; Decker et al., 2016), we hypothesized that after controlling for higher-order skills, word reading would *not* relate to distal, higher-order writing processes or overall writing quality or productivity (Shanahan and Lomax, 1986; Morris et al., 2017), but vocabulary would significantly predict writing quality (e.g., Shanahan and Lomax, 1986; Olinghouse and Wilson, 2013; Allen et al., 2014; Carretti et al., 2016; von Koss Torkildsen et al., 2016; Neumann et al., 2020; Truckenmiller and Petscher, 2020).

1.2. We hypothesized *word-sentence level connections* of vocabulary with planning and editing (e.g., Vanderberg and Swanson, 2006) but not revision (von Koss Torkildsen et al., 2016).

1.3. We hypothesized *sentence-text level connections* among knowledge, inferencing, and reading strategies, and writing quality (Allen et al., 2014), along with direct connections among higher-order reading skills and composition processes gleaned from early theoretical models (e.g., Tierney and Pearson, 1983; Kucer, 1985): background knowledge with planning; reading strategies with planning, editing, and revision; and inferencing with revision. We hypothesized that inference would relate to revision rather than editing, which requires superficial changes to text compared to revision.

Aim 2: To expand the Reading-to-Writing Skills model to include connections with R-W fluency (e.g., ORF and writing productivity; Model 2, Figure 2). As shown in Figure 2, we include ORF and SRF as measures of reading fluency and we incorporate writing productivity as the measure of discourse-level writing fluency.[1]

2.1. We hypothesized *word- and text-level connections* of vocabulary with writing productivity but not of word reading with productivity (von Koss Torkildsen et al., 2016). Furthermore, we hypothesized that for children with LDs ORF would relate to spelling (Bear, 1991; Lefly and Pennington, 1991), writing quality (Ritchey and Coker, 2014), and productivity (Ahmed et al., 2014; Tortorelli and Truckenmiller, 2023). We expected that after controlling for word-reading and ORF, SRF would not relate to word-level writing.

2.2. We hypothesized *sentence-text level connections* among reading fluency, writing processes (e.g., editing and revision). We expected that after controlling for ORF and SRF, reading comprehension would predict planning and writing quality but not productivity or self-regulatory processes of editing and revision, and that ORF would relate to planning (Bear, 1991) but not revision (von Koss Torkildsen et al., 2016), and SRF would relate to revision (Ahmed et al., 2014).

Aim 3: To build and test a Reading-to-Writing Mediation (RWM; Figure 3) model with multiple direct and indirect paths between DIME and NSVW component skills (Model 3). Figure 3 depicts the domain-specific direct and indirect effects specified by the DIME or NSVW models (cross-domain associations are omitted for illustration purposes).

3.1. We hypothesized *connections among reading skills* such that reading comprehension would be related to vocabulary, knowledge, and inferencing, but reading strategies would not be a significant predictor of reading comprehension (Ahmed et al., 2016). Word literacy (i.e., word decoding and encoding) would relate to reading comprehension but also to reading strategies because this factor was measured using writing-for-reading tasks (i.e., summarizing), which are related to spelling (Bahr et al., 2020).

3.2. We hypothesized *connections among writing skills* such that word literacy would relate to handwriting quality and editing, but not distal, higher-order writing skills (planning and revision) and that direct and indirect effects among handwriting, planning, editing, revision, and writing quality would remain significant in the mediation model.

3.3. We hypothesized *cross-domain connections* among higher-order reading (vocabulary, knowledge, inferencing, and

1 Additional writing dimensions were evaluated in the Reading-to-Writing Dimensions model (see Supplementary Appendix A).

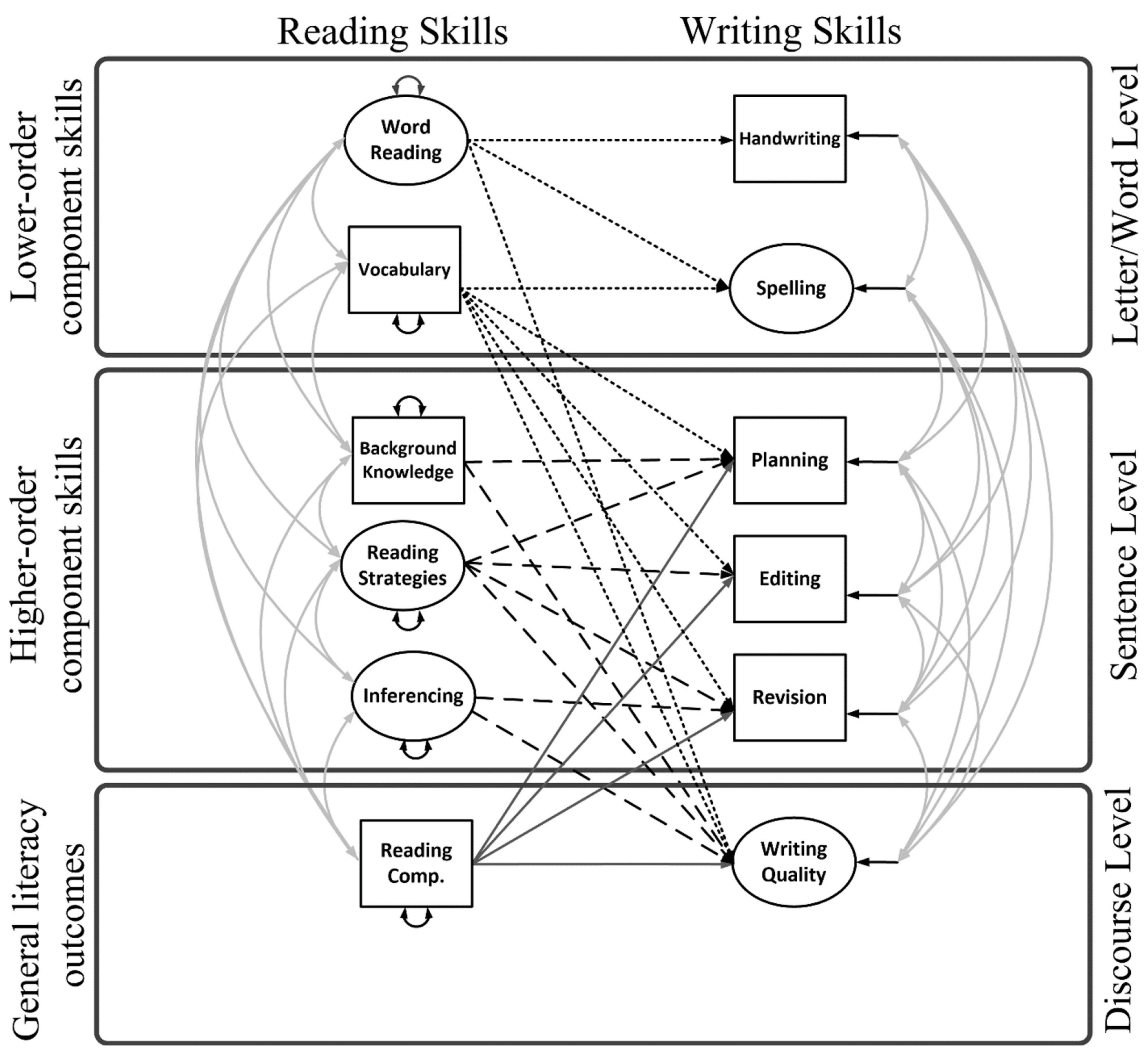

FIGURE 1
Reading-to-Writing Skills (RWS) Model without reading and writing fluency (Model 1). The component skills are grouped under (1) letter or word level, which encompasses code- and meaning-based skills mainly at the word level; (2) the sentence level, which encompasses meaning-making linguistics skills; and (3) general literacy outcomes at the discourse level. The component skills roughly correspond with the levels of languages specified in the figure because the granularity of a component skill may be dependent on a child's ability (e.g., planning may consist of single words for some students and sentences for others), the nature of the task (e.g., editing may involve correcting words or sentences), or the nature of scoring (e.g., legibility of letters and words were both considered for scoring handwriting quality). Small-dashed lines are 8 paths from lower-order reading skills to writing skills; long-dashed lines are 8 paths from higher-order reading skills to writing skills; solid lines are 4 paths from reading outcomes to writing skills. Double headed arrows are correlations or variances. Small single-headed arrows are residual variances.

strategies) and higher-order writing (planning, editing, revision) as well as reading comprehension and written expression. Figure 4 shows a mediation model in which (a) higher-order reading mediated the relations of basic literacy and knowledge with higher-order writing (e.g., vocabulary ➔ inferencing ➔ revision), (b) higher-order writing mediated the relations of higher-order reading and writing quality (e.g., reading strategies ➔ editing ➔ writing quality), and (c) higher order writing mediated the relations of basic literacy and knowledge with writing quality (e.g., background knowledge ➔ planning ➔ writing quality).

Aim 4: To expand the Reading-to-Writing Mediation model to include direct and indirect connections with R-W fluency (e.g., ORF, writing productivity; Model 4). Figure 5 depicts the domain-specific direct and indirect effects after including oral and silent reading fluency and writing productivity (cross-domain associations are omitted for illustration purposes).

4.1. We hypothesized *connections among reading skills* such that the direct effects of basic literacy and knowledge on reading comprehension would no longer be significant, but indirect effects would be found via oral and silent reading fluency. We hypothesized that connections among higher-order DIME skills would also change after controlling for SRF and ORF.

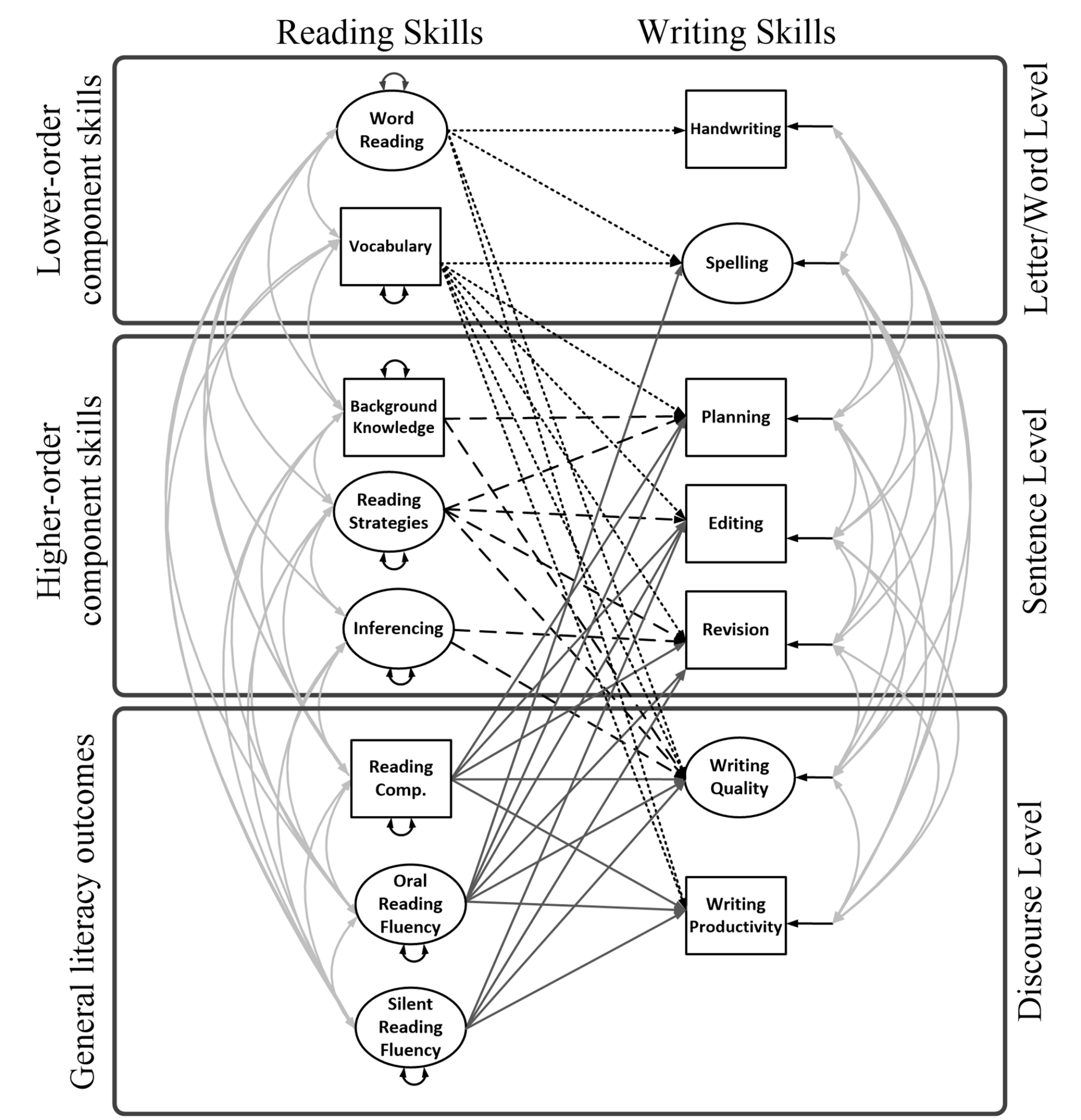

FIGURE 2
Full Reading-to-Writing Skills (RWS) Model with reading and writing fluency (Model 2). Silent reading fluency was measured using a sentence-level task, but it is included under discourse level because it measures comprehension of connected text and serves as a proxy for silent reading of longer texts. Small-dashed lines are 10 paths from lower-order reading skills to writing skills; long-dashed lines are 8 paths from higherorder reading skills to writing skills; solid lines are 15 paths from reading outcomes to writing skills. Double headed arrows are correlations or variances. Small single-headed arrows are residual variances.

4.2. We hypothesized *connections among writing skills* such the direct and indirect effects of writing skills would be significant for writing productivity and would remain significant for writing quality.
4.3. We hypothesized *cross-domain connections* would change as a function of R-W fluency. Figure 6 shows a mediation model in which higher-order reading mediated the relations of ORF and SRF with writing skills, and higher-order writing mediated the relations of ORF and SRF and writing quality because we hypothesized that fluent reading foments deeper cognitive processing (e.g., reading comprehension and revision), which in turn influence writing quality and productivity (e.g., silent reading fluency ➔ inferencing ➔ revision; oral reading fluency ➔ editing ➔ writing quality). In general, we expected SRF to mediate the effects of ORF on other R-W skills, noting that the literature on indirect effects is limited.

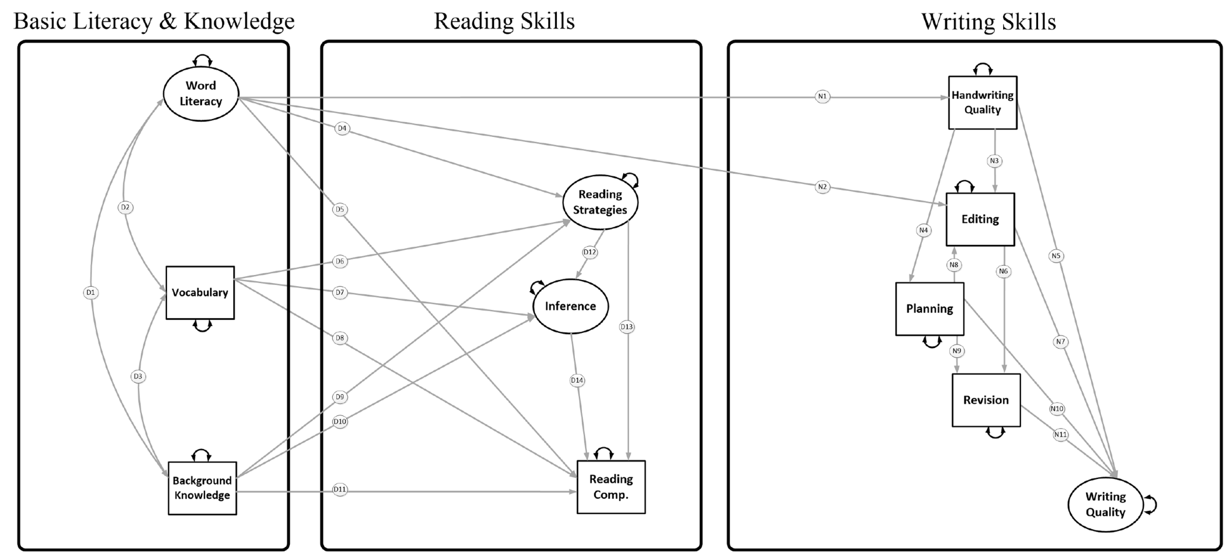

FIGURE 3
Reading-to-Writing Mediation (RWM) model (with cross-domain associations omitted for illustration; Model 3). The word literacy factor was measured by indicators of word reading (WJ-III Letter Word Identification and TOWRE Sight Word Efficiency) and spelling (WJ-III Spelling and percent words spelled correctly). Paths D1-D13 are correlations, direct, and indirect effects from the DIME model. D4 was added to account for the relation between spelling and summary writing (i.e., reading strategies). Paths N1-N11 are direct and indirect effects from the NSVW model.

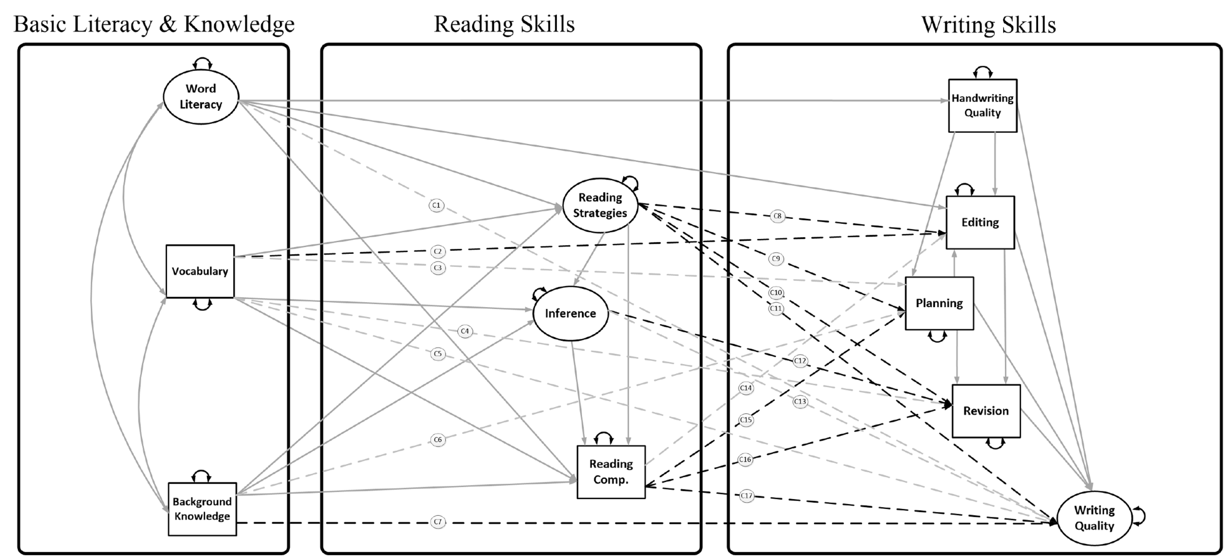

FIGURE 4
Reading-to-Writing Mediation (RWM) model (with cross-domain associations included; Model 3). Solid lines=within domain associations. Dashed lines=paths C1-C16 are cross-domain associations among reading and writing skills. Gray dashed lines were tested but omitted from the final model; black dashed lines were included in the final Model 3.

Method

Participants and procedures

Data were collected as part of a larger RCT of an after-school reading intervention (see Roberts et al., 2018) with a 2×2 factorial treatment design with 2 levels of reading intervention (foundational reading skills and text-processing or text-processing only) and 2 levels of modality of small group instruction (writing or self-regulation). All intervention conditions included individualized computer-based instruction and small-group instruction in the first and second phase, respectively, of each instructional session. However, the present study includes data from pre-test only (i.e., the interventions took place after the collection of the baseline battery of measures included in the present study and did not impact performance on any tests). Thus, in this study, we do not differentiate among experimental condition because no differences were apparent in the groups randomized to

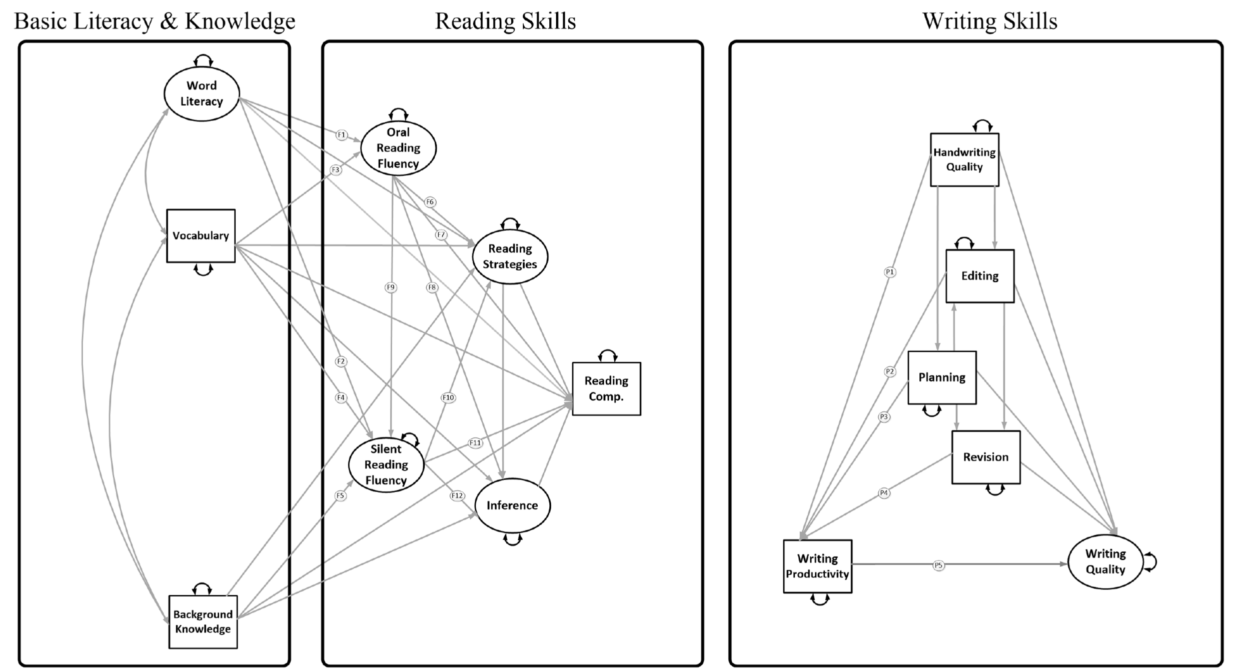

FIGURE 5
Full Reading-to-Writing Mediation (RWM) model (with cross-domain associations omitted for illustration; Model 4). Paths F1-F12 are paths to/from oral or silent reading Fluency; paths P1-P5 are paths to/from writing Productivity (fluency).

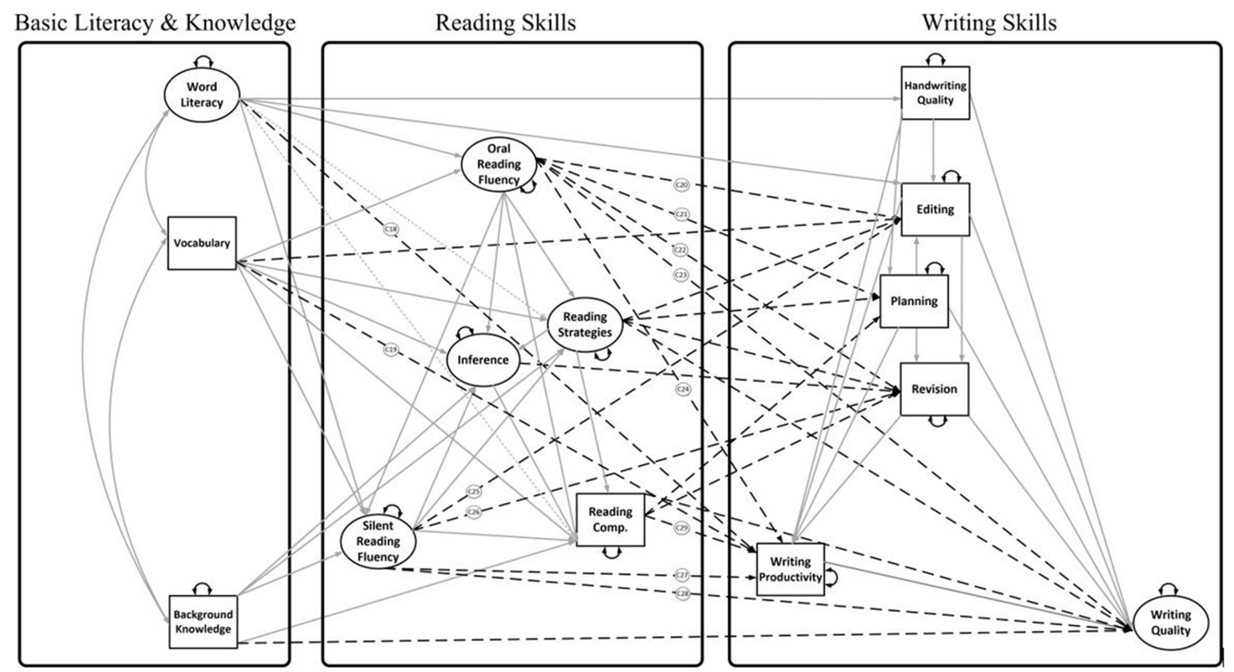

FIGURE 6
Full Reading-to-Writing Mediation (RWM) model (with cross-domain associations included; Model 4). Within-domain variables and paths are the same as Figure 5 but were rearranged to include cross-domain paths. Long-dashed lines=paths C17-C28 are cross domain associations to/from oral and silent fluency and writing productivity. Solid lines=within domain associations. Small-dashed lines=the model did not converge with the inclusion of these paths.

treatment and the business-as-usual control condition on the assessments or on demographic variables. The sample for the present study consisted of 405 children in Grades 3–5 who were identified as struggling readers using the 25th percentile cutoff on the Test of Silent Reading Efficiency and Comprehension (TOSREC). These students also struggled with written expression as evidenced by low scores on the Test of Written Language (TOWL). As Table 1 indicates, the average age of the sample was 10 and ranged from 6 to 12 years old. Most of the sample was economically disadvantaged (69% free/reduced lunch) and 20% were in special education and/or had limited English proficiency. The majority of the sample was White (52%), followed by Black (41%), multiple races (22%), American Indian or Alaskan Native (1.5%), and Asian (0.5%).

Measures

Reading measures

Word reading

Word reading was assessed using the Woodcock Johnson III Letter Word Identification (WJ-LWID; Woodcock et al., 2001) and the Sight Word Efficiency (SWE) subtest of the Test of Word Reading Efficiency (TOWRE; Torgesen et al., 1999), with both measures demonstrating adequate reliability ($\alpha = 0.91$ and $\alpha = 0.90–0.93$, respectively).

Vocabulary

The verbal knowledge subtest of the Kaufman Brief Intelligence Test (KBIT-2; Kaufman, 2004) was used to measure picture vocabulary. The students are required to point to a picture that shows the meaning of a word or provides the answer to a question. Reliability is adequate for verbal knowledge subtest ($\alpha = 0.86–93$).

Inferencing

The Bridge-It (Pike et al., 2010) test of inferencing measures the ability to integrate information presented in a statement sentence and a continuation sentence. Students are asked to read 4 sentences, one of which is the statement sentence, and a continuation sentence, which can either be a correct continuation (i.e., consistent with the situation model) or an incorrect continuation (i.e., inconsistent with the situation model). The statement sentence and the continuation sentence were separated by 3 sentences in the far condition and were adjacent in the near condition. This measure has adequate reliability ($\alpha = 0.73$).

Background knowledge

The Assessment of Writing, Self-Monitoring and Reading (AWSM Reading; Gioia et al., 2023) is a paper-and-pencil experimental test developed for the larger study. Background knowledge items were tied directly to three passages that students read for comprehension and were not tied to the topic the students wrote about. The background knowledge items (e.g., *What is found inside Yellowstone National Park?*) were presented prior to reading the passages. A composite score of the knowledge items was used in this study ($\alpha = 0.62–0.69$).

Reading strategies

Items from the AWSM Reader were also used to form a latent variable for strategies. Students read passages and provided short summaries of the passages as a performance measure of reading strategies. Reliability was high for summary writing ($\kappa = 0.92–0.97$) in this sample. The strategies factor also included a self-report measure of contextualized learning, Student Contextual Learning Scale (SCL; Cirino, 2012). The Strategies sub-scale of the SCL asks students to rate their beliefs, attitudes, and habits related to reading and learning strategies, with adequate reliability ($\alpha = 0.71–0.82$) in our sample.

Reading comprehension

The Gates–MacGinitie Reading Test (GMRT; MacGinitie et al., 2000) was used to measure reading comprehension. The GMRT requires students to read short passages and answer multiple choice questions. The test has adequate reliability (Kuder–Richardson 20 [K-R 20] = 0.93–0.94 for grades 3–5).

Oral reading fluency

Two forms of the AIMSweb Oral Reading Fluency (Shinn and Shinn, 2002) were administered. Students were asked to read appropriate grad-level passages and the number of words read correctly in 1 min were recorded. AIMSweb reports adequate alternate-forms reliability ($\alpha = 0.80–0.81$).

TABLE 1 Demographic characteristics by grade level.

Variable	Grade 3	Grade 4	Grade 5	Total
n	114	152	139	405
Age mean (SD)	8.81 (0.58)	9.77 (0.50)	10.84 (0.54)	9.85 (0.96)
Age range	6–10	7–11	9–12	6–12
Female	56 (52%)	81 (57%)	70 (52%)	207 (54%)
Free/Reduced lunch	89 (78%)	99 (65%)	92 (66%)	280 (69%)
Limited English proficiency	23 (28%)	20 (16%)	22 (19%)	65 (20%)
Special education	17 (20%)	16 (13%)	32 (28%)	65 (20%)
Race				
African American or Black	48 (45%)	52 (37%)	55 (41%)	155 (41%)
American Indian and Alaska native	1 (<1%)	3 (2%)	2 (2%)	6 (1.5%)
Asian	2 (2%)	–	–	2 (0.5%)
Multiple races	4 (4%)	11 (8%)	7 (5%)	22 (6%)
White	52 (49%)	76 (54%)	70 (52%)	198 (52%)

Silent reading fluency

Two forms of the Test of Silent Reading Efficiency and Comprehension (TOSREC; Wagner et al., 2010) were used. The TOSREC requires students to read sentences and verify the veracity of sentences (e.g., *Do birds fly?*). Alternate-forms reliability is high (0.86–0.93) in grades 3–5.

Writing measures

Spelling

The Woodcock Johnson III (WJ-III; Mather et al., 2001) Spelling subtest required students to spell phonetically regular (e.g., *under*) and irregular (e.g., *beautiful*) words. Reliability is high for grades 3–5 ($\alpha = 0.93$). Spelling was also measured by counting the percent of total words spelled correctly on the TOWL Story Composition subtest (described below), with high inter-rater reliability ($\kappa = 0.98$).

Handwriting

Scores were derived using the presentation domain (and handwriting subdomain) of the 6 + 1 traits rubric (described below). Inter-rater reliability was high ($\kappa = 0.91$).

Planning

Students were given 5 min to plan their TOWL Story Composition responses following TOWL administration guidelines (Hammill and Larsen, 2009). Because the TOWL does not include a separate rubric for scoring planning, we adapted a planning rubric from Olinghouse and Graham (2009), which consists of scores ranging from 1 (little or no planning) to 5 (detailed story elements). Inter-rater reliability was $\kappa = 0.75$.

Editing and revision

Items for the editing and revision measures were derived from the TOWL Contextual Conventions subscale. Editing items required knowledge of mechanics and Revising items required knowledge of writing elements that enhance meaning. Two independent raters classified the 21 items into two categories (editing or revision), with perfect agreement ($\kappa = 1.00$). The editing category included items related to grammar, capitalization, spelling, and punctuation. The revision category included items related to content, structure, syntax and organization (see Supplementary Appendix C for the list of items coded as editing or revision). Internal consistency in this sample was $\alpha = 0.62$ for Editing and $\alpha = 0.72$ for Revision. As additional evidence for internal validity, we present a factor model for the TOWL Editing and Revision sub-scales as supplementary analyses in Supplementary Appendix C. Further, external validity was established with the State of Texas Assessments of Academic Readiness (STAAR; Texas Education Agency, 2016) Editing and Revising subtests with a sub-sample of fourth grade students ($n = 73$) from the present study for whom data were available on the state-wide assessment. The STAAR test was administered in the semester following the administration of the TOWL. Data were only available for a subsample of students because the STAAR high stakes writing assessment is not administered in grades 3 or 5 in Texas and because the STAAR Writing data were obtained for a smaller project (see Reid et al., in press). The STAAR Editing and Revision subtests require reading grade-level compositions embedded with errors and answering multiple-choice questions to identify and/or correct the errors in the text (see Reid et al., in press, for additional details). The STAAR and TOWL Editing sub-scales ($r = 0.51$, $p < 0.001$) and the STAAR and TOWL Revision sub-scales ($r = 0.43$, $p < 0.001$) were moderately correlated.

Writing quality

The Story Composition subtest of the Test of Written Language – 4th Edition (TOWL; Hammill and Larsen, 2009) requires students to write a story in response to a picture prompt in 15 min. We used the TOWL scoring guidelines to obtain the Story Composition score, which is scored on criteria such as plot (storyline), if characters show feelings/emotions, and story action or energy level. In addition, we used the 6 + 1 traits rubric (Culham, 2003) to score the essays. The 6 + 1 traits rubric includes the following domains: (1) Ideas: whether the essay is focused and clearly communicates ideas; (2) Organization: if the logical structure makes ideas easy to follow; (3) Voice: whether the author writes in an engaging manner; (4) Word Choice: relates to how the student's choice of words creates a clear vision for the reader; (5) Sentence Fluency: how the author uses sentences and phrases to communicate; and (6) Conventions: errors related to punctuation, spelling, capitalization, grammar/usage. Inter-rater reliability ranged from $\kappa = 0.80$ for ideas to $\kappa = 0.91$ for word choice.

Writing productivity

The total words written were obtained for the TOWL Story Composition responses, as were correct minus incorrect word sequences (CIWS). CIWS is a curriculum-based measure of written grammar and mechanics (Espin et al., 2008). If two adjacent words are correctly spelled, capitalized, and punctuated that bigram results in a correct word sequence; otherwise, the bigram results in an incorrect word sequence. CIWS is calculated as the correct sequences minus any incorrect word sequences. Inter-rater reliability was $\kappa = 0.995$ for TWW and $\kappa = 0.98$ for CIWS.

Analytic approach

The present study consists of a secondary data analysis employing SEM to separately evaluate relations *among* reading components using the DIME model of reading comprehension as a theoretical framework (Ahmed et al., 2022b) and writing components using the NSVW as the theoretical framework (Ahmed et al., 2022a). We evaluate the relations *between* R-W components from these models, as shown in Figures 1, 2, 4, 6. The lack of empirical support for a path may reflect that research is lacking in a specific area, rather than support for a null relationship. Therefore, several paths were evaluated that have theoretical support but little empirical support (e.g., reading fluency and writing). Paths were not estimated if they were not significant in prior studies and there was no support in the theoretical literature (e.g., inference to handwriting and inference to spelling; Kim, 2020).

The SEM models were fit using Full Information Maximum Likelihood (FIML) in M-plus 8.6 (Muthen and Muthen, 1998–2017) to handle missing data (in the current sample, covariance coverage ranged from 0.81 to 0.99). Multiple criteria were considered to evaluate a model fit function (i.e., the extent to which the model fits the data) given a specific estimation method. Absolute model fit was evaluated using Akaike Information Criteria (AIC), Bayesian

Information Criteria (BIC) and sample-size adjusted BIC, which take sample size, model fit, and number of parameters into account, with lower values reflecting a better fit. The root mean square error of approximation (RMSEA) compensates for model complexity and standardized root mean square residual (SRMR) is the standardized difference between the observed and predicted correlations. RMSEA and SRMR values $\leq$0.05 indicate an adequate fit. The comparative fit index (CFI) and Tucker-Lewis index (TLI) are incremental indices that compare the fit of the hypothesized model with a more restricted, baseline model (i.e., a model in which all observed variables are uncorrelated). CFI and TLI values $\geq$0.95 indicate a good fit and values $\geq$0.90 indicate an acceptable fit (Hu and Bentler, 1999).

Aims 1 and 2 (direct effects models)

Aim 1 examined the direct effects of DIME to NSVW component skills shown in Figure 1 (Model 1). Aim 2 examined the direct effects of R-W skills with three nested models that systematically incorporated R-W fluency: a full[2] R-to-W Skills model depicted in Figure 2, and two nested models in which relations of each fluency skill (ORF or SRF) with writing skills were estimated independently of the other fluency skill. For example, the ORF model excluded any hypothesized relations of SRF with writing skills. The SRF model included all paths from the full model (Figure 2) but excluded any relations of ORF with writing skills. Nested models were compared with chi-square difference tests.

Aims 3 and 4 (mediation models)

The RWM models explored indirect effects of basic literacy (i.e., decoding and encoding) and knowledge (i.e., word and world knowledge) on writing skills via the indirect effects on reading skills. In addition, several indirect effects were evaluated within the reading domain (e.g., vocabulary ➔ inference ➔ reading comprehension) and writing domain (e.g., handwriting ➔ editing ➔ writing quality). The measurement models were similar to the RWS models of Aims 1–2, except that measures of word reading and spelling loaded on a single factor (Mehta et al., 2005). Consequently, in the RWM models, the word literacy factor predicted multiple R-W skills. As a first step, the RWM models included associations among DIME skills (paths D1-D14 in Figure 3) and NSVW skills (paths N1-N11 in Figure 3). We then evaluated the cross-domain associations shown in Figure 4 (paths C1-C17) by testing competing structural models. Due to the specification of a word literacy factor, these cross-domain associations are the 17 paths from Model 1 (Figure 1) which did not involve handwriting or spelling. The RWM model without fluency (Model 3) was generated by trimming paths without strong empirical support (i.e., gray dashed arrows in Figure 4; Mulaik and Millsap, 2000). The full RWM model with fluency (Model 4) retained the same variables and paths from the trimmed Model 3 and incorporated three R-W fluency variables (ORF, SRF, and writing productivity; Figure 5). Several direct and indirect effects were evaluated within the reading domain (e.g., ORF ➔ SRF ➔ inference ➔ reading comprehension; paths F1-F12 in Figure 5) and writing domain (e.g., handwriting ➔ productivity ➔ quality; paths P1-P5 in Figure 5) based on the literature reviewed. Cross-domain associations from Model 3 were retained (including ten cross-domain paths C2, C8-C12, C15-C17 which were not trimmed), and additional cross-domain associations were evaluated with R-W fluency skills (paths C18-C29 in Figure 6). The additional cross-domain associations are the 12 paths from Model 2 (Figure 2) originating from ORF or SRF, or going into writing productivity (with the exception of ORF ➔ spelling because in the RWM models spelling was combined with word reading in the word literacy factor). All indirect effects were estimated under FIML in Mplus and bias-corrected bootstrapped confidence intervals were obtained based on 1000–3000 bootstrap samples.

Alternative direct effects models

For space considerations the diagrams and results for the alternative models are presented in the Appendices. First, the Reading-to-Writing Domains model explored how reading skills differentially relate to writing *dimensions* depending on the skills assessed (Shanahan and Lomax, 1986; Kim and Graham, 2022). For example, ORF may predict sentence fluency because this dimension taps into the ability to use varied sentence structures that invite expressive oral reading. Similarly, ORF may predict scores on the voice dimension because this dimension taps into the ability to address the reader in an engaging way. In the present study, we measured six dimensions using the 6 + 1 traits rubric (Culham, 2003). In our approach to examining the R-W relationship, we also use correct minus incorrect word sequences (CIWS) as an overall indicator of writing. As a production-dependent metric, CIWS captures the amount of written text a student produces but also captures writing quality through consideration of spelling, grammar, and punctuation of adjacent words in the context of a sentence. Three R-to-W Dimensions models were evaluated: a full model depicted in Supplementary Appendix A and two reduced models for ORF and SRF, respectively. The R-to-W Dimensions Model included a general factor for writing which reflects the common variance across specific writing dimensions. Thus, the path from a specific reading skill to a specific dimension can be interpreted as a one unit change in the writing dimension as a function of the reading skill after controlling for (a) other reading skills and (b) for variance shared with other dimensions. Second, we evaluated a Writing-to-Reading Model because it is possible that the opposite directionality could fit the data equally well (i.e., due to model equivalence). Like the R-to-W models, paths for the W-to-R models were specified based on prior literature. For example, if there were no theoretical, experimental, or correlational studies surmising that better planning influences vocabulary then this path was omitted from the model. The W-to-R model (see Supplementary Appendix B) specified that: (a) handwriting and spelling predicted word reading; (b) spelling also predicted vocabulary, knowledge, ORF, and SRF; (c) higher-order writing (planning, editing, and revision) predicted reading strategies and inferencing; (d) planning predicted reading comprehension (e) editing and revision predicted reading comprehension, ORF, and SRF; (f) writing productivity predicted reading comprehension, ORF, and SRF; and (g) writing quality predicted all reading skills.

Results

Data were first screened for assumptions of normality and outliers, defined as data points with studentized residuals ±3 and high

2 *Full models* refer to structural models that include all the R-W constructs we evaluated (14 or 15 observed and latent variables). This is different from fully saturated models, which outline every possible path among the constructs. Thus, the term *full* here refers to the number of factors rather than the number of paths.

leverage. As the outliers did not represent minor or major reliability concerns (e.g., equipment failure), and the inclusion of the outliers did not change the results substantively, these data points were retained for the final analyses. As shown in Table 2, all assumptions of univariate normality were supported. The higher kurtosis on the AWSM Reader Summary 3 (5.43) is due to this passage's higher text difficulty (readability) in comparison to summary 1 and 2 (Gioia et al., 2023).

Reading-to-Writing Skills models

The reduced model depicted in Figure 1 (χ^2 (108) = 215.96, $p < 0.001$; RMSEA [90% CI] = 0.05 [0.04, 0.06]; CFI = 0.96; TLI = 0.93; SRMR = 0.04) and the full model depicted in Figure 2 (χ^2 (177) = 294.58, $p < 0.001$; RMSEA [90% CI] = 0.04 [0.03, 0.05]; CFI = 0.97; TLI = 0.95; SRMR = 0.04) provided a good fit to the data. These models explained 66–68% of variance in writing quality, 57–63% in spelling, 41–42% in editing, and a smaller percentage of variance in revision (22%), handwriting (12–16%), and planning (10%). The full RWS model also explained 16% variance in writing productivity (see Table 3).

All measures loaded significantly on their hypothesized factors (see Table 4). For the reading strategies factor, the loading of the self-report measure was smaller in magnitude (λ=0.13–0.14, $p < 0.05$) because all other loadings on this factor were from performance measures of strategies (summarizing). The correlations among reading variables in the full model are reported in Table 5, and correlations among residuals of the writing variables are reported in Table 6. Most reading variables were moderately to highly correlated, ranging from 0.25 for word reading and vocabulary (and reading strategies and vocabulary) to 0.90 for ORF and decoding. The largest residual correlation for the writing variables was between revision and writing quality ($r = 0.63$), and the smallest correlation was between spelling and total words written ($r = 0.03$; see Table 6). In addition, the disturbances of the WJ spelling and word reading subtests were allowed to correlate in all models because both subtests belong to the same family of tests ($r = 0.46$–0.54, $p < 0.05$).

Aim 1: RWS model without fluency

Several effects were in the expected range in the reduced model without R-W fluency (Model 1; see Table 7). Word reading predicted handwriting ($\beta = 0.39$, SE = 0.06, $p < 0.001$), spelling ($\beta = 0.76$, SE = 0.04, $p < 0.001$), and writing quality ($\beta = 0.22$, SE = 0.09, $p < 0.05$). Vocabulary predicted spelling ($\beta = 0.09$, SE = 0.05, $p < 0.05$), editing ($\beta = 0.20$, SE = 0.05, $p < 0.001$), and writing quality ($\beta = 0.11$, SE = 0.05, $p < 0.05$). Reading strategies predicted editing ($\beta = 0.44$, SE = 0.05, $p < 0.001$), revision ($\beta = 0.33$, SE = 0.08, $p < 0.001$), and writing quality ($\beta = 0.30$, SE = 0.09, $p < 0.001$). As hypothesized, higher-order reading skills such as reading strategies were related to writing quality, but contrary to our expectations, inferencing ($\beta = 0.14$, SE = 0.10, $p > 0.05$) and knowledge ($\beta = 0.06$, SE = 0.05, $p > 0.05$) were not related to writing quality. Similarly, reading strategies were related to higher-order writing skills (editing and revision), but other higher-order reading skills (background knowledge and inferencing) were not related to planning, editing, or revising (see results for Model 1 in Table 7). Finally, reading comprehension predicted planning ($\beta = 0.22$, SE = 0.06, $p < 0.001$), editing ($\beta = 0.18$, SE = 0.05, $p < 0.001$), revision ($\beta = 0.25$, SE = 0.07, $p < 0.001$), and writing quality ($\beta = 0.24$, SE = 0.07, $p < 0.001$).

Aim 2: RWS model with fluency

In the full Reading-to-Writing Skills model (Model 2, Figure 2) there were similarities in the pattern of associations with Model 1 and one notable difference. Word reading was still related to handwriting ($\beta = 0.35$, SE = 0.05, $p < 0.05$). Reading strategies still predicted editing ($\beta = 0.20$, SE = 0.07, $p < 0.05$), revision ($\beta = 0.20$, SE = 0.08, $p < 0.05$), and writing quality ($\beta = 0.24$, SE = 0.08, $p < 0.05$), and reading comprehension predicted planning ($\beta = 0.18$, SE = 0.07, $p < 0.05$), revision ($\beta = 0.23$, SE = 0.07, $p < 0.05$), and writing quality ($\beta = 0.31$, SE = 0.11, $p < 0.05$). However, vocabulary was only related to editing ($\beta = 0.16$, SE = 0.06, $p < 0.05$), and in this model ORF was related to spelling ($\beta = 0.50$, SE = 0.17, $p < 0.05$), planning ($\beta = 0.15$, SE = 0.08, $p < 0.05$), and editing ($\beta = 0.25$, SE = 0.10, $p < 0.05$). Writing productivity was predicted by reading comprehension ($\beta = 0.20$, SE = 0.10, $p < 0.05$), but not decoding, vocabulary, ORF, or SRF. As Table 7 shows, the nested model for SRF ($\Delta\chi^2$ (6) = 14.35, $p < 0.05$) was significantly worse fitting than the full model in terms of overall fit, whereas the model for ORF ($\Delta\chi^2$ (4) = 0.86, $p > 0.05$) was not significantly different from the full model, but these solutions pointed to a key difference: when the hypothesized direct effects of ORF on writing skills are not controlled for, SRF predicted the higher-order writing skills with heavier cognitive load, editing ($\beta = 0.40$, SE = 0.09, $p < 0.001$) and revising ($\beta = 0.23$, SE = 0.10, $p < 0.05$), whereas when the hypothesized direct effects of SRF on writing skills are not controlled for, ORF predicted the writing skills with lower (spelling; $\beta = 0.50$, SE = 0.16, $p < 0.05$) and higher cognitive load (planning, $\beta = 0.14$, SE = 0.07, $p = 0.05$; editing, $\beta = 0.31$, SE = 0.06, $p < 0.05$; and revising, $\beta = 0.18$, SE = 0.07, $p < 0.05$), and vocabulary predicted writing quality ($\beta = 0.12$, SE = 0.05, $p < 0.05$). However, when both ORF and SRF were evaluated simultaneously in the full model, only the effects of ORF remained statistically significant.

Reading-to-Writing Mediation models

The reduced RWM model without R-W fluency (Figure 4) provided a good fit to the data (χ^2 (df) = 202.80 (121), $p < 0.001$; RMSEA [90% CI] = 0.04 [0.03, 0.05]; CFI = 0.97; TLI = 0.95; SRMR = 0.04), as did the full RWM model (Figure 6; χ^2 (df) = 368.22 (195), $p < 0.001$; RMSEA [90% CI] = 0.05 [0.04, 0.05]; CFI = 0.96; TLI = 0.94; SRMR = 0.04). Table 3 shows that the RWM models explained a larger proportion of variance compared to the direct effects models (e.g., the full RWM model explained 90% variance in writing quality). These models also explained a large amount of variance in reading skills (e.g., the full RWM model explained 62% variance in inferencing and 94% in ORF). The measurement model solutions were similar to the solution of the RWS models presented above (see Table 4).

Aim 3: RWM model without fluency

First, the results of the RWM model showed that several direct effects of R-to-R skills were in the expected range: inferencing ($\beta = 0.48$, SE = 0.14, $p < 0.05$) and background knowledge ($\beta = 0.14$, SE = 0.05, $p < 0.05$) predicted reading comprehension; vocabulary ($\beta = 0.24$, SE = 0.06, $p < 0.001$) and reading strategies ($\beta = 0.53$,

TABLE 2 Descriptive statistics.

Variable	*n*	Mean	SD	Min	Max	Skew	Kurtosis
Word reading							
TOWRE SWE[1]	365	85.04	12.90	55.00	127.00	−0.05	0.04
WJ-III LWID[1]	386	94.03	11.82	41.00	155.00	−0.05	3.12
Vocabulary							
K-BIT	387	49.21	11.86	4.00	77.00	−0.75	1.30
Background knowledge							
AWSM reader – background knowledge	378	2.27	0.82	0.00	3.00	−0.79	−0.33
Strategies							
AWSM reader – summary 1	349	0.95	1.17	0.00	6.00	1.23	1.00
AWSM reader – summary 2	343	0.99	1.20	0.00	5.00	1.06	0.35
AWSM reader – summary 3	333	0.41	0.69	0.00	4.00	2.05	5.43
SCLC - Strategies	387	17.39	5.08	4.00	27.00	−0.33	−0.41
Inferencing							
Bridge-it near condition	376	5.54	2.16	0.00	10.00	−0.06	−0.72
Bridge-it far condition	376	4.51	1.86	0.00	10.00	0.06	−0.37
Reading comprehension							
GMRT[1]	387	451.01	31.95	349.00	547.00	−0.23	0.08
Oral reading fluency							
AIMSweb 1	386	80.57	32.67	4.00	181.00	0.00	−0.20
AIMSweb 2	385	78.90	31.10	1.00	175.00	−0.02	0.03
Silent reading fluency							
TOSREC 1	405	13.56	5.28	0.00	26.00	−0.35	−0.09
TOSREC 2	405	13.76	5.56	0.00	27.00	−0.42	−0.07
Handwriting							
Handwriting quality	377	2.85	1.13	1.00	6.00	0.31	−0.27
Spelling							
WJ-III spelling[1]	385	91.48	13.36	40.50	122.00	−1.22	1.59
PWSC	356	84.12	11.06	44.31	100.00	−0.69	1.22
Planning							
Planning	377	1.57	0.79	0.00	4.00	1.26	1.08
Editing							
Editing	359	5.56	2.91	0.00	14.00	0.47	−0.31
Revision							
Revision	360	3.50	2.66	0.00	13.00	1.01	0.94
Writing scores							
TWW	371	96.75	43.35	13.00	251.00	0.35	−0.21
CIWS	356	37.41	43.42	−99.00[2]	207.00	0.24	0.18
Ideas	377	2.87	1.07	1.00	6.00	0.23	−0.24
Organization	377	2.78	1.13	1.00	5.00	0.11	−0.77
Voice	377	2.77	1.17	1.00	6.00	0.35	−0.45
Word choice	377	2.66	0.98	1.00	5.00	0.15	−0.21
Sentence fluency	377	2.10	1.07	1.00	5.00	0.77	−0.05
Conventions	377	2.19	0.89	1.00	5.00	0.37	−0.14
6 Traits total score	377	15.37	5.40	6.00	31.00	0.27	−0.27

[1]Standard score; all other scores are raw scores. [2]Negative values indicate more incorrect word sequences than correct word sequences. CIWS, correct minus incorrect word sequences; PWSC, percent of total words spelled correctly; TWW, total words written.

TABLE 3 Variance explained in the direct effects models (RWS), mediation models (RWM), and alternative models.

Model	Handwriting	Spelling	Word literacy	Planning	Editing	Revision	Writing productivity	Writing quality
RWS Model 1	0.16	0.63	N/A	0.10	0.42	0.22	N/A	0.68
RWS Model 2	0.12	0.57	N/A	0.10	0.41	0.22	0.14	0.66
RWM Model 3	0.19	N/A	N/A	0.13	0.60	0.32	N/A	0.84
RWM Model 4	0.16	N/A	N/A	0.14	0.79	0.32	0.23	0.90
	Word reading	**Vocabulary**	**Background knowledge**	**Reading strategies**	**Inferencing**	**Oral reading fluency**	**Silent reading fluency**	**Reading comprehension**
RWM Model 3	N/A	N/A	N/A	0.50	0.50	N/A	N/A	0.49
RWM Model 4	N/A	N/A	N/A	0.51	0.62	0.90	0.93	0.52
W-to-R skills	0.51	0.16	0.21	0.51	0.45	0.56	0.58	0.42
	Organization	**Voice**	**Word choice**	**Sentence fluency**	**Conventions**	**Ideas**	**CIWS**	
R-to-W domains	0.79	0.76	0.68	0.52	0.51	0.83	0.42	

CIWS, Correct minus incorrect word sequences; RWS, Reading-to-Writing Skills; RWM, Reading-to-Writing Mediation; W-to-R, Writing to Reading. N/A, variable was an exogenous variable (word literacy, word reading, vocabulary, background knowledge) or was not included in the model (spelling, word literacy, oral/silent reading fluency or total words written).

SE = 0.08, $p < 0.001$) predicted inferencing; and word literacy predicted reading strategies ($\beta = 0.64$, SE = 0.06, $p < 0.001$). The effects of several W-to-W skills were also in the expected range: word literacy was related to handwriting ($\beta = 0.43$, SE = 0.05, $p < 0.05$) and editing ($\beta = 0.59$, SE = 0.10, $p < 0.001$); handwriting was related to planning ($\beta = 0.18$, SE = 0.06, $p < 0.001$), editing ($\beta = 0.10$, SE = 0.04, $p < 0.05$), and writing quality ($\beta = 0.25$, SE = 0.05, $p < 0.001$). Planning was related to revision ($\beta = 0.11$, SE = 0.05, $p < 0.05$) and writing quality ($\beta = 0.11$, SE = 0.04, $p < 0.05$), and editing was related to revision ($\beta = 0.31$, SE = 0.06, $p < 0.001$), which in turn was related to writing quality ($\beta = 0.31$, SE = 0.05, $p < 0.001$). Second, Table 8 shows that several cross-domain direct effects from the RWS model (Model 1) also remained significant (e.g., vocabulary ➔ editing, reading strategies ➔ writing quality, reading comprehension ➔ planning, reading comprehension ➔ revision, and reading comprehension ➔ writing quality), with some exceptions: reading strategies were no longer predictive of editing or revision. However, the total indirect effects of several variables were significant as the associations were driven by one or more mediators, as shown in Table 9. Three effects were partially mediated: the effects of reading strategies (*via* inferencing and reading comprehension), reading comprehension (*via* revision), and handwriting, on writing quality because zero was not included in the 95% confidence intervals for these effects (see Table 9). Five effects were completely mediated, indicating that the mediators explained all of the relationship between the variables: (1) vocabulary to reading comprehension (specifically, via inferencing), (2) reading strategies to reading comprehension (specifically, via inferencing), (3) inferencing to revision (specifically, via reading comprehension), (4) background knowledge to writing quality, and (5) editing to writing quality.

Aim 4: RWM model with fluency

The full RWM model (Model 4) included all the variables from Model 3 and specified relations with R-W fluency (ORF, SRF, and total words written). In this model, additional R-to-R paths were in the expected range (word literacy predicted ORF [$\beta = 0.94$, SE = 0.04, $p < 0.001$] and SRF [$\beta = 0.66$, SE = 0.34, $p < 0.05$]; vocabulary [$\beta = 0.27$, SE = 0.07, $p < 0.001$] and background knowledge [$\beta = 0.21$, SE = 0.07, $p < 0.001$] predicted SRF, but vocabulary was not related to ORF [$\beta = 0.04$, SE = 0.05, $p > 0.05$]). Contrary to our expectations, ORF and SRF were not significant predictors of inferencing, strategies, or comprehension after controlling for all other variables in the model. Two additional effects of W-to-W skills were in the expected range: revision predicted productivity ($\beta = 0.18$, SE = 0.05, $p < 0.05$), and productivity predicted writing quality ($\beta = 0.18$, SE = 0.05, $p < 0.001$). Unlike the RWS Model 2, writing productivity was not significantly predicted by reading comprehension in the RWM model (see Table 8).

Table 8 shows that most cross-domain effects from the RWS model (Model 2) also remained significant, with some exceptions: background knowledge did not have a direct effect on writing quality, and ORF was no longer predictive of planning or editing. However, the total indirect effect of background knowledge to writing quality was significant as these variables were indirectly related through multiple variables in the R-W system (e.g., knowledge ➔ SRF ➔ writing quality, as well as knowledge ➔ SRF ➔ reading comprehension ➔ writing quality), but none of these specific indirect effects were statistically significant. Overall, Table 9 shows few indirect effects were statistically meaningful (i.e., did not include 0 in the confidence intervals). While editing was not directly related to writing productivity in the RWM model (see Table 8), this effect was completely mediated by revision ($\beta = 0.06$, 95% CI [0.01, 0.14]). Finally, nested models that evaluated the hypothesized relations of SRF with writing variables independently of the relation of ORF with writing variables (and vice versa) did not yield a different pattern of results.

Alternative models

The Reading-to-Writing Domains model (alternative model 1) and the Writing-to-Reading Skills model (alternative model 2) provided a good fit to the data (e.g., CFI = 0.97, SRMR = 0.03; see Supplementary Appendixes A,B). The measurement models were

TABLE 4 Standardized solutions for the measurement models.

Variable	Reduced R-to-W skills (Model 1)		Full R-to-W skills (Model 2)			Reduced R-to-W mediation (Model 3)		Full R-to-W mediation (Model 4)	
	Parameter	SE	Parameter	SE	Variable	Parameter	SE	Parameter	SE
Word reading					*Word literacy*				
TOWRE SWE	0.69**	0.04	0.82**	0.03	TOWRE SWE	0.59**	0.05	0.71**	0.04
WJ LWID	0.70**	0.04	0.70**	0.03	WJ LWID	0.59**	0.05	0.62**	0.04
Spelling					WJ spelling	0.79**	0.04	0.70**	0.03
WJ spelling	0.87**	0.02	0.87**	0.02	%WSC	0.78**	0.04	0.68**	0.03
%WSC	0.84**	0.03	0.83**	0.02					
Reading strategies					*Reading strategies*				
CLS: strategies	0.14*	0.06	0.13*	0.06	CLS: strategies	0.14*	0.06	0.14*	0.06
Summary 1	0.69**	0.04	0.71**	0.04	Summary 1	0.71**	0.04	0.72**	0.04
Summary 2	0.83**	0.03	0.82**	0.03	Summary 2	0.81**	0.03	0.80**	0.04
Summary 3	0.65**	0.04	0.69**	0.04	Summary 3	0.68**	0.05	0.68**	0.05
Inference					*Inference*				
Bridge-It Near	0.78**	0.05	0.77**	0.05	Bridge-It Near	0.77**	0.05	0.77**	0.05
Bridge-It Far	0.53**	0.05	0.53**	0.05	Bridge-It Far	0.54**	0.05	0.54**	0.05
Oral reading fluency					*Oral reading fluency*				
AIMSweb 1	N/A	N/A	0.92**	0.01	AIMSweb 1	N/A	N/A	0.92**	0.01
AIMSweb 2	N/A	N/A	0.91**	0.01	AIMSweb 2	N/A	N/A	0.91**	0.01
Silent reading fluency					*Silent reading fluency*				
TOSREC 1	N/A	N/A	0.72**	0.03	TOSREC 1	N/A	N/A	0.67**	0.04
TOSREC 2	N/A	N/A	0.73**	0.03	TOSREC 2	N/A	N/A	0.69**	0.04
Writing					*Writing*				
TOWL story composition	0.73**	0.03	0.74**	0.03	TOWL story composition	0.73**	0.03	0.75**	0.03
6 + 1 traits	0.81**	0.03	0.80**	0.03	6 + 1 traits	0.82**	0.03	0.80**	0.03

**$p < 0.001$, *$p < 0.05$.
N/A, The variable was not included in the reduced models.

TABLE 5 Correlations among exogenous variables in the full Reading-to-Writing Skills model (Model 2).

	WORD	VOC	BK	RS	INF	RC	ORF
WORD	–						
VOC	0.25	–					
BK	0.34	0.32	–				
RS	0.58	0.25	0.39	–			
INF	0.50	0.42	0.42	0.60	–		
RC	0.38	0.37	0.44	0.48	0.65	–	
ORF	0.90	0.53	0.44	0.56	0.53	0.60	–
SRF	0.73	0.33	0.57	0.59	0.68	0.65	0.81

All correlations are significant at $p < 0.001$. WORD, word reading; BK, background knowledge; RS, reading strategies; INF, inferencing; RC, reading comprehension; ORF, oral reading fluency; SRF, silent reading fluency.

TABLE 6 Correlations among disturbances of writing variables from the full Reading-to-Writing Skills model (Model 2).

	HW	SPELL	PLAN	EDIT	REV	WQ
HW	–					
SPELL	0.12	–				
PLAN	0.18	0.06	–			
EDIT	0.24	0.44	0.10	–		
REV	0.15	0.31	0.16	0.30	–	
WQ	0.52	0.35	0.33	0.29	0.63	–
TWW	0.21	0.03	0.18	0.06	0.22	0.50

Correlations above 0.10 are significant at $p < 0.05$. HW, handwriting; SPELL, spelling; PLAN, planning; EDIT, editing; REV, revision; WQ, writing quality; TWW, total words written.

similar to that of the RWS model, but the R-to-W Domains model also included a general factor for writing because all the writing dimensions and the CIWS shared method variance (i.e., required human ratings and were derived from the same written response).

The R-to-W Domains model explained over half of the variance in writing dimensions (e.g., 83% for ideas; see Table 3). The model also explained 43% of the variance in CIWS. However, the R-to-W Domains model showed that multiple reading skills were not differentially related to specific writing dimensions, except for ORF, which predicted CIWS ($\beta = 0.26$, SE = 0.11, $p < 0.05$) but not

TABLE 7 Standardized solutions for the structural portion of the Reading-to-Writing Skills models.

	Model 1				Model 2			
	No fluency		ORF		SRF		ORF and SRF	
Parameter	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Word reading								
$\beta_{WORD\rightarrow HW}$	0.39**	0.06	0.35**	0.05	0.35**	0.05	0.35**	0.05
$\beta_{WORD\rightarrow SPELL}$	0.76**	0.04	0.25	0.16	0.73**	0.03	0.25	0.17
$\beta_{WORD\rightarrow WQ}$	0.22*	0.09	0.37	0.26	0.23	0.17	0.36	0.26
$\beta_{WORD\rightarrow TWW}$	N/A	N/A	0.21	0.24	0.21	0.16	0.18	0.24
Vocabulary								
$\beta_{VOC\rightarrow SPELL}$	0.09*	0.05	0.07*	0.05	0.11*	0.04	0.07	0.05
$\beta_{VOC\rightarrow PLAN}$	0.02	0.06	0.01	0.06	0.02	0.06	0.01	0.06
$\beta_{VOC\rightarrow EDIT}$	0.20**	0.05	0.18**	0.04	0.09*	0.05	0.16*	0.06
$\beta_{VOC\rightarrow REV}$	0.06	0.06	0.05	0.05	0.004	0.06	0.03	0.07
$\beta_{VOC\rightarrow WQ}$	0.11*	0.05	0.12*	0.05	0.12	0.08	0.12	0.06
$\beta_{VOC\rightarrow TWW}$	N/A	N/A	0.002	0.05	−0.002	0.08	−0.02	0.07
Background knowledge								
$\beta_{BK\rightarrow PLAN}$	0.06	0.06	0.05	0.06	0.02	0.06	0.05	0.06
$\beta_{BK\rightarrow WQ}$	0.06	0.05	0.07	0.05	0.07	0.05	0.08	0.05
Reading strategies								
$\beta_{RS\rightarrow PLAN}$	0.09	0.07	−0.002	0.08	0.07	0.07	−0.002	0.08
$\beta_{RS\rightarrow EDIT}$	0.44**	0.05	0.22**	0.06	0.24**	0.07	0.20*	0.07
$\beta_{RS\rightarrow REV}$	0.33**	0.08	0.21*	0.08	0.23*	0.08	0.20*	0.08
$\beta_{RS\rightarrow WQ}$	0.30**	0.09	0.24*	0.08	0.27**	0.08	0.24**	0.08
Inferencing								
$\beta_{INF\rightarrow REV}$	−0.08	0.10	−0.11	0.10	−0.13	0.11	−0.13	0.11
$\beta_{INF\rightarrow WQ}$	0.14	0.10	0.10	0.10	0.15	0.11	0.10	0.11
Reading comprehension								
$\beta_{RC\rightarrow PLAN}$	0.22**	0.06	0.18*	0.07	0.23**	0.06	0.18*	0.07
$\beta_{RC\rightarrow EDIT}$	0.18**	0.05	0.12	0.05	0.05	0.06	0.11	0.06
$\beta_{RC\rightarrow REV}$	0.25**	0.07	0.24**	0.07	0.20*	0.08	0.23*	0.07
$\beta_{RC\rightarrow WQ}$	0.24**	0.07	0.32*	0.11	0.24*	0.08	0.31*	0.11
$\beta_{RC\rightarrow TWW}$	N/A	N/A	0.22*	0.09	0.22*	0.08	0.20*	0.10
Oral reading fluency								
$\beta_{ORF\rightarrow SPELL}$	N/A	N/A	0.50*	0.16	@0	@0	0.50*	0.17
$\beta_{ORF\rightarrow PLAN}$	N/A	N/A	0.14*	0.07	@0	@0	0.15*	0.08
$\beta_{ORF\rightarrow EDIT}$	N/A	N/A	0.31**	0.06	@0	@0	0.25*	0.10
$\beta_{ORF\rightarrow REV}$	N/A	N/A	0.18*	0.07	@0	@0	0.12	0.12
$\beta_{ORF\rightarrow WQ}$	N/A	N/A	−0.13	0.28	@0	@0	−0.12	0.28
$\beta_{ORF\rightarrow TWW}$	N/A	N/A	0.02	0.27	@0	@0	0.01	0.26
Silent reading fluency								
$\beta_{SRF\rightarrow EDIT}$	N/A	N/A	@0	@0	0.40**	0.09	0.09	0.14
$\beta_{SRF\rightarrow REV}$	N/A	≤N/A	@0	@0	0.23*	0.10	0.11	0.18
$\beta_{SRF\rightarrow WQ}$	N/A	N/A	@0	@0	−0.002	0.26	0.004	0.18
$\beta_{SRF\rightarrow TWW}$	N/A	N/A	@0	@0	0.02	0.23	0.08	0.16

$^{**}p \leq 0.001$; $^{*}p \leq 0.05$.
N/A, fluency variables were not included in the model. @0, path was constrained to 0 (i.e., it was not estimated).

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TABLE 8 Standardized solutions for the structural portion of the Reading-to-Writing Mediation (RWM) models.

Reduced RWM Model (Model 3)				Full RWM Model (Model 4)			
Path	Parameter	SE	Path #	Path	Parameter	SE	Path #
Word literacy				*Word literacy*			
$\beta_{WORD\rightarrow HW}$	0.43*	0.05	N1	$\beta_{WORD\rightarrow HW}$	0.40**	0.05	N1
$\beta_{WORD\rightarrow EDIT}$	0.59**	0.10	N2	$\beta_{WORD\rightarrow EDIT}$	2.09	2.33	N2
$\beta_{WORD\rightarrow RS}$	0.64**	0.06	D4	$\beta_{WORD\rightarrow RS}$	N/A	N/A	D4
$\beta_{WORD\rightarrow RC}$	0.22	0.10	D5	$\beta_{WORD\rightarrow RC}$	N/A	N/A	D5
				$\beta_{WORD\rightarrow ORF}$	0.94**	0.04	F1
				$\beta_{WORD\rightarrow SRF}$	0.66*	0.34	F2
				$\beta_{WORD\rightarrow TWW}$	0.001	10.97	C18
Vocabulary				*Vocabulary*			
$\beta_{VOC\rightarrow EDIT}$	0.16**	0.05	C2	$\beta_{VOC\rightarrow EDIT}$	0.28	0.37	C2
$\beta_{VOC\rightarrow RS}$	0.04	0.06	D6	$\beta_{VOC\rightarrow RS}$	−0.30	0.39	D6
$\beta_{VOC\rightarrow INF}$	0.24**	0.06	D7	$\beta_{VOC\rightarrow INF}$	−0.11	0.41	D7
$\beta_{VOC\rightarrow RC}$	0.06	0.06	D8	$\beta_{VOC\rightarrow RC}$	−0.01	0.70	D8
				$\beta_{VOC\rightarrow ORF}$	0.04	0.05	F3
				$\beta_{VOC\rightarrow SRF}$	0.27**	0.07	F4
Background knowledge				*Background knowledge*			
$\beta_{BK\rightarrow WQ}$	0.09	0.04	C7	$\beta_{BK\rightarrow WQ}$	−0.03	0.11	C7
$\beta_{BK\rightarrow RS}$	0.10	0.06	D9	$\beta_{BK\rightarrow RS}$	−0.12	0.37	D9
$\beta_{BK\rightarrow INF}$	0.13	0.07	D10	$\beta_{BK\rightarrow INF}$	−0.16	0.33	D10
$\beta_{BK\rightarrow RC}$	0.14*	0.05	D11	$\beta_{BK\rightarrow RC}$	0.08	0.45	D11
				$\beta_{BK\rightarrow SRF}$	0.21**	0.07	F5
Reading strategies				*Reading strategies*			
$\beta_{RS\rightarrow INF}$	0.53**	0.08	D12	$\beta_{RS\rightarrow INF}$	0.13	0.38	D12
$\beta_{RS\rightarrow RC}$	−0.04	0.16	D13	$\beta_{RS\rightarrow RC}$	−0.03	0.58	D13
$\beta_{RS\rightarrow EDIT}$	0.07	0.09	C8	$\beta_{RS\rightarrow EDIT}$	0.03	0.34	C8
$\beta_{RS\rightarrow PLAN}$	0.06	0.07	C9	$\beta_{RS\rightarrow PLAN}$	0.02	0.08	C9
$\beta_{RS\rightarrow REV}$	0.23	0.14	C10	$\beta_{RS\rightarrow REV}$	0.20	0.17	C10
$\beta_{RS\rightarrow WQ}$	0.32**	0.08	C11	$\beta_{RS\rightarrow WQ}$	0.19	0.14	C11
				$\beta_{RS\rightarrow TWW}$	0.07	0.36	C24
Inferencing				*Inferencing*			
$\beta_{INF\rightarrow RC}$	0.48*	0.14	D14	$\beta_{INF\rightarrow RC}$	0.13	0.33	D14
$\beta_{INF\rightarrow REV}$	−0.15	0.18	C12	$\beta_{INF\rightarrow REV}$	−0.12	0.21	C12
Reading comprehension				*Reading comprehension*			
$\beta_{RC\rightarrow PLAN}$	0.24**	0.06	C15	$\beta_{RC\rightarrow PLAN}$	0.21**	0.06	C15
$\beta_{RC\rightarrow REV}$	0.20*	0.18	C16	$\beta_{RC\rightarrow REV}$	0.18*	0.08	C16
$\beta_{RC\rightarrow WQ}$	0.22**	0.05	C17	$\beta_{RC\rightarrow WQ}$	0.12	0.07	C17
				$\beta_{RC\rightarrow TWW}$	0.11	0.10	C29
Handwriting				*Handwriting*			
$\beta_{HW\rightarrow EDIT}$	0.10*	0.04	N3	$\beta_{HW\rightarrow EDIT}$	0.11*	0.04	N3
$\beta_{HW\rightarrow PLAN}$	0.18**	0.06	N4	$\beta_{HW\rightarrow PLAN}$	0.17**	0.06	N4
$\beta_{HW\rightarrow WQ}$	0.25**	0.05	N5	$\beta_{HW\rightarrow WQ}$	0.23**	0.05	N5
				$\beta_{HW\rightarrow TWW}$	0.18	0.35	P1

(Continued)

TABLE 8 (Continued)

Reduced RWM Model (Model 3)				Full RWM Model (Model 4)			
Path	Parameter	SE	Path #	Path	Parameter	SE	Path #
Plan				*Plan*			
$\beta_{PLAN\rightarrow EDIT}$	0.05	0.04	N8	$\beta_{PLAN\rightarrow EDIT}$	0.06	0.05	N8
$\beta_{PLAN\rightarrow REV}$	0.11*	0.05	N9	$\beta_{PLAN\rightarrow REV}$	0.12*	0.05	N9
$\beta_{PLAN\rightarrow WQ}$	0.11*	0.04	N10	$\beta_{PLAN\rightarrow WQ}$	0.09*	0.05	N10
				$\beta_{PLAN\rightarrow TWW}$	0.12	0.20	P3
Edit				*Edit*			
$\beta_{EDIT\rightarrow REV}$	0.31**	0.06	N6	$\beta_{EDIT\rightarrow REV}$	0.32**	0.07	N6
$\beta_{EDIT\rightarrow WQ}$	0.05	0.06	N7	$\beta_{EDIT\rightarrow WQ}$	−0.03	0.08	N7
				$\beta_{EDIT\rightarrow TWW}$	−0.06	3.01	P2
Revision				*Revision*			
$\beta_{REV\rightarrow WQ}$	0.31**	0.05	N11	$\beta_{REV\rightarrow WQ}$	0.29**	0.05	N11
				$\beta_{REV\rightarrow TWW}$	0.19*	0.07	P4
				Writing productivity			
				$\beta_{TWW\rightarrow WQ}$	0.18**	0.05	P5
				Oral reading fluency			
				$\beta_{ORF\rightarrow EDIT}$	−1.47	2.34	C20
				$\beta_{ORF\rightarrow PLAN}$	0.09	0.07	C21
				$\beta_{ORF\rightarrow REV}$	0.03	0.19	C22
				$\beta_{ORF\rightarrow WQ}$	−0.23	0.22	C23
				$\beta_{ORF\rightarrow TWW}$	0.08	9.01	C24
				$\beta_{ORF\rightarrow RS}$	−0.39	1.14	F6
				$\beta_{ORF\rightarrow RC}$	0.13	1.62	F7
				$\beta_{ORF\rightarrow INF}$	−0.58	0.87	F8
				$\beta_{ORF\rightarrow SRF}$	0.06	0.35	F9
				Silent reading fluency			
				$\beta_{SRF\rightarrow RS}$	1.25	1.50	F10
				$\beta_{SRF\rightarrow RC}$	0.27	2.52	F11
				$\beta_{SRF\rightarrow INF}$	1.30	1.40	F12
				$\beta_{SRF\rightarrow EDIT}$	−0.17	0.96	C25
				$\beta_{SRF\rightarrow REV}$	0.01	0.28	C26
				$\beta_{SRF\rightarrow TWW}$	0.09	2.29	C27
				$\beta_{SRF\rightarrow WQ}$	0.52	0.34	C28

**$p \leq 0.001$; *$p \leq 0.05$.
Path # corresponds to paths in Figures 3–6. N/A, the path was excluded because the model did not converge with the inclusion of this path. Word literacy was significantly correlated with vocabulary ($r = 0.31$–0.33, $p < 0.001$) and background knowledge ($r = 0.44$–0.45, $p < 0.001$), and vocabulary and background knowledge were significantly correlated ($r = 0.32$–0.33, $p < 0.001$). In these models, several residual covariances were estimated to account for common method variance: (1) WJ-III Letter Word Identification and TOWRE Sight Word Efficiency ($r = 0.26$–0.35, $p < 0.001$); (2) WJ-III Spelling and percent words spelled correctly ($r = 0.31$–0.46, $p < 0.001$); and (3) WJ-III Letter Word Identification and WJ-III Spelling ($r = 0.37$, $p < 0.001$).

the six traits (see Supplementary Appendix A). The nested models for ORF ($\Delta\chi^2$ (5) = 4.29, $p > 0.05$) and SRF ($\Delta\chi^2$ (4) = 5.55, $p > 0.001$) were not significantly different from the full model in terms of overall fit. The reduced model solutions again pointed to a key difference: when ORF did not make direct contributions to specific domains, word reading predicted word choice ($\beta = 0.10$, SE = 0.04, $p < 0.05$) and SRF also predicted conventions ($\beta = 0.21$, SE = 0.09, $p < 0.05$) and CIWS ($\beta = 0.44$, SE = 0.06, $p < 0.001$). When paths from SRF to writing domains were omitted, ORF predicted conventions ($\beta = 0.23$, SE = 0.12, $p < 0.05$) and CIWS ($\beta = 0.37$, SE = 0.05, $p < 0.05$).

The Writing-to-Reading Model specified regressions of reading skills on writing skills. The diagram and results of this model are presented in Supplementary Appendix B. Several effects were in the expected range: spelling predicted word reading ($\beta = 0.61$, SE = 0.07, $p < 0.001$), ORF ($\beta = 0.59$, SE = 0.07, $p < 0.001$), and SRF ($\beta = 0.40$, SE = 0.08, $p < 0.05$), and interestingly, spelling also predicted background knowledge ($\beta = 0.21$, SE = 0.07, $p < 0.001$); editing predicted

TABLE 9 Total indirect and specific indirect effects of the full Reading-to-Writing Mediation (RWM) models.

RWM Model 3				RWM Model 4			
Path	Parameter	SE	95% CI	Path	Parameter	SE	95% CI
Writing quality				Writing quality and productivity			
$\beta_{BK \rightarrow WQ}$	0.11**	0.03	[0.03, 0.18]	$\beta_{BK \rightarrow WQ}$	0.19*	0.10	[0.06, 0.85]
$\beta_{RS \rightarrow WQ}$[a]	0.13*	0.05	[0.01, 0.26]	$\beta_{RS \rightarrow WQ}$	0.07	0.12	[−1.67, 0.27]
$\beta_{RC \rightarrow WQ}$[b]	0.10*	0.04	[0.04, 0.20]	$\beta_{RC \rightarrow WQ}$	0.11*	0.04	[0.01, 0.21]
$\beta_{HW \rightarrow WQ}$	0.04*	0.01	[0.01, 0.09]	$\beta_{HW \rightarrow WQ}$	0.07**	0.02	[0.01, 0.11]
$\beta_{PLAN \rightarrow WQ}$	0.04*	0.02	[0.00, 0.09]	$\beta_{PLAN \rightarrow WQ}$	0.06*	0.02	[0.01, 0.12]
$\beta_{EDIT \rightarrow WQ}$	0.10**	0.03	[0.04, 0.18]	$\beta_{EDIT \rightarrow WQ}$	0.10	0.59	[−5.41, 1.53]
				$\beta_{ORF \rightarrow WQ}$	−0.10	0.45	[−4.33, 0.58]
				$\beta_{SRF \rightarrow WQ}$	0.45	0.56	[0.08, 10.22]
				$\beta_{WORD \rightarrow TWW}$	0.33	10.96	[−110.26, 26.57]
				$\beta_{VOC \rightarrow TWW}$	0.05	1.50	[−15.68, 5.99]
				$\beta_{ORF \rightarrow TWW}$	0.01	8.77	[−31.66, 55.39]
				$\beta_{SRF \rightarrow TWW}$	0.15	2.11	[−1.51, 11.08]
				$\beta_{HW \rightarrow TWW}$	0.03	0.35	[−3.86, 0.70]
				$\beta_{PLAN \rightarrow TWW}$	0.02	0.19	[−1.60, 0.78]
				$\beta_{EDIT \rightarrow TWW}$[g]	0.06	0.03	[0.01, 0.14]
Editing, planning, and revision				Editing, planning, and revision			
$\beta_{RS \rightarrow PLAN}$	0.05	0.03	[−0.01, 0.14]	$\beta_{RS \rightarrow PLAN}$	0.01	0.07	[−1.00, 0.09]
$\beta_{VOC \rightarrow EDIT}$	0.01	0.01	[−0.01, 0.05]	$\beta_{VOC \rightarrow EDIT}$	−0.10	0.36	[−1.69, 0.67]
$\beta_{RS \rightarrow EDIT}$	0.01	0.01	[−0.01, 0.04]	$\beta_{RS \rightarrow EDIT}$	0.01	0.01	[−0.02, 0.03]
$\beta_{HW \rightarrow EDIT}$	0.01	0.10	[−0.01, 0.04]	$\beta_{HW \rightarrow EDIT}$	0.01	0.01	[−0.01, 0.04]
$\beta_{RC \rightarrow REV}$	0.03*	0.01	[0.00, 0.09]	$\beta_{RC \rightarrow REV}$	0.03	0.02	[0.00, 0.08]
$\beta_{INF \rightarrow REV}$[c]	0.11	0.15	[0.03, 0.70]	$\beta_{INF \rightarrow REV}$	0.08	0.14	[−0.18, 0.46]
$\beta_{RS \rightarrow REV}$	−0.02	0.13	[−0.35, 0.18]	$\beta_{RS \rightarrow REV}$	0.01	0.16	[−1.21, 0.38]
$\beta_{PLAN \rightarrow REV}$	0.02	0.02	[−0.01, 0.06]	$\beta_{PLAN \rightarrow REV}$	0.02	0.02	[−0.02, 2.67]
				$\beta_{ORF \rightarrow PLAN}$	−0.02	0.09	[−0.41, 0.12]
				$\beta_{ORF \rightarrow EDIT}$	−0.02	0.95	[−9.36, 0.23]
				$\beta_{ORF \rightarrow REV}$	−0.47	0.67	[−6.41, 0.17]
				$\beta_{SRF \rightarrow EDIT}$	0.07	2.95	[−10.48, 3.41]
				$\beta_{SRF \rightarrow REV}$	0.19	0.74	[−0.49, 7.23]
Reading strategies, inferencing, and reading comprehension				Reading strategies, inferencing, reading fluency, and reading comprehension			
$\beta_{VOC \rightarrow INF}$	0.02	0.03	[−0.07, 0.11]	$\beta_{VOC \rightarrow INF}$	0.34	0.41	[0.06, 7.59]
$\beta_{BK \rightarrow INF}$	0.05	0.03	[−0.02, 0.15]	$\beta_{BK \rightarrow INF}$	0.30	0.32	[0.06, 4.90]
$\beta_{WORD \rightarrow RC}$	0.14*	0.07	[−0.07, 0.32]	$\beta_{WORD \rightarrow RC}$	0.47**	0.05	[0.35, 0.60]
$\beta_{VOC \rightarrow RC}$[e]	0.12*	0.04	[0.04, 0.28]	$\beta_{VOC \rightarrow RC}$	0.17	0.69	[−0.40, 12.37]
$\beta_{BK \rightarrow RC}$	0.08*	0.03	[−0.001, 0.23]	$\beta_{BK \rightarrow RC}$	0.11	0.45	[−0.38, 4.60]
$\beta_{RS \rightarrow RC}$[f]	0.25*	0.11	[0.10, 0.92]	$\beta_{RS \rightarrow RC}$	0.05	0.22	[−1.73, 0.29]
				$\beta_{VOC \rightarrow SRF}$	0.00	0.02	[−0.05, 0.09]
				$\beta_{ORF \rightarrow INF}$	0.04	0.84	[−1.95, 4.98]
				$\beta_{SRF \rightarrow INF}$	0.16	1.20	[−1.37, 7.07]
				$\beta_{ORF \rightarrow RC}$	−0.18	1.51	[−6.22, 3.51]
				$\beta_{SRF \rightarrow RC}$	0.53	2.24	[−0.92, 24.19]

*$p < 0.05$; **$p < 0.001$.

Statistically significant specific indirect effects: [a]$\beta_{RS \rightarrow INF \rightarrow RC \rightarrow WQ} = 0.06$ [0.02, 0.22]; [b]$\beta_{RC \rightarrow REV \rightarrow WQ} = 0.06$ [0.01, 0.16]; [c]$\beta_{INF \rightarrow RC \rightarrow REV} = 0.10$ [0.02, 0.66]; [e]$\beta_{VOC \rightarrow INF \rightarrow RC} = 0.11$ [0.04, 0.27]; [f]$\beta_{RS \rightarrow INF \rightarrow RC} = 0.25$ [0.10, 0.92]; [g]$\beta_{EDIT \rightarrow REV \rightarrow TWW} = 0.06$, 95% CI [0.01, 0.14].

vocabulary ($\beta = 0.26$, SE = 0.07, $p < 0.001$), inferencing ($\beta = 0.23$, SE = 0.08, $p < 0.05$), reading strategies ($\beta = 0.19$, SE = 0.07, $p < 0.05$), SRF ($\beta = 0.11$, SE = 0.07, $p < 0.001$), and reading comprehension ($\beta = 0.17$, SE = 0.06, $p < 0.05$); and writing quality predicted all reading skills, except for word reading. This model explained over half of the variance in reading strategies and ORF and SRF, and a smaller percent of variance in vocabulary and knowledge (see Table 3).

Discussion

A better understanding of the connection of R-W is of vital importance for supporting struggling writers considering the continuing difficulties exhibited and the documented relationships among these skills. Students who experience reading difficulties are increasingly likely to also experience difficulties in writing but teachers report sideling evidence-based writing instruction in the classroom (Graham et al., 2014). Understanding the skill patterns between R-W in ways that support the identification of other skill areas of need is critical.

Increasingly there are theoretical models that highlight R-W connections given their overlap in use of skills (Costa et al., 2016). In this study, we joined DIME components with NVSW to evaluate how lower- and higher-order skills in one domain impact counterpart skills in the other domain, including both ORF and SRF in the models. We limited the scope of the RWM model to *malleable* skills (i.e., those amenable to training) to increase its practical utility. Thus, we excluded the executive function (including attention, working memory, cognitive control, motivation, and self-efficacy) components of the NSVW model because there is a lack of compelling evidence that executive function training improve academic outcomes or predict response-to-intervention (Fletcher et al., 2018). We found support for the relations among DIME skills: mainly, vocabulary and strategies predicted inferencing, and higher-order knowledge and inferencing predicted reading comprehension. However, with the addition of fluency to the model, vocabulary predicted SRF instead of inferencing, and knowledge also predicted SRF instead of comprehension in line with recent research on this model (e.g., Oslund et al., 2018). We also found support for associations among component skills derived from the NSVW model: mainly among word literacy, handwriting and editing, as well as among planning, editing, revision, and writing quality and productivity. In the next sections, we highlight the findings of the cross-domain associations and their alignment with prior research.

Reading-to-Writing connections

Lower-order reading skills

The results revealed that decoding is related to transcription, specifically spelling and handwriting. This is consistent with previous research which has shown that word-level R-W are connected due to a shared set of skills and knowledge that influence both. Fitzgerald and Shanahan (2000) describe several universal text attributes that help explain the relationship between spelling and decoding, including letter knowledge, phonological and morphological awareness, and knowledge of the orthography of the language. Other studies have also shown that word reading is a correlate of spelling skills (e.g., Abbott et al., 2010), and that it can predict spelling in languages varying in orthographic transparency (Georgiou et al., 2020).

We hypothesized that decoding and vocabulary would not predict writing quality, after controlling for higher-order cognition and comprehension. However, we found that decoding played a role in writing quality, highlighting this fundamental connection for children with LD. Interestingly, the opposite direction did not hold in the W-to-R Model because writing quality predicted all reading skills except for decoding. Collectively, these findings suggest that decoding is an active self-regulatory process in writing, beyond higher-order self-regulation (e.g., editing). Further, when students can read words accurately and fluently, they are more likely to use those words correctly in their own writing, which can help them expand their vocabulary and spelling skills, leading to overall writing quality. The study also found that decoding predicted word choice, a specific component of composition, possibly due to shared knowledge of components involved in the R-W process and could reflect an artifact of print exposure. As students are exposed to print and words, and their meaning, they become stored in the mental lexicon, and thus, more accessible during the writing process. However, it's possible that students may select words that they know how to spell, thus reinforcing a potential W-to-R pathway. Future research is needed to disentangle these different mechanisms and to provide a more comprehensive understanding of the relationship between decoding, encoding, and word choice in composition.

We found that vocabulary was related to writing quality and editing, but not planning or revision. This suggests that stronger vocabulary facilitates conveying the intended meaning and identifying and correcting errors of spelling and usage effectively, but may not necessarily help revise (for content, organization, tone, and syntax), or help organize and structure ideas before beginning to write. Surprisingly, reading comprehension, rather than vocabulary, was related to productivity, possibly because better vocabulary allows students to express ideas succinctly and precisely but may relate less to total words written than other productivity measures that account for accuracy. On the other hand, comprehension may facilitate understanding the ideas and concepts students are writing about and avoid errors and misunderstandings in their writing that could slow them down.

Higher-order reading skills

In our analysis, we looked at the role of higher-level reading skills, such as background knowledge, inferencing, and reading strategies. Our hypothesis was that knowledge is important for planning because writers need to verbalize their knowledge of a topic before they start writing to focus their writing (Tierney and Pearson, 1983). This was possibly not supported because inexperienced writers simply retrieve ideas prompted by the topic and translate them into text without purposeful engagement in planning, while experienced writers develop a set of goals and generate ideas from their knowledge to achieve these goals (Kucer, 1985). It is also possible that the knowledge assessment in our study affected the results (i.e., it measured knowledge from the reading passages but that was not specific to the writing task). Importantly, we found evidence of an indirect relationship between general knowledge and writing quality. This is not surprising given the importance of knowledge access, use, and generation during the writing process (e.g., Bereiter and Scardamalia, 1987; Allen et al., 2014; Kim, 2020), but our findings suggest that general knowledge influenced writing through its indirect effect on other literacy skills although not via any specific indirect path. Future research should evaluate general and topic-specific knowledge in the context of multiple literacy skills.

Contrary to our hypothesis, inferencing did not predict revision possibly because students with LD are not sophisticated in their revision process to use inferencing skills to detect errors in meaning. Limpo et al. (2013) found that revision skills increase from elementary to secondary grades, but in general, students detect and correct mechanical errors more than substantive meaning errors, and further, students are significantly better at correcting than detecting errors in stories with errors deliberately embedded in them. Nonetheless, we found support for complete mediation in which the effect of inferencing on revision was mediated by reading comprehension. It is possible that students who are better at making inferences while reading (i.e., making logical and reasonable assumptions based on information that is not explicitly stated in texts) are better able to understand the deeper meaning of a text and draw connections between different pieces of information. Understanding and interpreting written text effectively may, in turn, allow them to make revisions so their writing is more effective.

Lastly, reading strategies were related to editing, revising, and quality, but the findings did not support our hypothesis that strategies would relate to planning. The performance measure of reading strategies involved reading a passage to compose a summary; students also completed a survey of reading and learning strategies. More strategic students demonstrated better editing and revising skills and produced higher quality compositions, as expected, because editing and revising are strategic and involve self-monitoring, although research on this is limited. Self-regulation (a strategic process) also distinguishes novice from expert writers and employing more strategies during writing likely results in higher quality compositions. Although the measure focused on reading strategies, there may be overlap with writing strategies due to shared knowledge and skills between the two. Procedural knowledge, purposive information access, and goal-setting could all be influencing factors.

Oral and silent reading fluency

ORF predicted spelling possibly because letter-sound knowledge (Paige et al., 2019) and conceptual word knowledge (Zutell and Rasinski, 1989) underlie both component skills. Zutell and Rasinski (1986) found that the correlation of spelling was higher with oral reading accuracy than rate or prosody, further emphasizing the important role of phonological and orthographic knowledge above and beyond speed or expressiveness of reading aloud. Further, Paige and colleagues evaluated the opposite directionality (spelling ➔ ORF) in a sample of third graders at risk for LDs and found a small, non-hypothesized direct effect of spelling on oral reading fluency after controlling for word- and non-word reading but they did not estimate indirect effects via word and non-word reading. Although these finding contribute to our understanding of the complex interactions among reading fluency and spelling, further research is needed to better understand the underlying mechanisms and directionality of the observed relationships.

ORF also predicted the sentence-level writing component with less cognitive load (editing), whereas SRF predicted planning, which requires deeper processing (Alamargot et al., 2006). Interestingly, both ORF and SRF were related to reviewing, and neither were predictive of discourse-level writing outcomes (productivity and quality), suggesting that ORF/SRF are implicated in specific writing processes (De Smet et al., 2018; Conijn et al., 2022). However, it should be noted that there is a lack of research available to definitively interpret the results of ORF/SRF with writing processes and dimensions.

Finally, ORF/SRF were related to specific dimensions of writing (CIWS and conventions). Interestingly, when paths for both SRF/ORF were included, SRF no longer related to writing dimensions. However, when paths from ORF were excluded, both SRF and decoding predicted conventions, and word reading predicted word choice. These findings emphasize the differential relations of fluency skills with writing dimensions, further emphasizing (a) the importance of the construct of fluency and the connections between fluency in R-W, and (b) the value of ORF/SRF not only as indicators of overall reading but as broader language indicators that capture dimensions such as CIWS, which is thought to reflect both fluency and accuracy of writing. It is therefore not surprising that ORF/SRF were also related to conventions (Conijn et al., 2022), given its design to capture elements of capitalization and punctuation, as these elements are also captured in the CIWS metric. Although based on fluency, ORF was originally designed to serve as an overall indicator of reading performance (Deno, 2003), capturing fluency and related skills (e.g., vocabulary and reading comprehension). The intention of reading fluency to function in this capacity can be seen particularly in the outcomes for our alternative Reading-to-Writing Domains model. To further advance our understanding of the complex relationship between reading fluency and writing processes/domains, future research should aim to explore the co-development of these skills in students with LDs. This research could benefit from utilizing experimental measures and procedures borrowed from the discourse-processing literature, such as eye-tracking technology to investigate concurrent, silent reading and writing processes (Anson and Schwegler, 2012) in addition to standardized measures of ORF/SRF. Such methods can provide valuable insights into the underlying cognitive mechanisms involved in the development of reading fluency and writing skills and could ultimately inform more effective interventions for students with LDs.

Reading comprehension

Contrary to our expectations, we found that writing quality and productivity were not related to ORF and SRF, but rather to reading comprehension. This means that just knowing more words or reading with accuracy, speed, and expression does not automatically lead to a deeper level of written expression or self-regulatory writing activities. Similarly, we found that reading comprehension (and not ORF/SRF, inferencing or strategies) played a significant role in multiple indirect effects. First, we expected that higher-order reading would mediate the relationship between word/world knowledge and writing processes (e.g., vocabulary ➔ inference ➔ revision, or vocabulary ➔ strategies ➔ planning), as students with stronger foundational skills could apply those skills better in R-W activities like planning. However, higher-order skills were found to mediate other higher-order skills and writing processes or outcomes (e.g., strategies ➔ inference ➔ reading comprehension ➔ writing quality), although these effects were small. Revision mediated the relationship between reading comprehension and writing quality, suggesting that comprehension is related to writing quality because it facilitates making revisions. Inferencing and reading comprehension mediated the relationship between reading strategies and writing quality, indicating that reading strategies facilitate better inferencing and understanding of the text, which in turn improves writing.

Our findings also showed that adequate reading comprehension relates to planning, editing, and revision and writing quality and productivity. Stronger comprehension facilitates generating and organizing ideas, communicating thoughts effectively in writing, and analyzing one's own writing to identify and correct errors. These findings demonstrate that the connection between reading comprehension and writing goes beyond shared content or domain knowledge. The comprehension-planning link points to the connection with procedural knowledge for accessing information purposely, setting goals, and analyzing. The comprehension-editing link points to the pragmatic knowledge of text attributes (words, syntax, usage). The comprehension-revision link points to meta-knowledge about written language (functions and purposes).

The results suggest knowledge and abilities in R-W skills may transfer across domains. Teaching a skill in one domain (e.g., reading comprehension) can directly impact another (e.g., written expression). Implicit R-W connections may also develop (e.g., improved reading comprehension through targeted inferencing instruction may lead to better writing and revision). These findings have important implications for targeted interventions, particularly when paired with screeners like ORF in the context of MTSS.

Writing-to-Reading connections

The W-to-R model fit well and provided evidence for robust effects of spelling, editing, and writing quality on word/letter-, sentence-, and text-level reading. Although the reading skills of inferencing and knowledge did not predict writing quality, the opposite directions held in the W-to-R model, which is an important finding. Effective writing requires anticipating the reader's potential inferences and identifying important themes and connections from knowledge to produce coherent text. Better writers likely produced clearer and logically consistent texts, although we did not score the essays for logical coherence. Similarly, editing predicted inferencing, but planning and revision were not predictive of reading skills, suggesting that editing (the ability to correct errors in spelling, grammar, punctuation, and syntax) facilitates meaning making processes (i.e., inferencing) because both skills require detecting inconsistencies in meaning using context clues and background knowledge whereas planning does not necessarily rely on context cues. Revision involves making changes to the content or structure of text, which may not necessarily rely on the use of context clues or background knowledge in the same way as editing. Our findings suggest that writing activities (e.g., writing-to-learn) may build word/world knowledge and meaning-making processes (e.g., inferencing and comprehension monitoring) by providing opportunities to write about new topics, using new vocabulary, and monitoring inconsistencies and meaning in their texts. Additional research is needed to fully understand the W-to-R directionality in multiple instructional contexts (e.g., integrated R-W instruction using writing-to-learn or reading-to-write approaches) in ways that direct both theory and practice for specific populations like those with LDs.

Limitations and future directions

The findings of this study are limited to students with/at-risk for LDs and should be replicated and systematically contrasted with both typically developing and other special populations. Further, the nature of the measures impacted our results. For example, planning was not affected by knowledge, possibly because the knowledge measure was not aligned with the writing prompt. The planning measure may have been insufficient to capture the student's necessary background knowledge, as students were only given 5 min to plan without explicit instructions or tools. Also, writing requirements in most strategy assessments may align more with editing and revision than with planning. Alternative performance measures, such as comprehension monitoring, and the inclusion of writing-specific self-reported strategy use could potentially yield different results. In the RWM Model specifically, editing and revision are framed as activities that take place during writing, but their measures were based on a TOWL subtest that assessed the use of contextual conventions in student essays. Future research should incorporate experimental indicators for capturing inter- and intra-individual editing and revision patterns alongside offline measures of grammar, syntax, and organization, for example. It is possible that sentence-level measurement of SRF is insufficient and alternative indicators are necessary to capture the SRF needed for advanced text reading and composition. Similarly, we measured handwriting quality, not fluency (the ability to write quickly and legibly). Future research using measures of handwriting fluency could help further our understanding of how handwriting accuracy and rate impact associations among R-W, particularly in conjunction with ORF, SRF, and writing productivity. Lastly, regarding measurement used in the study, the individual traits of the 6+1 rubric have poor reliability and multicollinearity issues, as shown by high correlations among the traits in the present study ($r = 0.53–0.81$). Future research should assess writing dimensions using measures/indicators with high content and face validity. Future studies should also aim to include multiple prompts, genres, and types of measures and evaluate the common method variance in component skills models that make use of a single writing prompt to derive multiple indicators.

Another limitation is that insufficient data were available on the specific components, frequency, and duration of the writing instruction each student received. Bi-directional relations among malleable component-skills, such as those in the R-to-W models of the present study, should be systematically evaluated by introducing variations in (a) instruction and (b) executive function and motivation requirements of the task. For example, the DIME model's direct/indirect relations changed as a function of the focus of intervention (e.g., foundational skills vs. text processing; Ahmed et al., 2022b). We expect that means in R-W skills, and pattern of direct/indirect effects in R-to-W and W-to-R models will be disrupted as a function of the instruction (e.g., writing-for-reading, text-structure) and task requirements. Future research is needed to evaluate the proposed model and alternative specifications (including W-to-R) in multiple instructional and assessment contexts.

Conclusion

Despite existing evidence of the general connection between reading and writing for children with learning difficulties, an evaluation of the specific relationships between different literacy sub-skills is crucial for identifying potential areas for improvement and understanding instructional challenges. This study investigated higher-order reading skills of the Direct and Inferential Mediation (DIME) model as mediators between basic literacy and knowledge, and the writing processes and products of the Not-so-Simple View of Writing (NSVW) model. This study offers a comprehensive evaluation of connections among higher-order skills in both reading and writing domains in component-skills models, considering a range of model constellations that systematically explore the role of oral and silent reading fluency and comprehension skills. The three reading-to-writing models evaluated in the current study (Reading-to-Writing Skills, Reading-to-Writing Dimensions, and Reading-to-Writing Mediation) and the Writing-to-Reading alternative models are comprehensive in scope (in terms of the number of higher-order skills included) and depth (in terms of the granularity of constructs). The findings provide ongoing support for the importance of the constructs of higher-order reading and writing, and fluency, and add to the empirical literature on the direct and indirect effects among components skills at the sub-word/word, sentence, and text-levels. Specifically, the study's findings highlight the intricate interplay between reading and writing skills, emphasizing the explicit roles of decoding, comprehension, fluency, and strategies in shaping writing quality and productivity, and the implicit roles of background knowledge and inferencing in shaping writing processes and quality. We found that, as opposed to vocabulary, decoding predicted word choice, and reading comprehension had an impact on writing productivity. Background knowledge exerted an indirect influence on writing through its effects on other literacy skills, and we identified a mediation effect of inferencing impacting revision through reading comprehension. Additionally, distinctions between oral and silent reading fluency emerged, with the former predicting spelling and editing and the latter predicting planning. Both types of fluency were linked to reviewing and specific dimensions of writing. Finally, writing quality was found to predict inferencing and knowledge, while editing predicted inferencing. These findings highlight the importance of fostering strong reading abilities and writing skills to enhance students' overall literacy performance, emphasizing the need for a comprehensive approach to literacy education that nurtures both reading and writing competencies. Studying the relationship between reading fluency and writing skills across different levels of language is critical, given the reliance on ORF for screening and progress monitoring in practice. The study's findings suggest that ORF may serve as an indicator of both reading difficulty and writing performance across different levels of writing. However, the results of the present study should serve as the basis for further studies on the relationship between reading fluency and component skills of writing.

Data availability statement

The data are available upon request from the Texas Institute for Measurement, Evaluation, and Statistics (TIMES). Requests to access these datasets should be directed to yusra.ahmed@times.uh.edu.

Ethics statement

The studies involving human participants were reviewed and approved by the Institutional Review Boards of the University of Houston and the University of Texas at Austin. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

YA conceived of the presented idea and performed the computations. YA, SCK, and MKM refined the ideas, discussed the results, and contributed to the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1033970/full#supplementary-material

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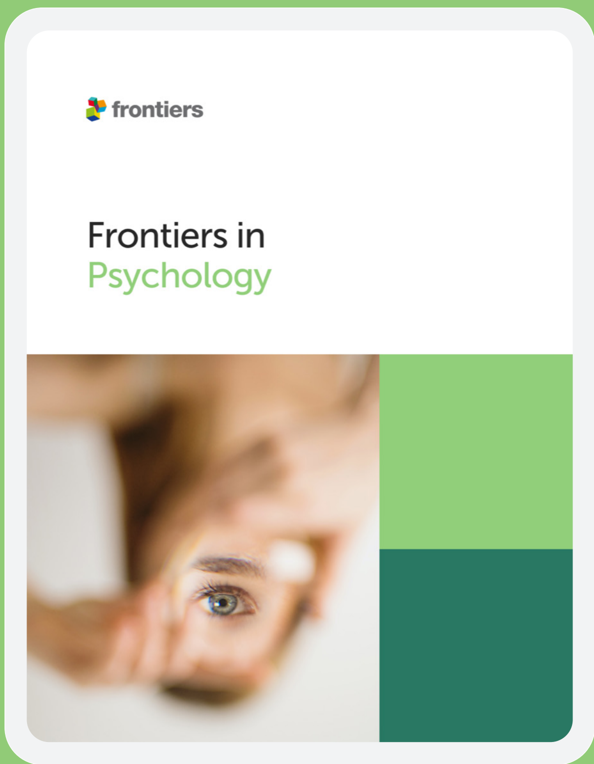

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