INTERPRETING THE COMORBIDITY OF LEARNING DISORDERS

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INTERPRETING THE COMORBIDITY OF LEARNING DISORDERS

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Editorial: Interpreting the Comorbidity of Learning Disorders

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Editorial on the Research Topic

Interpreting the Comorbidity of Learning Disorders

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Reading, spelling, and arithmetic are crucial domains of school achievement, and neurodevelopmental learning disorders in written language processing (dyslexia) and arithmetic (dyscalculia) have a marked impact on children's academic careers and professional perspectives (Ritchie and Bates, 2013). Prevalence studies clearly show high rates of co-occurrence (comorbidity) between these learning disorders as well as with other neurodevelopmental disorders, such as attention-deficit-hyperactivity disorder (ADHD), developmental language disorder, or even developmental motor disorder, so that the concept of "*specific*" learning disorders, affecting one learning domain only, is seriously challenged.

The high co-occurrence rate between learning disorders has also been acknowledged in the latest edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5; American Psychiatric Association, 2013) which now places a variety of disorders across several learning domains (i.e., reading decoding and comprehension, spelling and written expression, number sense, and mathematical reasoning) under a single diagnostic category. Still, the category used ("*Specific Learning Disorder*") maintains the ambiguous term "specific" presumably with the aim to highlight that deficits in learning are not due to other developmental disorders or intellectual disabilities.

THE ROLE OF COMORBIDITY FOR ADVANCING CAUSAL MODELS OF LEARNING DISORDERS

In the past, our knowledge on the manifestation and causation of neurodevelopmental learning disorders has derived mostly from studies investigating each learning disorder separately (either dyslexia or dyscalculia). These studies have often either deliberately excluded individuals with additional learning problems, interpreted such problems as a consequence of the disorder studied, or simply neglected co-occurring disorders. However, single deficit models may not provide good explanations for the high *heterogeneity* in the symptomatology of learning disorders. Overall, there is growing consensus that the etiology of neurodevelopmental disorders is best interpreted within a *multiple-deficit framework* (Pennington, 2006; McGrath et al., 2020). This aims to provide the theoretical background for explaining both co-occurrence of and dissociations between, disorders. Comorbidity is explained by risk factors that are shared between disorders, while dissociations are explained by disorder-specific risk factors. The pattern of symptoms in individual cases is also likely to be influenced by protective factors, which however are rarely considered in research. Altogether multiple risk and protective factors determine the behavioral outcome (Pennington et al., 2012) and may thus provide a better account for the heterogeneity observed in neurodevelopmental disorders.

Risk (and protective) factors are probabilistic and interact with each other, with some factors being more relevant and more specific for a certain disorder than others. The search for these factors represents a new and challenging field of research. Several relevant cognitive risk factors have been identified that influence a child's susceptibility to developing a single disorder (e.g., a phonological deficit in dyslexia) or a combination of learning disorders (e.g., deficits in language, working memory, or executive functions). Still, the complex interplay between these risk factors and thus the mechanisms underlying the large variability of individual profiles are not well-understood.

Similarly, neurobiological studies have identified differences in brain structure and function associated with a single disorder as well as differences potentially associated with the overlap between learning disorders. For example, much research has aimed to uncover structural and functional differences both in the case of dyslexia (e.g., Richlan et al., 2009; Ozernov-Palchik et al., 2016) and dyscalculia (Landerl et al., 2021; Vogel and De Smedt, 2021). However, studies explicitly investigating the neuronal overlap between dyslexia and dyscalculia and the complex interplay between the different levels of analyses (i.e., neurobiological and cognitive) and the behavioral manifestations are as yet rare (see for example Peters et al., 2018). Similar considerations may apply to the overlap between learning disorders and other developmental disorders, such as ADHD and motor disorders (Pennington et al., 2019).

The present Research Topic (RT) brings together a number of studies that try to elucidate cognitive risk (and protective) factors focussing particularly on the relationship between reading and math skills (and deficits) but also considering other disorders such as ADHD and motor difficulties, as well as protective factors (such as cognitive strengths), helping children to compensate for their learning disorders.

COGNITIVE FACTORS UNDERLYING THE RELATIONSHIP BETWEEN READING AND MATH SKILLS

Dyslexia is characterized by significant and persistent difficulties related to reading, such as reading accuracy, fluency, or comprehension. About 40% of children with reading problems also have low spelling skills (Moll and Landerl, 2009; Moll et al., 2014). Dyscalculia also has a broad range of manifestations, including deficits in numerical abilities, i.e., understanding and processing of non-symbolic numerosity and/or its symbolic representations (Arabic numbers and number words), deficits in arithmetic, i.e., mental calculations, fact retrieval and calculation procedures, and problems in math reasoning. Prevalence studies consistently report high comorbidity rates between dyslexia and dyscalculia, ranging between 11 and 70% (for an overview see: Moll et al., 2014), depending on cut-off criteria applied and tasks and constructs (and thus symptoms) used to define the disorders (Dirks et al., 2008; Landerl and Moll, 2010).

Various studies in the RT jointly examined reading and math skills in samples of typically developing children with the aim to elucidate the cognitive factors which may account for the overlap among these skills (and potentially increase the risk of developing both a reading and math problem). Bernabini et al. used a dimensional approach to examine the relationship between reading and math in a sample of 4^{th}- and 5^{th}-grade children. Their approach envisaged both examining the influence of reading and math skills on their putative cognitive predictors as well as the opposite, that is the influence of cognitive abilities in predicting reading and math. These two ways of looking at data provide interesting complementary information on the overlap between reading and math skills. In a carefully planned longitudinal study, Amland et al. examined whether the quality of phonological representations could provide the possible foundation of the association between reading and math skills (as well as disorders). Results did not show a direct effect of phonological awareness in arithmetic development, although an indirect influence of this parameter did emerge on verbal arithmetic (but not fluency). The authors emphasize the importance of accurate control of all possible confounders in the examination of common risk factors. Geary et al. examined the contribution of general cognitive abilities (including intelligence, verbal short-term and working memory, visuospatial memory, attention, and ability measures) and academic attitudes (particularly in-class attentive behavior) in predicting reading and math achievement (separately as well in co-morbidity fashion).

A complementary (though less frequently investigated) perspective is that of examining cognitive strengths that may help children to compensate for their learning disorders. Huijsmans et al. carried out one such study including children with isolated mathematical learning difficulties and children with comorbid mathematical and reading difficulties. Data indicated that strong rapid naming skills provided partially effective mechanism for children with math deficiencies (though not for children with both reading and math problems).

In understanding the overlap between reading and math difficulties, important aspects to consider are the learning environment at home as well as the presence and type of parental difficulties on the development of reading and math skills. Khanolainen et al. carried out a large longitudinal study examining these factors. The results indicated the interrelated role of familial risk, parental education, and type of learning environment at home in shaping the acquisition of math and reading skills.

Examining disorders from a comorbidity perspective may also help in pinpointing a more comprehensive description of the disorder. Kißler et al. investigated the possible presence of subtypes of dyscalculia in two samples in which the diagnosis was based either with a focus on calculation or on numerical capacities. Independent of the type of diagnosis results based on a mixture model analysis revealed the presence of two main sub-types of dyscalculia. The main difference was in terms of the degree of math impairment but also differences in attention skills contributed to the distinction, indicating the role of comorbidity in shaping dyscalculia subtypes.

MODELING READING, SPELLING, AND MATH

The growing knowledge about the common factors underlying reading, spelling and math creates the necessary premise to build a unitary architecture of these skills (and deficits).

Based on data from a group of typically developing children, Zoccolotti et al. proposed a multi-level model to account for the association among reading, spelling, and math skills which capitalize on the distinction among competence, performance, and acquisition (automatization). The model aims to provide a heuristic to account for the comorbidity of learning disorders in these areas, in particular with the aim of explaining both dissociations (related to the presence of distinct competencies) and associations (related to the influence of common performance factors as well as to the widespread effect of deficits in automatization).

SPECIFIC LEARNING DISORDERS AND ADHD

A well-known association with learning disorders concerns the ADHD symptomatology (e.g., Pham and Riviere, 2015). Jointly examining individuals with both dissociated and associated symptomatology may prove as an effective paradigm for the understanding of both disorders.

In a study using latent profile analysis, Laasonen et al. examined how measures based on different non-verbal theories (including temporal processing impairment, abnormal cerebellar functioning, procedural learning difficulties, visual processing, and attention deficits) would allow classifying adults with dyslexia, ADHD, or both. The authors showed that participants did not cluster according to their original diagnosis and thus underscored the "*continuous and overlapping nature of the observed difficulties.*"

Crisci et al. examined the possible role of comorbidity between specific learning disorders (SLD) and ADHD on executive functions by testing children with either SLD, ADHD, or both. Results indicated a widespread association of SLD, ADHD with inhibition and shifting tasks as well as a more selective influence on updating tasks. While children with SLD were impaired in verbal updating those with ADHD or with both SLD and ADHD were most impaired in spatial updating. Thus, it appears that considering the comorbidity between SLD and ADHD is important for a better understanding of both disorders.

LITERACY AND MOTOR DISORDERS

Some evidence indicates that comorbidity encompasses a wide spectrum of developmental disorders including both cognitive and motor difficulties (e.g., Cruddace and Riddell, 2006), though the nature of this comorbidity is still poorly understood.

Downing and Caravolas examined the possible association between reading and motor difficulties and evidenced a high co-morbidity between the two; indeed, the joint presence of literacy and motor difficulties was five times higher than what was expected based on the prevalence rates for each disorder (Study 1). In a further study, they searched for both independent and shared factors in the cognitive profile of these disorders: phonological processing and selective attention were risk factors for literacy disorders and visuospatial processing for motor disorders. Memory proved as a risk factor for the comorbid presence of literacy and motor disorders. These results confirm that also motor disorders can be interpreted within a multi-factorial perspective (Pennington, 2006).

CONCLUSION

The working hypothesis guiding the present RT was that single deficit models do not provide good explanations for the high *heterogeneity* in the symptomatology of learning disorders. In keeping with this idea, various studies in this RT provide new information on the characteristics of several developmental disorders (including dyslexia, ADHD, motor difficulties). Additional information in this RT comes from studies of typically developing children which also provide clues as to factors that underly the co-variation among reading, spelling, and math skills. It appears that to see skills (and relative deficits) in a comorbidity perspective represents an effective prospect to understand a wide spectrum of developmental disorders.

AUTHOR CONTRIBUTIONS

KM and PZ: wrote part of the first draft of the paper. MD, KL, and CB: made several changes to various versions of the manuscript. All authors gave a similar contribution.

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Project DyAdd: Non-linguistic Theories of Dyslexia Predict Intelligence

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Two themes have puzzled the research on developmental and learning disorders for decades. First, some of the risk and protective factors behind developmental challenges are suggested to be shared and some are suggested to be specific for a given condition. Second, language-based learning difficulties like dyslexia are suggested to result from or correlate with non-linguistic aspects of information processing as well. In the current study, we investigated how adults with developmental dyslexia or ADHD as well as healthy controls cluster across various dimensions designed to tap the prominent non-linguistic theories of dyslexia. Participants were 18–55-year-old adults with dyslexia (n = 36), ADHD (n = 22), and controls (n = 35). Non-linguistic theories investigated with experimental designs included temporal processing impairment, abnormal cerebellar functioning, procedural learning difficulties, as well as visual processing and attention deficits. Latent profile analysis (LPA) was used to investigate the emerging groups and patterns of results across these experimental designs. LPA suggested three groups: (1) a large group with average performance in the experimental designs, (2) participants predominantly from the clinical groups but with enhanced conditioning learning, and (3) participants predominantly from the dyslexia group with temporal processing as well as visual processing and attention deficits. Despite the presence of these distinct patterns, participants did not cluster very well based on their original status, nor did the LPA groups differ in their dyslexia or ADHD-related neuropsychological profiles. Remarkably, the LPA groups did differ in their intelligence. These results highlight the continuous and overlapping nature of the observed difficulties and support the multiple deficit model of developmental disorders, which suggests shared risk factors for developmental challenges. It also appears that some of the risk factors suggested by the prominent non-linguistic theories of dyslexia relate to the general level of functioning in tests of intelligence.

Keywords: dyslexia, ADHD, temporal processing, procedural learning, eyeblink conditioning, visual processing, visual attention, comorbidity

INTRODUCTION

Comorbidity between developmental and learning disorders is very common. Accordingly, it has been suggested that various developmental challenges result from risk and protective factors, some of which are shared and some specific for a given condition (Pennington, 2006; Pennington and Bishop, 2009). Related to this, language-based learning difficulties like dyslexia have been suggested to result from or correlate with non-linguistic aspects of information processing. In the current study, we investigate how adults with developmental dyslexia (dyslexia, DD) or attention deficit hyperactivity disorder (ADHD) and controls cluster across various dimensions designed to tap the prominent non-linguistic theories of dyslexia.

Developmental dyslexia is among the most intensively investigated developmental challenges. Despite the amount of research, the causative, correlative, and resulting as well as shared and differentiating factors with other developmental challenges, such as ADHD, are yet to be confirmed. Dyslexia is most often considered to belong to a continuum of language-based developmental and learning difficulties and impaired phonological processing is considered to be its proximal cognitive cause (Wagner, 1986; Torgesen et al., 1994; Snowling, 1995; Boets et al., 2013). Some researchers suggest, however, that impaired phonological processing is only an endophenotype that increases the risk for dyslexia (Snowling and Melby-Lervåg, 2016) or that the phonological processing and reading difficulties that characterize dyslexia could result from a more general cognitive—but non-linguistic—processing impairments.

One of the oldest non-linguistic hypotheses of dyslexia suggests that a general temporal processing impairment results in poorly defined phonological representations and, therefore, in difficulties in grapheme–phoneme mapping and ultimately in poor reading (Tallal, 1980). Another hypothesis suggests that dyslexic readers suffer from abnormal cerebellar functioning, which results in articulatory problems that lead to poor phonological representations and processing as well as to poor general skill and knowledge automatization (Nicolson and Fawcett, 2007, 2011). Related to this, dyslexia has been suggested to be explained by impaired procedural but intact declarative learning (the procedural deficit hypothesis) (Ullman, 2004; Ullman and Pullman, 2015). Finally, difficulties in visual processing and especially attention have been suggested to result in poor reading as well, because reading is a process that stresses the visual system.

Consensus as to whether dyslexia is caused by a purely phonological deficit or if more general, non-linguistic, deficits are involved has not been reached at this point. Proponents of the phonological deficit hypothesis suggest that other difficulties are comorbid or result from the phonological and reading difficulties or from reduced reading experience (Goswami, 2015; Huettig et al., 2018). On the other hand, the more general non-linguistic explanations of dyslexia have been defended based on findings suggesting that (i) the phonological representations in dyslexia might not be impoverished (Ramus and Szenkovits, 2008; Boets et al., 2013), (ii) not all those with dyslexia have phonological difficulties (Valdois et al., 2011), and (iii) some who have phonological difficulties do not have dyslexia (Snowling, 2008; Snowling and Melby-Lervåg, 2016). Thus, phonological skills alone do not fully explain variation in reading abilities (Kibby et al., 2014). Likewise, no single cognitive factor alone can explain all the behavioral variation in every individual with dyslexia (Ramus and Ahissar, 2012). All this suggests that characteristics of developmental disorders are multiple, continuous, and possibly shared with other developmental challenges.

To resolve some of these open questions, Project DyAdd[1] tested the prominent non-linguistic theories of dyslexia, at different levels of analysis, in adults with developmental dyslexia or ADHD as well as in healthy controls with the main objective of defining the differentiating and shared characteristics. Neurocognitive difficulties were investigated with clinical neuropsychological methods (behavioral level) (Laasonen et al., 2009c, 2010; Kivisaari et al., 2012), and basic cognitive functions were assessed with experimental methods (cognitive level). Biological measures used in the project were serum lipid fatty acids and measures of cerebellar functioning (biological level). Abnormalities in fatty acid metabolism have been suggested to contribute to both ADHD and dyslexia as well as their cognitive and behavioral profiles (as reviewed by Laasonen et al., 2009a,b). Similarly, the cerebellum has been implicated to contribute to the behavioral and cognitive profile of dyslexia (Nicolson et al., 2001). Associations between neuropsychological, experimental, and biological measures were studied as well (Laasonen et al., 2009a,b). The experimental paradigms of Project DyAdd targeted the prominent non-linguistic theories of developmental dyslexia, that is, temporal processing impairment, abnormal cerebellar functioning, procedural learning difficulties, as well as visual processing and attention deficits.

Below, we shortly describe our previous results for the four paradigms used in the current study. These include group differences between healthy controls, adults with developmental dyslexia or ADHD, as well as correlations between the performance in the experimental paradigms and dyslexia-related and ADHD-related cognition.

Temporal processing was assessed with tasks where the participant judged the order or the simultaneity/non-simultaneity of visual stimuli (Sarkio, 2009). The group differences have not been published, but in our other studies with similar tasks, impaired temporal processing has been found in adults with dyslexia across sensory modalities and their combinations (Laasonen et al., 2001, 2002a,b; Virsu et al., 2003). Further, in our previous studies, temporal processing has been shown to correlate with phonological processing in both dyslexic and fluent readers (Laasonen et al., 2001, 2002b, 2012c; Laasonen, 2002; Virsu et al., 2003). Taken together, we have shown that temporal processing impairment associates with dyslexia and dyslexia-related cognition of phonological processing.

We investigated the role of the cerebellum with two paradigms of classical eye-blink conditioning (Laasonen et al., 2012a). The group with dyslexia was slower overall in their learning compared to the control group and had pronounced difficulties in a medio-temporal-dependent paradigm compared

[1] https://www.helsinki.fi/en/researchgroups/project-dyadd

to the more cerebellum-dependent paradigm. Over all groups, responses in the cerebellum-dependent paradigm correlated positively with reading performance and, within those who acquired conditioned behavior, responses of the medio-temporal-dependent paradigm correlated positively with spelling. Taken together, we showed that cerebellum-based classical eye-blink conditioning did not associate with dyslexia, although it did relate to dyslexia-related cognition of reading.

Procedural learning was investigated by us with two paradigms (Laasonen et al., 2014). The groups with dyslexia and ADHD did not differ from each other or controls in sequence learning, but only the control group learned the grammar in an artificial grammar learning (AGL) task. Total group correlations indicated that explicit knowledge of the grammar correlated positively with phonological processing and reading performance. No correlations were found for the implicit knowledge. Taken together, in our previous study, impaired procedural learning was associated with both dyslexia and ADHD but only with dyslexia-related cognition, that is, phonological processing and reading.

We investigated visual attention processes with three paradigms (Laasonen et al., 2012b). Adults with dyslexia were not impaired in their capacity of visual attention but had difficulties in temporal and spatial aspects. The ADHD group did not have any difficulties in the tasks. When all the participants were analyzed together, spatial and capacity of visual attention positively predicted performance in phonological processing and reading. Taken together, we showed that visual attention was associated with dyslexia and dyslexia-related cognition, that is, phonological processing and reading.

In **Figure 1**, we present a summary of the published results of Project DyAdd across the behavioral, cognitive, and biological levels of analysis. Results presented in **Figure 1** and those detailed above indicate that performance in tasks tapping the prominent non-linguistic theories of developmental dyslexia correlates with dyslexia-related cognition when inspected over all participants, that is, phonological processing and reading. However, those with dyslexia are not always impaired in these same tasks compared to controls and it is difficult to differentiate individuals with dyslexia from those with ADHD. All this suggests that the characteristics related to dyslexia are continuous in a way that the associations emerge also in other populations and that the risk factors across developmental difficulties are shared in a way that makes them difficult to differentiate from each other. One possible explanation for the findings is the Pennington's multiple deficit model (Pennington, 2006; Pennington and Bishop, 2009), which suggests that the continuous nature of a given developmental disorder cannot be explained by a single gene or cognitive factor. Instead, developmental disorders share many probabilistic genetic and environmental risk and protective factors, and this leads to the high comorbidity between them both at the neural, cognitive, and behavioral levels.

In the current study, we re-analyzed the data from Project DyAdd with latent profile analysis (LPA) using measures from the experimental designs probing the prominent non-linguistic theories of dyslexia, that is, temporal processing impairment, abnormal cerebellar functioning, procedural learning difficulties, and visual attention deficits. We investigate how adults with developmental dyslexia or ADHD and a healthy control group cluster when all the experimental designs are considered at the same time and whether specific profiles of difficulties can be identified. The profiles of the groups emerging from LPA are investigated further across domains of neuropsychological functioning that characterize dyslexia and ADHD as well as general level of functioning in tests of intelligence. We hypothesize that dyslexia and ADHD will not emerge as separate groups in the LPA with the possible exception of time-constrained sequential processing (see the summary of **Figure 1**). The neuropsychological profiles of the LPA groups are expected to reflect this as well. Consequently, we expect not to find dyslexia-specific or ADHD-specific profiles in the LPA groups.

MATERIALS AND METHODS

Description of the general methods of project DyAdd can be found in a previous article (Laasonen et al., 2009c).

Participants

Participants in the current study were those who participated in project DyAdd and its experimental tasks (Laasonen et al., 2012a,b, 2014). General inclusion criteria were as follows: Finnish as the native language, age between 18 and 55 years, and Wechsler Abbreviated Scale of Intelligence–Full intelligence quotient, WASI FIQ (Wechsler, 1999, 2005), over 70 because of the ICD-10 criteria for specific reading disorder (World Health Organization, 1998). General exclusion criteria were brain injury, somatic or psychiatric condition affecting cognitive functions (including major depression), psychotropic drugs affecting cognitive functions, and substance abuse. Blood samples were collected to rule out endocrinopathies (e.g., dysfunction of the thyroid gland), diabetes, renal dysfunction, abuse of alcohol, and similar somatic states that might compromise cognitive functions. Laboratory tests included hemoglobin, red blood count, white blood count, platelet count, thyroid stimulating hormone, serum creatinine, alanine aminotransferase, gamma-glutamyltransferase, and fasting blood glucose.

Participants in the dyslexia group (n = 36) had a history of reading difficulties and a prior diagnosis. Their phonological processing and reading performance were assessed at the time of the study. All performed 1 SD below the mean in both, with the exception of one participant with poor residual phonological processing only (Laasonen et al., 2009c) as assessed with phonological naming [rapid alternate stimulus naming (RAS) speed/accuracy, Wolf, 1986], phonological awareness (phonological synthesis accuracy, Laasonen et al., 2002b), phonological memory (WAIS digit span forward length, Wechsler, 2005), and reading (oral reading speed/accuracy, task details in Laasonen et al., 2002b). ADHD diagnosis and a history of ADHD-related difficulties were exclusion criteria. The latter was screened with the Wender Utah Rating Scale (WURS)

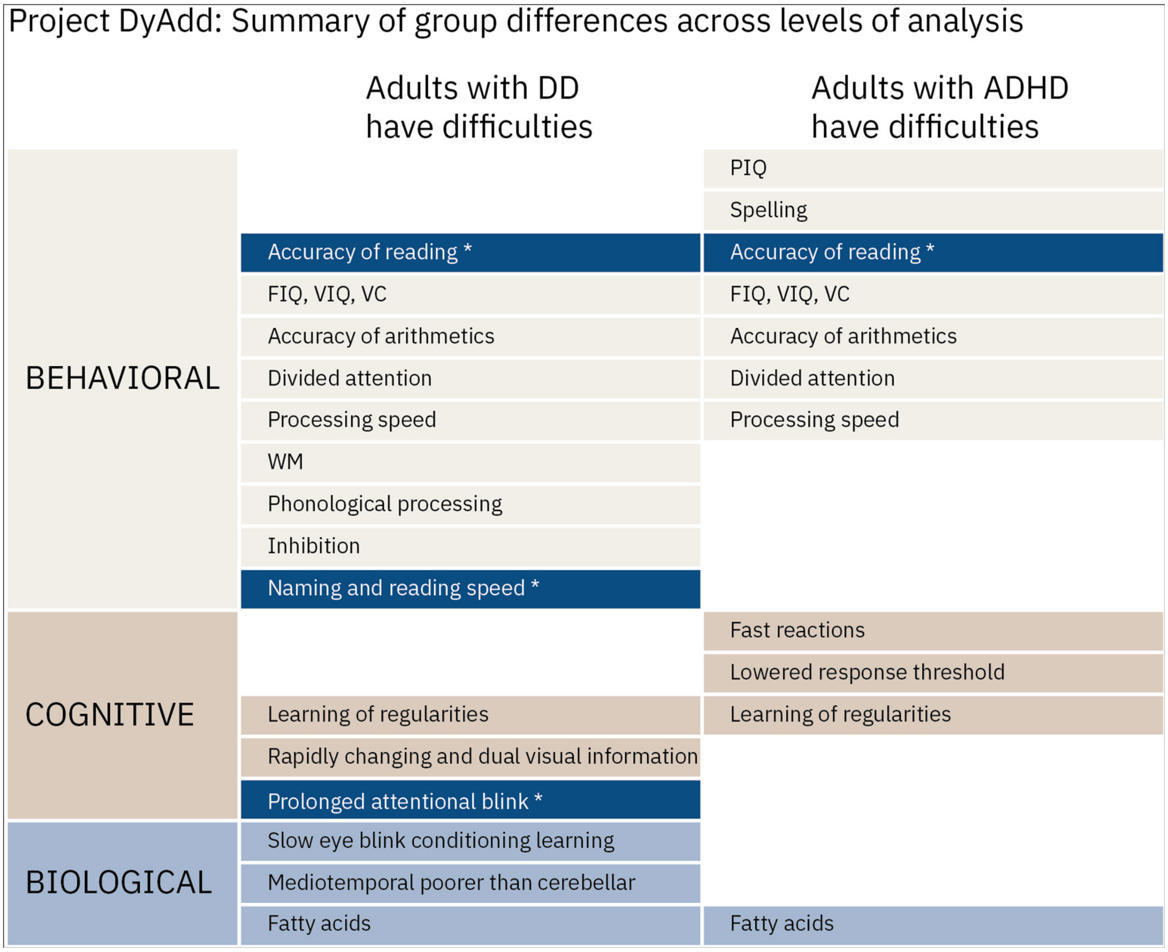

FIGURE 1 | Summary of the published results of project DyAdd. Named difficulties indicate significant differences compared to controls. Asterisks indicate differences where those with dyslexia differed not only from controls but also from those with ADHD. FIQ, full Intelligence quotient; PIQ, performance intelligence quotient; VIQ, verbal intelligence quotient; VC, verbal comprehension; and WM, working memory from the Wechsler Adult Intelligence Scale (Wechsler, 2005). NB, nota bene. Temporal processing is not included in the figure. References to the original articles (Laasonen et al., 2009a,b,c, 2010, 2012a,b, 2001).

(Ward et al., 1993) and the Adult Problem Questionnaire (APQ) (De Quiros and Kinsbourne, 2001).

Participants with ADHD (n = 22) had a history of ADHD-related difficulties and a prior diagnosis based on the DSM-IV criteria (American Psychiatric Association, 1994) using CAADID (Epstein et al., 2001) by a medical doctor specialized in neuropsychiatry (author SL or PT in most cases). Participants with any of the three subtypes of ADHD were eligible for the study. Confounding psychiatric disorders were excluded by structured diagnostic interviews (SCID-I and SCID-II) (First et al., 1996, 1997). Dyslexia diagnosis and a history of dyslexia-related difficulties were exclusion criteria. The latter was screened with Adult Reading History Questionnaire (ARHQ) (Lefly and Pennington, 2000). Participants with ADHD participated in the project unmedicated. A wash-out period of at least 1 week was required before and during the study appointments if they were using methylphenidate. Those with medication with a longer half-life were excluded from the project. Exclusion criteria for the Control group (n = 35) were a history of reading or ADHD-related difficulties or a prior diagnosis of dyslexia or ADHD.

Experimental Designs

Detailed description of the experimental tasks and procedures can be found in previous articles (Laasonen et al., 2012a,b, 2014). Below, we present the variables used and, in case of composites, their Cronbach's alpha reliabilities.

Temporal processing (Sarkio, 2009) was assessed with two visual tasks, which were both realized with gray or green stimuli on a black background. (1) Temporal order judgment (TOJ) assessed participant's 74% correct threshold in milliseconds in assessing the order of two visual stimuli that were presented one above the other. (2) Temporal processing acuity (TPA) estimated the 74% correct threshold for assessing correctly the simultaneity/non-simultaneity of streams of three visual stimuli, which were presented one stream above the other. For this study, we collapsed four variables (thresholds: gray or green × TPA or TOJ) into a single measure using a principal component analysis

(PCA) over all the groups (α = 0.55, removing the threshold for green TPA resulted in α = 0.7). To that end, we calculated and saved the regression-based component scores.

Cerebellar functions were assessed with two classical eye-blink conditioning tasks (Laasonen et al., 2012a). Both included a preconditioning phase (20 trials: randomly presented 10 tones and 10 air puffs to the corner of the eye), a conditioning phase (80 trials: blocks of tones and tones + air puffs), and an extinction phase (20 trials: tones only). Eye-blink responses were recorded with EMG. (1) In the delay conditioning paradigm (DCP), the 800-ms tone and the 100-ms air puff ended simultaneously in the conditioning phase. (2) In the trace conditioning paradigm (TCP), the 100-ms tone and the 100-ms air puff were separated by an interval of 600 ms. The DCP assesses mostly cerebellum-based procedural learning, while the TCP measures mostly declarative learning involving also the medio-temporal areas. Outcome measures were the number of conditioned responses as well as their peak amplitude, peak latency, and magnitude. For this study, we kept two variables: number of conditioned responses in the DCP and in the TCP.

Procedural learning (Laasonen et al., 2014) was assessed with two tasks. (1) The serial reaction time (SRT) task was a choice reaction time task in which the participants did not know that the presentation order of stimuli was defined by a grammar (Knowlton et al., 1992). Stimuli were geometrical non-linguistic shapes, each presented at a constant spatial location, that were presented in blocks (block 1: random, 2–11: structured, 12: random, 13: structured). Learning was expected to result into faster reaction time in the structured compared to random blocks. The outcome measures were the average percentage of erroneous answers and the average reaction time for correct answers per block. Implicit procedural learning was operationalized by comparing the performance in the last random block to the average of the adjacent structured blocks. (2) AGL was assessed with a task where the participants had to memorize horizontal strings of 2–6 geometrical non-linguistic shapes. Afterwards, they were told that the strings followed a set of rules (Abrams and Reber, 1988; Knowlton and Squire, 1996) and classified a new set of strings into grammatical and non-grammatical. The outcome measures were the percentage of correct grammatical and similar answers. The latter was defined by chunk strength, which is based on fragment overlap. Implicit procedural learning was operationalized as better than chance performance in grammatical accuracy. For this study, we used the following four variables. For SRT, we kept accuracy in the last random block divided by average accuracy in adjacent blocks and reaction time in the last random block divided by average reaction time in adjacent blocks; for AGL, we kept grammatical accuracy and similarity ratings.

Visual processing and attention (Laasonen et al., 2012b) were assessed with three tasks. (1) Spatial characteristics of visual attention were estimated with useful field of view (UFOV) where the participant fixated centrally and conducted a yes/no decision to detect the presence or absence of a target (control condition). Some trials required locating an additional peripheral target without distractors (experimental condition without distractors) or with them (experimental condition with distractors). The four outcome measures for each condition were the presentation duration of the stimuli to reach a 79.3% correct threshold for both the central and peripheral task with and without distractors. (2) Temporal characteristics of visual attention were estimated with the attentional blink (AB) paradigm using a similar method to Green and Bavelier (2003). Again, the participant fixated centrally and was presented with black letters (presentation time 26.7 ms with 106.7 ISI), a white letter, the first target to be identified (T1), other black letters, and a black X to be detected, the second target (T2), that appeared in 50% of the trials. A trial consisted of 16–24 letters. Outcome measures were the proportion of correct detection of T2 (baseline), the proportion of correct identification of T1 while correctly detecting T2 (dual task), and, finally, T2 detection accuracy as a function of T1–T2 lag when T1 was correctly identified (dual task), which were used to estimate the four parameters of Cousineau and colleagues (Cousineau et al., 2006): lag-1 sparing, width, amplitude, and minimum. (3) Capacity of visual attention was estimated with multiple object tracking (MOT), where the participant fixated centrally and tracked peripherally 16 randomly moving dots. One, three, five, or seven of the tracked dots were blue and the rest were yellow. After 2 s of movement, all the dots turned yellow and moved for another 5 s. After this, movement stopped, and one of the dots turned white, and the participant made a yes/no decision whether the white dot had been one of the blue targets. The outcome measures were the percent correct as a function of the number of dots to be tracked. For this study, we aggregated the four UFOV variables (thresholds for the four conditions: distractors or no distractors × peripheral stimulus at 7° or 21°) into a single variable by inserting them into a PCA over all the groups (α = 0.6). We also kept for the temporal characteristics two variables: Cousineau parameters for AB length (width) and depth (minimum). Lastly, one variable for capacity was kept: Percent correct for the four MOT conditions (1, 3, 5, or 7 dots to follow) were inserted into a PCA over all the groups in order to get one measure for the four conditions (α = 0.8).

Domains of Neuropsychological and General Level of Functioning

These tests were included into the neuropsychological assessment battery that was divided into two separate sessions. Detailed description of the neuropsychological tasks can be found in previous articles (Laasonen et al., 2012b). For this study, we used the neuropsychological domains of phonological processing (average of awareness, memory, and naming speed), technical reading (average of speed and accuracy), reading comprehension (average of speed and accuracy), spelling (accuracy), arithmetic (accuracy), executive functions (average of set shifting, inhibition, and planning), and attention (average of sustained and divided). These are presented in more detail in **Supplementary Appendix 1**. Cronbach's alpha reliabilities conducted over the variables were acceptable, except for the domain of executive functions. Removing variables from this composite did not enhance its internal consistency.

To assess general level of functioning, we used intelligence, more specifically, four indices from the Wechsler Intelligence

Scale for Adults, third revision (Wechsler, 2005). These were verbal comprehension (subtests: similarities, vocabulary), working memory (subtests: arithmetic, digit span, letter–number sequencing), perceptual organization (subtests: block design, matrix reasoning), and processing speed (subtest: digit-symbol coding).

Statistical Analyses

The variables of the experimental designs are described above. To remove the effect of extreme values in the data, we used 90% winsorizing over all the groups and then substituted the remaining extreme values with the value of the poorest non-outlier. After this, the few missing values were imputed using expectation maximization (EM) techniques over all experimental design variables and participants with the group as two dummy variables. Finally, the variables were z-standardized based on the control group values and, when needed, inverted to indicate better performance with positive values resulting in variables with the mean of 0 and SD of 1.

The variables of the neuropsychological domains and general level of functioning are described above. The same neuropsychological composite variables were used as in the previous studies; that is, the scores of all participants were transformed based on the age-corrected performance of the control group and converted, if necessary, to indicate better performance with a larger positive value resulting in variables with a mean of 10 and an SD of 3 (Laasonen et al., 2012b). Regarding intelligence, the standardized norms that are based on the age-corrected performance of the normative group were used and the scores were converted to the same scale as the neuropsychological domains, that is, their mean was also 10 and SD was 3. After this, the few missing values were imputed using EM techniques over all neuropsychological and intelligence composites and participants with the group as two dummy variables. Finally, the neuropsychological composites were restricted to the same scale as the intelligence composites (1–19).

For statistical analyses, LPA was used in order to investigate how the original groups clustered based on the variables retrieved from the experimental designs. Differences in the distribution of participants into the LPA groups as well as differences in the background variables between the LPA groups were analyzed with Chi-squared tests and ANOVAs. The LPA group profiles in the experimental designs as well as domains of neuropsychological and general level of functioning were analyzed with multivariate ANCOVA (a Wilks test) and, in the case of a significant main effect, with one-way ANCOVAs. Level of significance was set at $p = 0.05$ with Bonferroni correction for the *post hoc* tests. More detailed description can be found in the results.

For the literature search presented in the discussion, we searched the Web of Science on December 10, 2019 with the following syntax: TOPIC:(dyslexia) AND ALL FIELDS:(temporal OR implicit OR procedural OR cerebellum OR cerebellar OR vision OR visual). Timespan: Last 5 years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC.

RESULTS

Latent Profile Analysis

Latent profile analysis was used in order to investigate how the original groups (dyslexia, ADHD, control) clustered based on the 11 variables retrieved from the experimental designs. R version 3.2.1 (R Core Team, 2018) with mclust version 5.2 (Scrucca et al., 2016) was used for the analyses. In a nutshell, LPA tries to fit a certain number of multivariate normal distributions on the data so as to maximize the fit. The number of distributions is varied (from 1 to 9); there are also various constraints that are tested (e.g., equal variance, absence of covariance, etc.). The most successful yet parsimonious model, as assessed by a BIC index of fit, is retained. The solution found was a mixture of three distributions (each having zero covariance but distinct variances; e.g., a VII solution; see Scrucca et al., 2016). Loglikelihood was −1462.55 for 55 free parameters.

The three LPA groups (see **Table 1**) differed greatly in their size, and the distribution of participants in the LPA groups did not mirror very well the participant's original group [$\chi^2(4) = 8.25$, $p = 0.083$]. Analyses on the background variables indicated that gender, handedness, and level of education did not differentiate the LPA groups, but age did (see **Table 1**). Bonferroni-corrected *post hoc* tests showed that those in the LPA3 were older than those in LPA1 ($p = 0.037$) or LPA2 ($p < 0.001$). Thus, age was used as a covariate in the following analyses.

LPA Group Profiles in Experimental Designs

The profiles of the LPA groups were inspected with a multivariate ANCOVA (a Wilks test) where the LPA group was the between-subjects factor and the variables of the experimental designs were the multivariate factors (in z-scores) of the dependent measure and age as the covariate. The difference between the LPA groups was significant, $F(22,158) = 11.37$, $p < 0.001$, $\Lambda = 0.15$, and $\eta_p^2 = 0.61$. This result indicates that the LPA groups differed strongly in their overall pattern of performance in the experimental designs. Using the temporal processing composite with better internal consistency did not affect the results [$F(22,158) = 10.75$, $p < 0.001$, $\Lambda = 0.16$, and $\eta_p^2 = 0.60$]. In follow-up ANCOVAs for the experimental designs, significant differences between the LPA groups emerged in temporal processing [$F(2,89) = 19.63$, $p < 0.001$, $\eta_p^2 = 0.31$] where those in the LPA3 group were slower compared to the other groups (Bonferroni-corrected comparisons for estimated marginal means, all $ps < 0.001$), cerebellar functions [delay conditioning, $F(2,89) = 43.65$, $p < 0.001$, $\eta_p^2 = 0.50$, with LPA2 having more conditioned responses than the other groups (all $ps < 0.001$)], trace conditioning [$F(2,89) = 23.47$, $p < 0.001$, $\eta_p^2 = 0.35$, with LPA2 having again more conditioned responses than the other groups (all $ps < 0.001$)], procedural learning [SRT accuracy, $F(2,89) = 3.39$, $p = 0.038$, $\eta_p^2 = 0.07$, with the Bonferroni corrections, comparisons for estimated marginal means were not significant], and visual processing and attention [UFOV, $F(2,89) = 58.55$, $p < 0.001$, $\eta_p^2 = 0.57$, with LPA3 being poorer than the other groups (all $ps < 0.001$); MOT, $F(2,89) = 6.48$,

TABLE 1 | Number of participants in the original and LPA groups as well as background variables.

		LPA-generated groups			Total F/x^2
		LPA1	LPA2	LPA3	
Original groups					
Dyslexia		19 (53%)	7 (19%)	10 (28%)	36
ADHD		16 (73%)	5 (23%)	1 (5%)	22
Control		27 (77%)	4 (11%)	4 (11%)	35
Total		62 (67%)	16 (17%)	15 (16%)	93
Age in years	Mean	35.60	29.25	42.80	(2,90) = 7.40**
	SD	(10.43)	(8.23)	(8.46)	
Gender					
Female	Count	29	7	8	(2) = 0.31
Male	Count	33	9	7	
Handedness					
Right	Count	54	16	13	(2) = 2.33
Left	Count	8	0	2	
Ambi	Count	0	0	0	
Education[1]					
Basic	Count	28	9	6	(4) = 2.87
Middle	Count	14	4	6	
High	Count	19	3	3	

***p < 0.01. [1]Basic, primary and secondary education; middle, vocational high school; high, university.*

$p = 0.002$, $\eta_p^2 = 0.13$, with LPA3 poorer than LPA1 ($p = 0.003$)]. **Figure 2** depicts the LPA group's mean performance in the experimental designs. LPA1 performed on average within −1 to +1 SD in all assessed areas. LPA2 performed on average within −1 to +1 SD in all areas, except for the number of conditioned responses that were large. LPA3 was poor in visual processing and attention as well as temporal processing.

LPA Group Profiles in Domains of Neuropsychological and General Level of Functioning

Next, we inspected the profiles of the LPA groups across the neuropsychological domains, again, with a multivariate ANCOVA (a Wilks test) where the LPA group was the between-subjects factor and the neuropsychological domains as the multivariate factors (in standardized scores) of the dependent measure and age as the covariate. The main effect of LPA group was not significant, $F(14,166) = 1.288$, $p = 0.219$, $\Lambda = 0.81$, and $\eta_p^2 = 0.098$, indicating that the groups did not differ in their dyslexia- or ADHD-related neuropsychological performance. Removing the executive functioning composite with poor internal consistency from the analysis did not affect the results [main effect of LPA group, $F(12,168) = 1.44$, $p = 0.153$, $\Lambda = 0.822$, and $\eta_p^2 = 0.093$]. Further, a multivariate ANCOVA (a Wilks test) over the separate executive function variables of the composite, described in **Supplementary Appendix 1**, resulted in a non-significant main effect of LPA group as well [$F(14,160) = 1.46$, $p = 0.130$, $\Lambda = 0.786$, and $\eta_p^2 = 0.114$]. **Figure 3** depicts the LPA groups' performance in the domains neuropsychological functioning (the seven points to the left of the plot). All the LPA groups performed on average within −1 to +1 SD in all assessed areas, except in technical reading and spelling.

For the measures of intelligence in standardized scores, the results appeared somewhat different. Now, the main effect of the LPA group was significant [$F(8,172) = 2.086$, $p = 0.040$, $\Lambda = 0.83$, $\eta_p^2 = 0.09$]. One-way ANCOVAs with age as a covariate indicated that the LPA groups differed in all the subdomains, that is, verbal comprehension [$F(2,89) = 3.22$, $p = 0.045$, $\eta_p^2 = 0.07$], working memory [$F(2,89) = 4.74$, $p = 0.011$, $\eta_p^2 = 0.10$], perceptual organization [$F(2,89) = 4.96$, $p = 0.009$, $\eta_p^2 = 0.10$], and processing speed [$F(2,89) = 5.39$, $p = 0.006$, $\eta_p^2 = 0.11$]. Bonferroni-corrected comparisons for estimated marginal means indicated that LPA3 was poorer than the other groups in working memory (ps < 0.045), perceptual organization (ps < 0.026), and processing speed (ps < 0.026), and almost in verbal comprehension (ps < 0.073). **Figure 3** depicts the LPA groups' performance in the general level of functioning (the four last points to the right of the plot). LPA1 and LPA2 performed on average within 0 to +1 SD in all assessed areas, whereas those in the LPA3 performed at −1 to 0.

DISCUSSION

In the current study, we investigated how adults with developmental dyslexia, ADHD, and controls cluster across various dimensions designed to tap the prominent non-linguistic theories of dyslexia. Tested domains included temporal processing impairment, abnormal cerebellar functioning, procedural learning difficulties, and visual attention deficits. LPA was conducted over all participants and experimental designs.

First, we hypothesized that dyslexia and ADHD would not emerge as separate groups in the LPA with the possible exception of time-constrained sequential processing (see the summary of results in **Figure 1**). The results showed indeed that the participants did not group very well based on their original status. Instead, the LPA resulted in three groups: the largest LPA1 group with 67% of the participants had average performance in the experimental designs. This indicates that most participants do not have difficulties in any of the experimental tasks whether they belong to the group of controls, ADHD, or dyslexia. The second LPA2 group with 17% of the participants consisted of participants predominantly from the clinical groups who exhibited enhanced conditioning learning. Age is one of the factors that is well known to have an effect on conditioning learning (Woodruff-Pak, 2002) and of the background variables, participants in the LPA2 group were the youngest. However, as participant age was controlled in the analyses, age or factors closely related to it cannot explain the finding of enhanced conditioning. There are multiple other factors that might have been unevenly distributed across our LPA groups but were not, unfortunately, assessed. For example, anxiety and the temperamental trait of behavioral inhibition covary with enhanced conditioning learning (Caulfield et al., 2013; Allen et al., 2019). The third LPA3 group with 16%

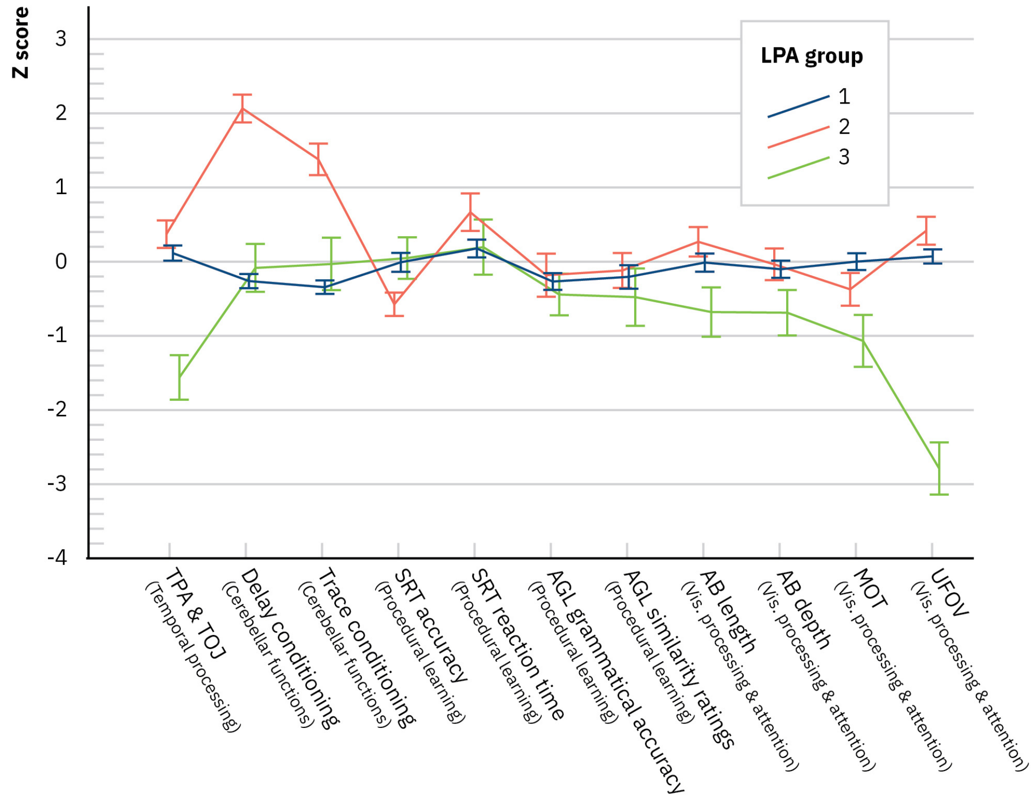

FIGURE 2 | Latent profile analysis groups' performance in the experimental designs (mean with SE). AB, attentional blink; AGL, artificial grammar learning; MOT, multiple object tracking; SRT, serial reaction time; TPA, temporal processing acuity; TOJ, temporal order judgment; UFOV, useful field of view. NB, nota bene. Presented values are not corrected for the covariate age.

of the participants, predominantly from the dyslexia group, had difficulties in temporal processing as well as in visual processing and attention, a finding in line with our expectations related to time-constrained sequential processing. Also, these types of tasks are known to be affected by increasing age (Laasonen et al., 2002a; Virsu et al., 2003), and this group was the oldest one. However, as noted above, age was used as a covariate in all the analyses.

Second, we expected that the neuropsychological profiles of the LPA groups would reflect the fact that dyslexia, ADHD, and healthy controls could not be separated in a way that we would find dyslexia-specific or ADHD-specific profiles in the LPA groups. The results confirmed this, as the LPA groups did not differ in their dyslexia or ADHD-related neuropsychological profiles.

These two sets of results together align with the suggestions of Pennington's multiple deficit model (Pennington, 2006; Pennington and Bishop, 2009) as it appears that the original groups of the current study share many risk and perhaps also protective factors, which lead to overlapping LPA groups and to the high similarity between LPA groups at the neuropsychological level. Inherent to the multiple deficit model is that the risk and protective factors are continuous. In line with this, we have shown that those with developmental dyslexia are poorer in temporal processing compared to fluent readers but in a way that the distribution of their performance is restricted to the areas of poor and mostly average performance, none of them reaching the threshold of above average performance (Service and Laasonen, 2019). Thus, the place of the distribution for risk and protective factors might vary across conditions and with sampling, sometimes resulting in significant group differences.

The most remarkable finding of the current study was that the LPA groups that were formed based on their performance in tasks designed to tap the non-linguistic theories of dyslexia differed most clearly in their intelligence. The third LPA3 group with difficulties in temporal processing as well as visual processing and attention exhibited lower scores than the other groups across the standardized and age-corrected IQ indices, that is, working memory, perceptual organization, processing speed, and at a trend level in verbal comprehension. This pattern of results indicates differences in the levels of severity across the different LPA groups and suggests that the group with the lowest IQ score, although at average, also had difficulties in temporal processing and in visual processing and attention. This finding did not generalize to abnormal cerebellar functioning or procedural learning difficulties.

Inspired by this finding, we searched for original research and review articles (as well as articles cited by these reviews) published during the last 5 years on the topic of dyslexia and temporal

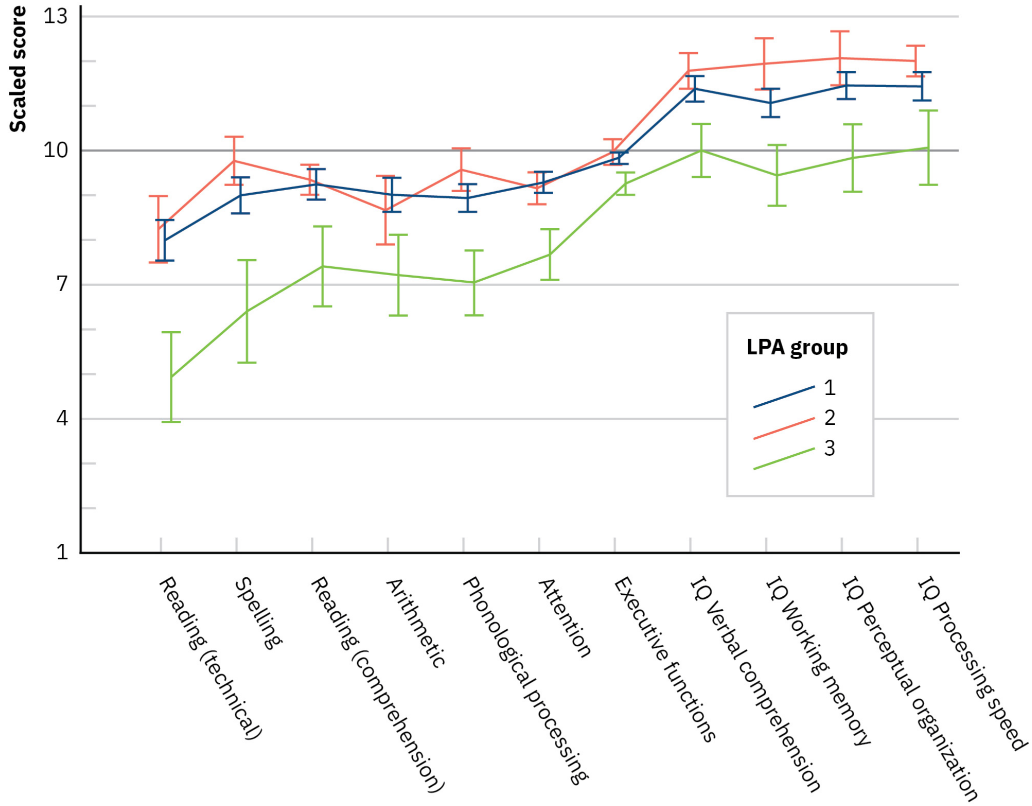

FIGURE 3 | Latent profile analysis groups' performance in the domains of neuropsychological and general level of functioning (mean with SE). IQ, intelligence quotient (Wechsler, 2005). NB, nota bene. Presented values are not corrected for the covariate age.

processing, cerebellar functions, procedural learning, or visual processing and attention. Surprisingly, a pattern emerged again. For publications on temporal processing and visual processing and attention, only very seldom were the group IQs reported or compared in a way that group-level matching requires. Most often, the groups were characterized as having normal IQ or the exact values were not reported. For example, for temporal or magnocellular processing, papers presented either no or insufficient information on IQ, or group-level matching was imperfect (Gori et al., 2016; Moll et al., 2016; Casini et al., 2018; Fostick and Revah, 2018; Mascheretti et al., 2018; Stefanac et al., 2019). For visual attention or processing, IQs were not reported or matched between the groups (Bosse and Valdois, 2003; Bosse et al., 2007; Germano et al., 2014; Lobier and Valdois, 2015; Zoubrinetzky et al., 2016). Thus, conducting a meta-analysis on the subject became impossible. This was reflected in our results, where IQ appeared to covary with especially temporal processing as well as visual processing and attention. Also in our previous studies, performance in tasks of temporal processing (Laasonen et al., 2001; Laasonen, 2002) as well as visual processing and attention (unpublished analyses from Laasonen et al., 2012b) has correlated with measures of intelligence. One has to ask, then, whether some of the non-linguistic theories of dyslexia predict also minor variations in intelligence. Historically, a discrepancy between poorer reading and better intelligence was required for the identification of a specific reading disability (Rutter and Yule, 1975). Later, the importance of IQ has been emphasized less (Morris and Fletcher, 1988). In the future, although strict IQ or IQ-reading discrepancy criteria for dyslexia might not be justifiable, research focusing on non-linguistic correlates of dyslexia should consider the role of other possibly explaining factors for their findings more rigorously, including age and especially intelligence.

One intriguing possibility that could explain the current findings is that intelligence and reading or its difficulties do covary to some extent after all. Recent results in the area of genetics provide support for this. For example, a general genetic factor has been suggested that would explain variation in both non-verbal intelligence and reading (Lazaroo et al., 2019), and significant overlap between word reading and intelligence has emerged in a recent genome-wide association study (Price et al., 2020). Further, it has been shown for dyslexia that there is an interrelation between genotype, brain anatomy, and neurofunctionality (Skeide et al., 2015, 2016; Neef et al., 2017). All this points to a multifactorial and multigenetic background for dyslexia that has a role for both intelligence and perhaps also non-linguistic processing.

In our statistical analyses, the clinical groups did not cluster into corresponding LPA groups, nor did the LPA groups differ in their neuropsychological functioning although intelligence differentiated between them. However, **Table 1** suggests that there were rather many dyslexic readers in the LPA3 group. Further, **Figure 3** suggests that the LPA groups could be interpreted to reflect levels of severity across tasks of dyslexia-related and ADHD-related cognition, in addition to intelligence. Specifically, it appears that the LPA3 group with many dyslexic readers had difficulties in temporal processing as well as in visual processing and attention, that is, in time-constrained sequential processing. LPA3 was the most impaired also across the areas of neuropsychological functioning and intelligence, although, in our analyses, the differences did not always reach statistical significance. In the future, focusing on both the non-linguistic aspects of performance as well as intelligence with larger sample sizes may increase our understanding of the condition and possibly form a fruitful basis for prediction and early diagnosis (Mannel et al., 2015; Muller et al., 2016). Our current sample size might not have been large enough to reveal all the significant effects, and a preplanned sample size could have led to more adequate power (Tabachnick and Fidell, 2014).

CONCLUSION

In the current study, we investigated how adults with developmental dyslexia or ADHD and controls cluster across various dimensions designed to tap the prominent non-linguistic theories of dyslexia. Tested domains included temporal processing impairment, abnormal cerebellar functioning, procedural learning difficulties, and visual attention deficits. Our results highlight the continuous and overlapping nature of the observed difficulties and support the multiple deficit model of developmental disorders, which suggests shared risk factors for developmental challenges. Further, it appears that some of the risk factors suggested by the prominent non-linguistic theories of dyslexia are related to the general level of functioning in tests of intelligence.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: Datasets are available on request. Requests to access these datasets should be directed to marja.laasonen@helsinki.fi.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethical Board of the Helsinki Uusimaa Hospital District. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

ML is the PI of Project DyAdd and responsible for the original idea, statistical analyses, and writing of the article. PL-N is responsible for the statistical design as well as the illustrations of the article. SL and PT are responsible for the ADHD and HH for the cerebellar patient expertise and diagnoses in the Project DyAdd. JW is responsible for the eyeblink designs, and EP and AC are responsible for the procedural learning designs in the Project DyAdd. HO-H participated in the latter as a postgraduate researcher and contributed to an original publication. MD and DC are responsible for the visual attention designs and DC for their analysis in the original publication of the Project DyAdd. LH is responsible for the clinical neuropsychological expertise on ADHD and participated as the second core senior to the project DyAdd in addition to ML. All authors have contributed substantially to the conception or design of the work or the acquisition, analysis, or interpretation of data for the work. All authors have collaborated on drafting the work and revising it critically for important intellectual content. All authors have given their final approval of the version to be published.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2020.00316/full#supplementary-material

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ORIGINAL RESEARCH
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Longitudinal Effects of the Home Learning Environment and Parental Difficulties on Reading and Math Development Across Grades 1–9

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This study focuses on parental reading and mathematical difficulties, the home literacy environment, and the home numeracy environment as well as their predictive role in Finnish children's reading and mathematical development through Grades 1–9. We examined if parental reading and mathematical difficulties directly predict children's academic performance and/or if they are mediated by the home learning environment. Mothers (n = 1590) and fathers (n = 1507) reported on their reading and mathematical difficulties as well as on the home environment (shared reading, teaching literacy, and numeracy) when their children were in kindergarten. Tests for reading fluency, reading comprehension, and arithmetic fluency were administered to children in Grades 1, 2, 3, 4, 7, and 9. Parental reading difficulties predicted children's reading fluency, whereas parental mathematical difficulties predicted their reading comprehension and arithmetic fluency. Familial risk was associated with neither formal nor informal home environment factors, whereas maternal education had a significant relationship with both, with higher levels of education among mothers predicting less time spent on teaching activities and more time spent on shared reading. In addition, shared reading was significantly associated with the development of reading comprehension up to Grades 3 and 4, whereas other components of the home learning environment were not associated with any assessed skills. Our study highlights that taken together, familial risk, parental education, and the home learning environment form a complex pattern of associations with children's mathematical and reading skills.

Keywords: reading difficulties, mathematical difficulties, home literacy environment, home numeracy environment, familial risk, skill development, comorbidity

INTRODUCTION

Literacy and numeracy development are strongly interrelated, and the comorbidity of reading and mathematical difficulties is frequent (e.g., Purpura et al., 2011; Davidse et al., 2014; Purpura and Ganley, 2014; Korpipää, 2020). Of the people with either reading or mathematical difficulties, up to 70% also perform worse than average in the other domain (Landerl and Moll, 2010;

Moll et al., 2019; Joyner and Wagner, 2020). Research has identified multiple shared and unique risk factors for reading and mathematical difficulties at the level of cognitive skills (Geary, 2011; Moll et al., 2016; Child et al., 2019) and brain processes (Raschle et al., 2011; Evans et al., 2015; Norton et al., 2015). At the etiological level, both reading and mathematical difficulties are known to be heritable (Kovas et al., 2013; de Zeeuw et al., 2015; Little et al., 2017). Having a parent with reading difficulties, for example, increases the risk of children developing similar problems by up to 66% (van Bergen et al., 2014a; Hulme et al., 2015; Torppa et al., 2015; Esmaeeli et al., 2019). Significantly less is known about familial risk (FR) for mathematical difficulties (e.g., Soares et al., 2018). FR acts via genes, but environmental factors have been shown to play an important role in the development of both reading (Evans and Shaw, 2008; Mol and Bus, 2011; Manolitsis et al., 2013) and mathematical skills (Dunst et al., 2017; Daucourt, 2019). Studies on the interaction of FR and the home literacy environment (HLE) are emerging (Hamilton et al., 2016; Dilnot et al., 2017; Esmaeeli et al., 2018), but comparable studies on the home numeracy environment (HNE) remain scant (Silinskas et al., 2010). Moreover, until recently, HLE and HNE have been separately studied, whereas their cross-domain and joint roles in children's reading and mathematical development have received very little research attention.

In view of the existing gaps in the literature, this study aims to gain new insights into the etiology of the comorbidity of reading and mathematical difficulties. To this end, the study examines the effects of FR for mathematical and reading difficulties together with the effects of the HLE and HNE on children's (aged 7–16 years) reading and mathematical skills from a long-term developmental perspective. To our knowledge, this is the first study with such an objective.

Familial Risk and the Comorbidity of Reading and Mathematical Difficulties

The multiple deficit model (e.g., Pennington, 2006) explains the emergence of learning difficulties and their comorbidity by the complex interactions between multiple risk factors at different levels (genes, brain, cognition, and environment), which can be either domain-specific (i.e., associated only with difficulties in one domain—either reading or mathematics) or domain-general (i.e., associated with difficulties in multiple domains). It has been established that, for example, a deficit in phonological awareness is specific to reading difficulties (Melby-Lervåg et al., 2012) and a deficit in numerosity processing is specific to mathematical difficulties (Hannula et al., 2010; Anobile et al., 2016), whereas difficulties in working memory, processing speed, and oral language are likely to affect more than one learning domain (Koponen et al., 2007; Moll et al., 2019; Daucourt et al., 2020).

The multiple deficit model (MDM) has gained wide recognition over the years. However, Pennington (2006) importantly noted that compared with single deficit models, testing the MDM would represent a much more serious challenge, calling for the test of multiple hypotheses. In their theoretical article, van Bergen et al. (2014b) stressed the unique role of familial risk studies in testing and specifying the MDM—these studies have already provided important evidence suggesting that parents confer liability to reading difficulties via interconnected genetic and environmental risk factors.

In this study, we aim to add knowledge on the intergenerational transmission of reading and mathematical difficulties as well as their comorbidity. To this end, we include FR for both reading and mathematics and examine the effects of both within-domain and cross-domain FR on reading and mathematical development. Although multiple studies have established that FR for reading difficulties is among the strongest predictors for dyslexia (Scarborough, 1990; Pennington and Lefly, 2001; van Bergen et al., 2014a; Torppa et al., 2015; Esmaeeli et al., 2019), so far, only few studies have suggested that the same is true for dyscalculia (Shalev and Gross-Tsur, 2001; Soares et al., 2018). In addition, unlike most studies, we include the parental reading and mathematical difficulties of both mothers and fathers in our analysis to examine if the effects of having one parent with difficulties are different from the effects of having both parents with difficulties. Based on the MDM, it can be expected that when both parents have learning difficulties, children's liability increases more than when having only one parent with difficulties.

Home Literacy and Numeracy Environment

The effects of FR on children's skill development may act through the genetic pathway; both twin and molecular genetic studies have produced compelling evidence for the strong heritability of both reading and mathematical skills (Docherty et al., 2010; Kovas et al., 2013; de Zeeuw et al., 2015; Little et al., 2017). However, parental reading/mathematical difficulties have also been shown to be transmitted through the environmental pathway (Petrill et al., 2005; de Zeeuw et al., 2015; Hart et al., 2016; van Bergen et al., 2017). Therefore, we examine if parental reading and mathematical difficulties impact the home environment and if they affect children's skills not only directly but also indirectly via the home environment.

The home learning environment is often divided into two main components: HLE and HNE. HLE refers to home-based interactions between parents and their children, parental attitudes, and at-home materials related to literacy. HLE has long been considered an important factor for the development of reading skills (see Bus et al., 1995; Evans and Shaw, 2008; Flack et al., 2018; Grolig et al., 2019). In a seminal study, Sénéchal and Lefevre (2002) formulated the home literacy model and showed that to adequately assess the effects of HLE, it is important to differentiate its activities into two separate categories: "formal" and "informal" activities. In their 5-year longitudinal study, children's skills were followed until the end of Grade 3 and HLE was assessed with parental self-reports. The home literacy model was predicated on analysis that revealed that parental teaching (formal learning) and storybook exposure (informal learning) were uncorrelated, with the former explaining children's emergent literacy and the latter explaining children's receptive language.

Further evidence has supported the home literacy model, showing that formal and informal activities contribute to the development of different skills (Sénéchal and Lefevre, 2002). Code-related, formal parent–child literacy interactions in the form of direct teaching (for example, instructing children on how to divide words into phonemes and showing that graphemes correspond to phonemes) contribute to the development of early word recognition and decoding skills, whereas informal literacy activities (for example, shared reading and discussions over a story) mostly involve meaning-related practices and are associated with the development of vocabulary knowledge, reading comprehension, and broader language skills (e.g., Sénéchal, 2006, 2015; Mol et al., 2008; Sénéchal et al., 2008; Martini and Sénéchal, 2012; Sénéchal and Lefevre, 2014).

However, some studies have reported negligible independent effects of formal and informal HLE activities. For example, Manolitsis et al. (2013) and Silinskas et al. (2020) found that the effects of formal learning (at-home teaching) were significantly smaller in the contexts of transparent orthographies (Greek and Finnish) than those previously demonstrated in the contexts of opaque orthographies (English and French). The authors argued that in the context of transparent orthographies, direct at-home teaching could only provide short-term gains that fade away as soon as children get exposed to schooling because learning to read is relatively easy and most children very quickly learn to read.

Using the home literacy model (Sénéchal and Lefevre, 2002) as a guiding framework, a similar model for HNE was developed and tested by Skwarchuk et al. (2014). In a cross-sectional study with 5- and 6-year-old children, the researchers assessed the formal activities of HNE (using parental self-reports of home teaching of arithmetic skills) and informal activities (using a number game title checklist for parents, which is comparable to the storybook exposure checklist designed for HLE). The study revealed that formal parent–child interactions contributed to children's symbolic number knowledge (number identification, counting, and ordinal numbers), whereas informal game-based numeracy-related activities contributed to children's non-symbolic arithmetic skills (addition, subtraction, and matching tasks with toy animals).

It has to be stressed, however, that research focusing on the role of HNE remains rather scant and much less conclusive in comparison to studies on HLE. Whereas some studies suggest that the HNE is a significant contributor to the development of mathematical skills (Niklas and Schneider, 2014; Skwarchuk et al., 2014; Hart et al., 2016; Napoli and Purpura, 2018), other research finds a non-significant or even negative association between children's mathematical development and HNE (Blevins-Knabe et al., 2000; Silinskas et al., 2010; Missall et al., 2015; Zippert and Rittle-Johnson, 2020).

Importantly, from the perspective of understanding comorbidity, a recent study among parents of children aged 3–5 years (Napoli and Purpura, 2018) established a strong relationship between HLE and HNE after analyzing extensive parental self-reports of at-home literacy practices (printing letters, identifying letters and letter sounds, and reading storybooks) and numeracy practices (counting objects, printing numbers, working with number activity books, comparing quantities, counting down, and learning written numbers and simple sums). Results showed that the parents who were actively promoting the skills of their children in one domain were more likely to do the same in the other domain (Napoli and Purpura, 2018). This strong positive association between HLE and HNE could be one of the reasons why researchers find that HLE predicts both reading and mathematical skills (Melhuish et al., 2008; Baker, 2014). In a longitudinal study with pre-school children aged 3–4 years who were followed for 3 years, Anders et al. (2012) found that HLE was an even better predictor of early mathematical skills than HNE. The researchers argued that verbal literacy is a pre-requisite for acquiring numeracy skills, as has been suggested by von Aster and Shalev (2007) and later reported by Purpura and Ganley (2014). This evidence shows that studying both HLE and HNE together is necessary to understand the impact of the home environment on children's skill development. Noting that previous studies mainly focused on early childhood, the present study aims to add knowledge on how the processes of developing reading and mathematical skills are interconnected by extending research to school-aged children. Furthermore, the inclusion of FR and parental education in our study enables us to investigate if the possible correlation between HLE and HNE can be further explained to help understand why some parents are more likely to support their children's skill development (Napoli and Purpura, 2018).

Familial Risk Studies and Home Learning Environment

To establish whether FR is mediated via the home learning environment, studies have compared the HLE factors in families with and without FR for reading difficulties. Whether such an indirect relationship exists, however, is still unclear owing to the scarcity of research (e.g., Snowling and Melby-Lervåg, 2016) as well as to contradictory findings. Some studies found that FR families provide a more disadvantageous HLE for their children than non-FR families do (Hamilton et al., 2016; Dilnot et al., 2017; Esmaeeli et al., 2018). Other studies reported that there were no significant differences between the at-home learning activities of FR families and non-FR families and that parents with reading difficulties taught their children as much academic skills as the parents without such difficulties did (Elbro et al., 1998; Laakso et al., 1999; Torppa et al., 2007). Comparable studies investigating FR for mathematical skills and HNE are scarce. However, in one longitudinal study, Silinskas et al. (2010) showed that Finnish mothers' mathematical difficulties positively predicted their teaching of mathematics.

Few studies have gone further to investigate if HLE can act as a mediator between parental reading difficulties and children's literacy outcomes. In their large-scale study with 6-year-old children, Esmaeeli et al. (2019) suggested that HLE could play the role of a protective factor mediating the adverse influences of FR on children's reading skills. However, Puglisi et al. (2017)

reported that informal HLE did not predict any children's outcomes when maternal language and phonological skills were controlled for. The researchers then argued that the associations found between children's skills and informal HLE might only be a reflection of intergenerational transmission—parents with stronger language skills involve their children in more informal learning activities but also provide genes that predispose their children to have stronger language skills. To disentangle these familial and environmental influences, more studies are needed.

To summarize the previous research, numeracy and literacy are highly interconnected, complex cognitive skills and parents can pass down both reading and mathematical difficulties to their children through genetic and environmental pathways. The exact mechanism of a child developing either one or both sets of difficulties remains poorly understood, but it appears that this process is shaped by the interaction of multiple deficits (domain-specific and domain-general). Moreover, HLE has been repeatedly shown to be associated with children's language and literacy development, and in some recent studies also with mathematical skill development. Clear effects of different HNE activities on numeracy have been found only in a handful of studies and require more research. There is also a particular need for more studies on FR for mathematical difficulties, cross-domain FR effects, and parental comorbidity effects on the development of reading and mathematical skills. In addition, it remains to be seen if FR and non-FR families provide different HLE and/or HNE, and if the influence of FR on children's skills can be mediated through the home environment.

Present Study

Our analysis of the gaps in research suggests that further exploring how the development of reading and mathematical skills is influenced by parental reading and mathematical difficulties (FR for reading and mathematics, respectively) as well as home environment factors is important. Evidence from previous studies is scant because most of the studies on HLE and HNE were cross-sectional and/or small-scale and focused on early development. In contrast, the present study is a large-scale longitudinal study spanning across the compulsory education until adolescence. Based on theory and previous empirical evidence, we divided environment variables into formal (teaching of literacy and numeracy skills) and informal home inputs (shared reading) (Sénéchal, 2006; Sénéchal and Lefevre, 2014; Hamilton et al., 2016; Puglisi et al., 2017). Because parental education has been shown to be reflected in HLE (e.g., Torppa et al., 2006; Park, 2008; Hamilton et al., 2016; van Bergen et al., 2017), it is included in all our models.

We aim to answer the following research questions:

(1) Does FR for reading and/or mathematical difficulties predict the reading and mathematical development of children from Grade 1 to 9?
(2) Do home environment factors (literacy teaching, numeracy teaching, and shared reading) predict the reading and mathematical development of children from Grades 1–9?
(3) Does FR for reading and mathematical difficulties predict the home learning environment?
(4) Are the effects of FR on children's reading and mathematical development mediated by the home environment factors?

In this study, we estimate three different models: for reading fluency, for reading comprehension, and for arithmetic fluency based on our hypothesized models. In view of the research reviewed above, we constructed our hypothesized models (see **Figure 1** for the model of reading fluency; other models were estimated with the same logic) with the expectation to find the following: (1) paths from parental reading difficulties (Pennington and Lefly, 2001; Torppa et al., 2011; van Bergen et al., 2012; Hulme et al., 2015) and parental mathematical difficulties (Shalev and Gross-Tsur, 2001; Soares et al., 2018) to the respective skills in children; (2) cross-domain paths from parental mathematical difficulties to children's reading skills and from parental reading difficulties to children's mathematical skills (Landerl and Moll, 2010; Moll et al., 2015); (3) paths from HLE and HNE to both respective and cross-domain skills in children (Melhuish et al., 2008; Anders et al., 2012; Kleemans et al., 2012; Baker, 2014; Napoli and Purpura, 2018); (4) paths from parental education to children's skills (Torppa et al., 2006; Hamilton et al., 2016; van Bergen et al., 2017); (5) paths from parental education to HLE and HNE (Hamilton et al., 2016); and (6) paths from FR to the home environment (Scarborough et al., 1991; Bus et al., 1995; Elbro et al., 1998; Snowling, 2000; Hamilton et al., 2016; Esmaeeli et al., 2019), including also the examination of the indirect relationships (FR → home environment → children's skills), as Esmaeeli et al. (2019) argued that these paths need to be tested in future studies. Finally, we expected that the paths to later skill assessments run through the early skill assessments.

MATERIALS AND METHODS

Participants and Procedure

This study is a part of a large-scale longitudinal First Steps Study (Lerkkanen et al., 2006) where children (n = 2525) were followed from kindergarten to Grade 9. The children were born in the year 2000 and came from four municipalities: one in an urban area, one in a rural area, and two in, similarly, semi-rural areas in central, western, and eastern Finland. Of all contacted families, 78–89%, depending on municipality, agreed to participate in the study. Ethnically and culturally, the sample was very homogeneous and representative of the Finnish population. Marital statuses as well as the educational levels of the parents were very close to the national distribution of Finland (Statistics Finland, 2007). The study was reviewed and approved by the Ethical Committee of the University of Jyväskylä in 2006, and all participants (children and their parents) gave their informed consent before participation in the study.

Trained specialists administered both individual and group tests in suitable rooms in each school. Children absent from school on the day of testing were tested immediately after they came back to school. Tests for reading fluency, reading

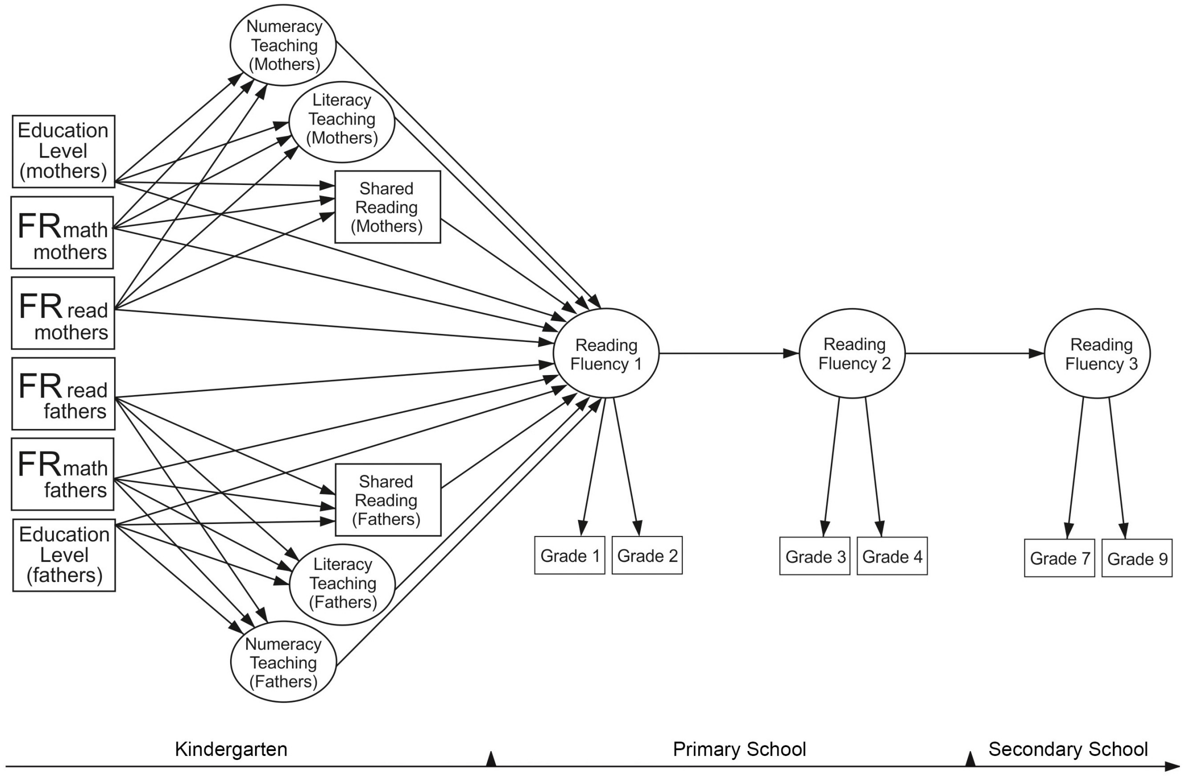

FIGURE 1 | Hypothesized model for reading fluency. Familial risk (FR for reading and mathematical difficulties of mothers and fathers); Reading Fluency 1–Reading Fluency 3, time points of assessments; Grade 1–9, assessments that took place in Grades 1–9. Literacy teaching and numeracy teaching were added in the model as latent variables; they were measured with two questionnaire items each. Shared reading was measured with one questionnaire item making up the observed variables (one for mothers and one for fathers). Other hypothesized models (for reading comprehension and mathematical skills) were constructed with the same logic.

comprehension, and mathematics were administered to children in Grades 1, 2, 3, 4, 7, and 9.

Measures

Reading Fluency

To assess reading fluency, three group-administered tests were administered: a word reading fluency task, a word chain task, and a sentence reading task. The mean of the three standardized reading fluency measures was used as the score. Cronbach's alpha reliability coefficients for the fluency composite were 0.94 in Grade 1, 0.93 in Grade 2, 0.93 in Grade 3, 0.93 in Grade 4, 0.93 in Grade 7, and 0.94 in Grade 9.

The word reading fluency task is an 80-item subtest of the nationally normed reading test battery (ALLU; Lindeman, 2000). Each item comprises a picture and a set of four phonologically similar words. The children were asked to silently read the words and decide which one of them semantically matched the picture. All the words and pictures in the task were simple and frequently used and thus were familiar to young children. The score was calculated as the number of correct answers achieved within 2 min. The score reflects both the word-reading speed and accuracy.

In the word chain task (Nevala and Lyytinen, 2000), children were presented with 10 chains of 4–6 words in a row written without spaces between them. The children were asked to silently read each row and draw a boundary line between each word pair they find. The sum score was based on the number of correct answers given within a set time limit (1.25 min in Grades 1 and 2, 1.20 min in Grade 3, 1.05 min in Grade 4, 1 min in Grades 6 and 7, and 1.30 min in Grade 9).

Sentence reading efficiency in Grades 1–4 was assessed with the Test of Silent Reading Efficiency and Comprehension (TOSREC; Wagner et al., 2010; Finnish version by Lerkkanen and Poikkeus, 2009). The children were asked to read and assess the truthfulness of as many simple sentences as possible (e.g., Strawberries are blue) out of a set of 60 items within 3 min. In Grades 7 and 9, the children were asked to complete a standardized Finnish reading test for lower secondary school sentence reading that had the same instruction as earlier sentence reading measures but slightly different items (YKÄ; Lerkkanen et al., 2018) were used. The sum score was based on the number of correct answers.

Reading Comprehension

To assess reading comprehension in Grades 1–4, a group-administered subtest of a nationally normed reading test battery was used (ALLU; Lindeman, 2000). The children were required to read a short fiction story and answer 11 multiple-choice questions and 1 question in which they had to arrange 5 statements in the correct sequence based on the information gathered from the text. For each correct answer, 1 point was given (max = 12). The children could work at their own pace but for a maximum of 45 min. Then, in Grades 7 and 9, a similar standardized reading comprehension test for lower secondary school (with the same instruction and time limit but different texts and questions) was employed (YKÄ; Lerkkanen et al., 2018). The sum score was based on the number of correct answers. Cronbach's alpha reliability coefficient for the comprehension composite ranged between 0.82 and 0.84 in different grades (0.84 in Grade 1, 0.82 in Grade 2, 0.83 in Grade 3, 0.82 in Grade 4, 0.82 in Grade 7, and 0.83 in Grade 9).

Arithmetic Fluency

Arithmetic fluency was assessed with a group-administered subtest of the arithmetic test (Räsänen and Aunola, 2007) that comprises 14 addition (e.g., $3 + 2 =$ __, $3 + 6 + 4 =$ __) and 14 subtraction tasks (e.g., $6 - 1 =$ __, $20 - 4 - 3 =$ __). Performance on this test depends on both speed and accuracy, and allows for the assessment of the automatization of basic mathematical computations. The sum score was based on the number of correct answers given within 3 min. Cronbach's alphas varied between 0.91 and 0.92 (0.92 in Grade 1, 0.91 in Grades 2–4, 7, and 9).

Familial Risk for Reading Difficulties

When the children participating in the study were in kindergarten, their mothers and fathers were asked to fill in a questionnaire asking if they themselves and/or the other parent of the child had experienced learning difficulties in reading and/or mathematics. The questionnaire included one question about their own reading difficulties, one about their own mathematical difficulties, and two in regard to their spouse. Each question could be answered on a three-point scale (1 = no difficulties, 2 = some difficulties, 3 = clear difficulties). The children were considered to have FR if they had at least one parent with some or clear difficulties, and the variable for FR was then dichotomized: 0 = no FR (report of no difficulties) and 1 = FR (report of some or clear difficulties). In the descriptive analysis, we also considered if a child has one or two parents with learning difficulties (**Tables 2**, **3**).

Parental Education

Mothers and fathers were asked to indicate their own educational level on a seven-point scale [1 = no vocational education (5.1% of mothers and 1.8% of fathers), 2 = vocational courses (3.1% of mothers and 1.7% of fathers), 3 = vocational school degree (30.8% of mothers and 14.3% of fathers), 4 = vocational college degree (23.2% of mothers and 10.1% of fathers), 5 = polytechnic degree or bachelor's degree (9.7% of mothers and 4.2% of fathers), 6 = master's degree (23.7% of mothers and 8.0% of fathers), 7 = licentiate or doctoral degree (4.4% of mothers and 2.7% of fathers)].

Home Learning Environment (Home Teaching and Shared Reading)

Mothers and fathers were also asked to complete a questionnaire about their at-home learning activities, which was based on the questions developed by Sénéchal et al. (1998) and previously used in the Finnish context (e.g., Silinskas et al., 2012, 2020). The questionnaire included one question regarding shared reading—"How often do you read books to your child or together with your child"? The answers were given on a five-point Likert-type scale (1 = less than once a week, 2 = 1–3 times a week, 3 = 4–6 times a week, 4 = once a day, 5 = more than once a day). There were four items related to home teaching activities: teaching letters, teaching reading, teaching numbers, and teaching arithmetic skills. The answers were given on a five-point scale (1 = never at all/rarely to 5 = very often/daily). We obtained the sum scores by summarizing the individual scores for each activity of mothers and fathers.

Statistical Analysis

When investigating the predictive longitudinal relations between FR, home activities, and children's skills, longitudinal path models were constructed using MPlus Version 7.4. Three separate models (**Figure 1**) were fitted to the data: for reading fluency, for reading comprehension, and for arithmetic fluency. Latent variables were built for reading fluency, reading comprehension, and arithmetic fluency to increase the reliability of the assessment and to minimize measurement error. The skill assessments in Grades 1 and 2 were grouped into Time Point 1, in Grades 3 and 4 into Time Point 2, and in Grades 7 and 9 into Time Point 3.

Latent factors were also built for the home environment measures. The factor structure of the home environment (shared reading and the four teaching items) was validated with confirmatory factor analysis (CFA). We first tested a model with four latent variables grouped as follows: the three literacy items of mothers (including shared reading), the two numeracy items of mothers, the three literacy items of fathers, and the two numeracy items of fathers, as it seemed theoretically plausible. However, this model had a poor fit with the data [χ^2 (29) = 141.19, $p < 0.001$, root-mean-square error of approximation (RMSEA) = 0.05, comparative fit index (CFI) = 0.87, standardized root-mean-square residual (SRMR) = 0.07]. The main reason for the misfit was that the correlations between the literacy teaching and numeracy teaching items were too high to form separate constructs. In view of this, we next constructed a two-factor model wherein all home environment items of mothers were loaded to one factor and all home environment items of fathers were loaded to another factor. This model also did not fit the data well [$\chi^2(33) = 107.31$, $p < 0.001$, RMSEA = 0.04, CFI = 0.91, SRMR = 0.07]. Because the shared reading items had very low factor loadings, we constructed another model with one latent factor for mothers' teaching items, including two items of teaching reading and two items of teaching mathematics, and another latent factor for fathers' teaching items. Shared reading items of mothers and fathers were separately added as observed variables. This model fitted the data well [$\chi^2(31) = 55.81$, $p < 0.01$, RMSEA = 0.02, CFI = 0.97, SRMR = 0.03] and significantly better than the model where the shared reading item was included in the latent factor, as suggested by the Satorra-Bentler corrected chi-square difference test: $\Delta\chi^2(1) = 22.23$, $p < 0.001$. This confirmed our initial hypothesis that the shared reading items should be added in the models as separate variables (informal home environment inputs) from the teaching items (formal home environment inputs).

The measure distributions were close to normal distribution, except for comprehension in early grades that had a slight skew to the left (**Table 1**). Therefore, all models were estimated using Maximum likelihood estimation with robust standard errors. The variables were standardized before fitting the models. A few outliers were present in the distributions of all skills, which were moved to the tails of the distributions before analyses.

To evaluate model fit, chi-square values and a set of fit indexes were used as follows: (a) CFI; (b) RMSEA, and (c) SRMR. Good model fit is indicated by a small, preferably non-significant χ^2, CFI > 0.95, RMSEA < 0.06, and SRMR < 0.08 (Hu and Bentler, 1999). Because the chi-square test is sensitive to a large sample size, the chi-square statistics were not regarded as conclusive.

RESULTS

Descriptive Statistics

Descriptive statistics for children's skill development and HLE measures are reported for all participants in **Table 1**, as a function of FR for reading difficulties in **Table 2**, and as a function of FR for mathematical difficulties in **Table 3**. One-way ANOVAs were conducted to compare the children with no FR (NFR), the children with one parent with difficulties (FR1), and the children with two parents with difficulties (FR2) (**Tables 2**, **3**) and showed significant differences between the NFR group, FR1 group, and FR2 group for all the skills throughout Grades 1–9 except arithmetic skills in Grade 7 as a function of parental reading difficulties. This analysis also demonstrated that parental education was significantly higher in the NFR group than in the FR1 and FR2 groups, whereas there were no group differences in the home environment measures.

Pairwise comparisons of the groups with parental reading difficulties (FR1 and FR2) revealed significant differences in children's reading fluency in Grades 1 and 4 (**Table 2**), whereas comparisons of the groups with parental mathematical difficulties (FR1 and FR2) showed that children significantly differed in their

TABLE 1 | Descriptive statistics for all variables across time.

	N	Minimum	Maximum	Mean	SD	Skewness	Kurtosis
Reading fluency (z-scores)							
Grade 1	2,052	−2.44	4.03	0.00	1.00	0.62	0.44
Grade 2	2,006	−2.89	3.88	0.00	1.00	0.26	0.23
Grade 3	1,995	−4.41	3.18	0.00	1.00	−0.04	0.43
Grade 4	1,954	−4.62	2.76	0.00	1.00	−0.17	−0.30
Grade 7	1,770	−4.19	3.04	0.00	1.00	−0.07	−0.00
Grade 9	1,721	−2.94	2.98	0.00	1.00	−0.09	−0.14
Reading comprehension							
Grade 1	2,035	0.00	12.00	5.50	3.18	−0.00	−0.96
Grade 2	1,974	0.00	12.00	8.51	2.71	−0.73	0.20
Grade 3	1,988	0.00	12.00	9.08	2.16	−1.17	1.73
Grade 4	1,950	0.00	12.00	8.10	2.52	−0.47	−0.21
Grade 7	1,758	0.00	12.00	6.59	2.54	0.05	−0.65
Grade 9	1,702	0.00	12.00	7.01	2.43	−0.15	−0.58
Arithmetic fluency							
Grade 1	2,050	0	28	10.51	4.12	0.33	0.25
Grade 2	2,001	0	28	16.05	4.92	−0.10	−0.45
Grade 3	1,994	0	28	19.61	4.62	−0.65	0.48
Grade 4	1,953	0	27	17.03	4.09	−0.64	0.81
Grade 7	1,749	0	27	13.68	3.81	−0.17	0.34
Grade 9	1,705	1	27	14.89	3.92	−0.13	0.05
Parental education							
Mother	1,563	1	7	4.18	1.52	−0.00	−0.12
Father	1,117	1	7	4.12	1.50	−0.20	−0.15
Home learning environment factors (mean composites)							
Shared reading, mother	1,559	1	7	2.29	1.15	−0.15	−1.01
Shared reading, father	1,104	1	7	2.35	1.15	0.47	−0.89
Teaching, mother	1,115	1	5	2.54	0.75	0.08	−0.11
Teaching, father	1,567	1	5	2.60	0.79	0.02	−0.19

TABLE 2 | ANOVA comparisons among the three risk groups for reading difficulties (RD) for all variables.

	No family risk for RD (NFR)			One parent risk for RD (FR1)			Both parents risk for RD (FR2)					
	N	***M***	***SD***	***N***	***M***	***SD***	***N***	***M***	***SD***	***df* within groups**	**F**	**Pairwise comparisons (Bonferroni)**
Reading fluency (z-scores)												
Grade 1	979	0.18	0.85	377	−0.14	0.82	58	−0.56	0.69	1,411	26.90***	NFR > FR1, FR1 > FR2, NFR > FR2
Grade 2	957	0.20	0.83	362	−0.20	0.83	58	−0.52	0.69	1,374	34.23***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 3	941	0.17	0.82	362	−0.11	0.85	57	−0.56	0.63	1,357	19.50***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 4	921	0.19	0.81	356	−0.11	0.87	53	−0.56	0.64	1,327	25.38***	NFR > FR1, FR1 > FR2, NFR > FR2
Grade 7	697	0.19	0.83	268	−0.13	0.94	33	−0.26	0.79	995	12.26***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 9	682	0.19	0.84	260	−0.07	0.91	33	−0.26	0.70	972	9.20***	NFR > FR1, FR1 = FR2, NFR > FR2
Reading comprehension												
Grade 1	977	6.06	3.19	373	5.13	3.08	58	4.09	2.87	1,405	20.14***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 2	945	8.98	2.51	358	8.22	2.75	58	7.50	2.93	1,358	17.81***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 3	939	9.43	1.97	361	8.79	2.29	57	8.89	2.12	1,354	13.58***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 4	920	8.58	2.29	356	7.92	2.57	53	7.58	2.54	1,326	12.77***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 7	691	7.02	2.52	268	6.51	2.63	33	5.97	2.36	989	5.88**	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 9	680	7.40	2.41	255	6.96	2.39	32	6.22	1.93	964	6.20**	NFR > FR1, FR1 = FR2, NFR > FR2
Arithmetic fluency												
Grade 1	979	11.10	4.10	376	10.24	4.11	58	9.71	3.97	1,410	8.13***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 2	953	16.81	4.78	362	15.99	4.83	58	14.19	4.97	1,370	10.70***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 3	941	20.23	4.37	362	19.50	4.62	57	18.11	4.94	1,357	8.59***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 4	920	17.59	3.86	356	16.96	4.14	53	16.40	4.22	1,326	4.89**	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 7	690	14.15	3.82	265	13.91	3.66	34	13.29	3.61	986	1.11	NFR = FR1, FR1 = FR2, NFR = FR2
Grade 9	676	15.49	3.74	256	14.70	3.87	34	14.53	3.83	963	4.69**	NFR > FR1, FR1 = FR2, NFR > FR2
Parental education												
Mother	1,009	4.37	1.48	397	4.04	1.48	66	3.38	1.24	1,469	19.20***	NFR > FR1, FR1 > FR2, NFR > FR2
Father	759	4.28	1.49	287	3.82	1.52	48	3.71	1.23	1,091	12.06***	NFR > FR1, FR1 = FR2, NFR > FR2
Home learning environment factors (mean composites)												
Shared reading, mother	1,007	2.96	1.13	397	2.86	1.16	66	2.67	1.17	1,467	2.87	NFR = FR1, FR1 = FR2, NFR = FR2
Shared reading, father	752	2.38	1.16	280	2.30	1.15	47	2.30	1.16	1,076	0.56	NFR = FR1, FR1 = FR2, NFR = FR2
Teaching, mother	1,010	2.60	0.79	399	2.59	0.79	67	2.46	0.84	1,473	0.95	NFR = FR1, FR1 = FR2, NFR = FR2
Teaching, father	756	2.54	0.73	286	2.51	0.80	48	2.64	0.81	1,087	0.62	NFR = FR1, FR1 = FR2, NFR = FR2

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

TABLE 3 | ANOVA comparisons among the three risk groups for mathematical difficulties (MD) for all variables.

	No family risk for MD (NFR)			One parent risk for MD (FR1)			Both parents risk for MD (FR2)					
	N	***M***	***SD***	***N***	***M***	***SD***	***N***	***M***	***SD***	***df* within groups**	**F**	**Pairwise comparisons (Bonferroni)**
Reading fluency (*z*-scores)												
Grade 1	963	0.17	0.87	383	−0.11	0.78	63	−0.49	0.82	1,406	21.76***	NFR > FR1, FR1 > FR2, NFR > FR2
Grade 2	941	0.19	0.85	369	−0.14	0.78	62	−0.48	0.86	1,369	25.19***	NFR > FR1, FR1 > FR2, NFR > FR2
Grade 3	927	0.17	0.83	369	−0.09	0.81	60	−0.36	0.82	1,353	17.16***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 4	907	0.20	0.82	360	−0.14	0.81	58	−0.35	0.88	1,322	23.00***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 7	700	0.18	0.86	263	−0.10	0.83	32	−0.21	1.05	992	9.36***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 9	686	0.19	0.86	254	−0.05	0.84	32	−0.26	0.74	969	7.91***	NFR > FR1, FR1 = FR2, NFR > FR2
Reading comprehension												
Grade 1	961	6.06	3.13	379	5.13	3.19	63	4.22	3.31	1,400	19.46***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 2	928	9.03	2.47	367	8.23	2.74	61	6.75	3.13	1,353	31.35***	NFR > FR1, FR1 > FR2, NFR > FR2
Grade 3	925	9.42	2.03	368	8.90	2.13	60	8.47	2.48	1,350	12.59***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 4	906	8.64	2.29	360	7.78	2.62	58	7.62	2.25	1,321	19.54***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 7	696	7.06	2.56	263	6.42	2.53	32	5.53	2.24	988	10.27***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 9	681	7.45	2.36	251	6.84	2.45	32	6.09	2.37	961	9.87***	NFR > FR1, FR1 = FR2, NFR > FR2
Arithmetic fluency												
Grade 1	962	11.20	4.11	383	10.17	4.02	63	8.94	3.86	1,405	15.82***	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 2	938	17.08	4.70	368	15.46	4.90	62	13.68	4.55	1,365	26.75***	NFR > FR1, FR1 > FR2, NFR > FR2
Grade 3	927	20.42	4.38	369	19.20	4.47	60	17.57	4.73	1,353	19.27***	NFR > FR1, FR1 > FR2, NFR > FR2
Grade 4	906	17.84	3.79	360	16.63	4.05	58	14.88	4.36	1,321	25.10***	NFR > FR1, FR1 > FR2, NFR > FR2
Grade 7	692	14.29	3.86	261	13.67	3.52	32	12.38	3.53	982	5.94**	NFR > FR1, FR1 = FR2, NFR > FR2
Grade 9	681	15.57	3.76	249	14.65	3.79	33	13.36	3.69	960	9.62***	NFR > FR1, FR1 = FR2, NFR > FR2
Parental education												
Mother	990	4.48	1.49	403	3.85	1.35	72	4.25	3.95	1,462	50.71***	NFR > FR1, FR1 < FR2, NFR = FR2
Father	749	4.35	1.51	292	3.76	1.40	51	3.20	1.17	1,089	27.52***	NFR > FR1, FR1 > FR2, NFR > FR2
Home learning environment factors (mean composites)												
Shared reading, mother	988	2.94	1.13	401	2.92	1.18	74	2.72	1.05	1,460	1.29	NFR = FR1, FR1 = FR2, NFR = FR2
Shared reading, father	738	2.39	1.15	287	2.30	1.18	52	2.12	1.18	1,074	1.86	NFR = FR1, FR1 = FR2, NFR = FR2
Teaching, mother	991	2.60	0.81	405	2.60	0.94	74	2.60	0.85	1,467	0.09	NFR = FR1, FR1 = FR2, NFR = FR2
Teaching, father	745	2.54	0.75	291	2.60	0.74	52	2.21	0.77	1,085	5.67**	NFR = FR1, FR1 > FR2, NFR > FR2

**p < 0.05, **p < 0.01, ***p < 0.001.*

reading comprehension skills in Grades 1 and 2 as well as in arithmetical fluency skills in Grades 2, 3, and 4 (**Table 3**).

Pearson correlation coefficients are reported across all measures in **Table 4**. All skills were significantly related with one another, but the strongest correlations were found in lower grades. The correlations between the reading and mathematical measures and the home teaching environment and shared reading were small, ranging from 0.01 to 0.19.

The Model for Reading Fluency

Figure 2 presents the final model for reading fluency with statistically significant standardized estimates, and **Table 5** reports all the path estimates and residual correlations of the model. The model fitted the data well: $\chi^2(171) = 247.90$, $p < 0.001$, RMSEA = 0.02, CFI = 0.98, SRMR = 0.03. Two significant predictors of reading fluency emerged: children's reading fluency at the first time point was predicted by fathers' reading difficulties and by mothers' educational level. That is, fathers' reading difficulties and lower maternal education predicted poorer performance in reading fluency tasks among their children. However, the effects were small, explaining 2 and 1% of the variance, respectively. There were no significant effects of any of the home environment factors on reading fluency and parental reading, and mathematical difficulties did not predict the home environment factors. However, higher levels of education among mothers predicted less time spent on teaching activities and more time spent on shared reading. In addition, higher levels of education of mothers and fathers were associated with more shared reading with fathers. Again, the amounts of explained variance in the home environment owing to educational level were low, between 1 and 4%. This model did not reveal any significant indirect effects. Reading fluency demonstrated very high stability across time. The first time point explained 85% of the variance in reading fluency at the second

TABLE 4 | Correlations between all variables.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Grade 1	1													
2. Grade 2	0.80**	1												
3. Grade 3	0.75**	0.82**	1											
4. Grade 4	0.71**	0.79**	0.85**	1										
5. Grade 7	0.61**	0.67**	0.71**	0.75**	1									
6. Grade 9	0.58**	0.64**	0.67**	0.72**	0.81**	1								
7. Grade 1	0.63**	0.60**	0.55**	0.56**	0.47**	0.45**	1							
8. Grade 2	0.48**	0.49**	0.47**	0.47**	0.42**	0.43**	0.53**	1						
9. Grade 3	0.33**	0.35**	0.34**	0.37**	0.33**	0.35**	0.39**	0.48**	1					
10. Grade 4	0.37**	0.39**	0.40**	0.41**	0.41**	0.39**	0.44**	0.55**	0.47**	1				
11. Grade 7	0.26**	0.30**	0.26**	0.30**	0.37**	0.39**	0.36**	0.45**	0.40**	0.51**	1			
12. Grade 9	0.29**	0.32**	0.28**	0.30**	0.35**	0.40**	0.37**	0.43**	0.36**	0.43**	0.51**	1		
Arithmetic Fluency (z-scores)														
13. Grade 1	0.51**	0.48**	0.46**	0.46**	0.33**	0.32**	0.40**	0.29**	0.19**	0.21**	0.14**	0.17**	1	
14. Grade 2	0.47**	0.50**	0.49**	0.49**	0.39**	0.37**	0.39**	0.32**	0.23**	0.27**	0.19**	0.16**	0.69**	1
15. Grade 3	0.46**	0.49**	0.53**	0.53**	0.40**	0.38**	0.40**	0.32**	0.25**	0.27**	0.20**	0.17**	0.64**	0.75**
16. Grade 4	0.44**	0.48**	0.50**	0.53**	0.41**	0.40**	0.40**	0.34**	0.27**	0.33**	0.24**	0.20**	0.61**	0.70**
17. Grade 7	0.36**	0.37**	0.37**	0.37**	0.41**	0.41**	0.33**	0.32**	0.27**	0.31**	0.34**	0.29**	0.51**	0.59**
18. Grade 9	0.37**	0.37**	0.34**	0.36**	0.39**	0.40**	0.35**	0.32**	0.27**	0.29**	0.35**	0.31**	0.54**	0.59**
Parental Reading Difficulties														
19. Mother	−0.13**	−0.16**	−0.12**	−0.14**	−0.10**	−0.08*	−0.12**	−0.12**	−0.10**	−0.13**	−0.02	−0.05	−0.06*	−0.07**
20. Father	−0.16**	−0.18**	−0.14**	−0.15**	−0.13**	−0.12**	−0.13**	−0.12**	−0.10**	−0.08**	−0.12**	−0.10**	−0.09**	−0.10**
21. Mother	−0.12**	−0.13**	−0.11**	−0.13**	−0.09**	−0.07*	−0.10**	−0.15**	−0.11**	−0.14**	−0.10**	−0.09**	−0.10**	−0.15**
22. Father	−0.14**	−0.15**	−0.13**	−0.14**	−0.11**	−0.11**	−0.15**	−0.15**	−0.10**	−0.11**	−0.12**	−0.11**	−0.14**	−0.14**
Parental Education														
23. Mother	0.13**	0.15**	0.12**	0.16**	0.13**	0.17**	0.18**	0.17**	0.17**	0.22**	0.19**	0.19**	0.12**	0.15**
24. Father	0.13**	0.16**	0.12**	0.16**	0.14**	0.13**	0.18**	0.18**	0.19**	0.20**	0.17**	0.18**	0.12**	0.16**
Home Learning Environment														
25. Shared reading, mother	0.02	0.05*	0.04	0.07*	0.07*	0.09**	0.10**	0.14**	0.11**	0.20**	0.19**	0.17**	−0.01	0.01
26. Shared reading, father	0.02	0.04	0.06	0.09**	0.08*	0.08*	0.11**	0.12**	0.16**	0.19**	0.14**	0.15**	0.01	0.05
27. Teaching literacy, mother	0.08**	0.07**	0.10**	0.06*	0.08*	0.09**	0.10**	0.06*	0.03	0.07**	0.03	0.06	0.02	0.03
28. Teaching literacy, father	0.02	−0.02	−0.01	−0.01	0.04	0.03	0.06	0.01	0.02	0.01	0.03	0.06	0.01	−0.01
29. Teaching numeracy, mother	−0.04	−0.05*	−0.01	−0.03	−0.04	−0.02	−0.03	−0.05	−0.05	−0.00	−0.05	−0.03	0.00	0.02
30. Teaching numeracy, father	−0.06	−0.05	−0.04	−0.05	−0.02	−0.00	−0.02	−0.03	−0.01	0.01	0.01	−0.00	0.05	0.04

(Continued)

TABLE 4 | Continued

	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1. Grade 1																
2. Grade 2																
3. Grade 3																
4. Grade 4																
5. Grade 7																
6. Grade 9																
7. Grade 1																
8. Grade 2																
9. Grade 3																
10. Grade 4																
11. Grade 7																
12. Grade 9																
Arithmetic Fluency (z-scores)																
13. Grade 1																
14. Grade 2																
15. Grade 3	1															
16. Grade 4	0.77**	1														
17. Grade 7	0.60**	0.68**	1													
18. Grade 9	0.61**	0.67**	0.75**	1												
Parental Reading Difficulties																
19. Mother	−0.07**	−0.05	−0.02	−0.06	1											
20. Father	−0.09**	−0.10**	−0.09**	−0.08**	−0.04	−0.08*	0.10**	1								
21. Mother	−0.13**	−0.14**	−0.07*	−0.09**	0.30**	0.13**	1									
22. Father	−0.13**	−0.17**	−0.10**	−0.15**	0.16**	0.38**	0.13**	1								
Parental Education																
23. Mother	0.17**	0.18**	0.21**	0.19**	−0.15**	−0.10**	−0.23**	−0.15**	1							
24. Father	0.15**	0.20**	0.16**	0.19**	−0.06*	−0.14**	−0.14**	−0.20**	0.53**	1						
Home Learning Environment																
25. Shared reading, mother	−0.01	0.01	−0.01	0.05	−0.07**	−0.02	−0.05	0.01	0.21**	0.12**	1					
26. Shared reading, father	0.05	0.06	0.05	0.09*	−0.02	−0.03	−0.06	−0.03	0.23**	0.20**	0.48**	1				
27. Teaching literacy, mother	0.03	−0.00	−0.01	−0.04	−0.04	−0.03	−0.04	0.03	−0.06*	−0.05	0.14**	0.04	1			
28. Teaching literacy, father	−0.02	−0.04	0.00	0.05	0.08**	−0.04	0.03	−0.06	0.00	−0.01	0.12**	0.24**	0.26**	1		
29. Teaching numeracy, mother	0.02	0.01	0.00	−0.02	−0.02	0.01	−0.02	0.00	−0.11**	−0.10**	0.12**	0.01	0.68***	0.20**	1	
30. Teaching numeracy, father	0.02	0.01	0.06	0.03	0.01	−0.02	0.00	−0.10**	0.03	0.00	0.07*	0.19**	0.19**	0.67***	0.22**	1

*$p < 0.05$, **$p < 0.01$, *** $p < 0.001$.*

time point, which then explained 75% of the variance at the third time point.

The Model for Reading Comprehension

Figure 3 reports the final model for reading comprehension. The model fitted the data well: $\chi^2(170) = 248.42$, $p < 0.001$, RMSEA = 0.02, CFI = 0.97, SRMR = 0.03. The model suggested several statistically significant predictors of reading comprehension. Mothers' and fathers' mathematical difficulties predicted poorer reading comprehension among children, each predicting 1% of the variance. Mothers' and fathers' levels of education were significant positive predictors of children's reading comprehension, each explaining 2% of the variance. Shared reading with fathers was also found to have a direct positive effect on children's reading comprehension (explaining 1% of the variance) at the first time point, whereas shared reading with mothers was predictive of children's comprehension at the second time point (explaining 2% of the variance). In addition, higher levels of education among mothers predicted more time spent on shared reading and less time spent on teaching activities. The higher levels of education of mothers and fathers were associated with more shared reading with fathers. This model did not reveal any significant indirect effects. In addition, reading comprehension demonstrated very high stability across time. The first time point explained 72% of the variance in reading comprehension at the second time point, which then explained 87% of the variance at the third time point.

The Model for Arithmetic Fluency

Figure 4 reports the model for arithmetic fluency. The model fitted the data well: $\chi^2(170) = 255.33$, $p < 0.001$, RMSEA = 0.02, CFI = 0.979, SRMR = 0.03. Similarly to the comprehension model, this model revealed that only mathematical but not reading difficulties of mothers and fathers predicted children's

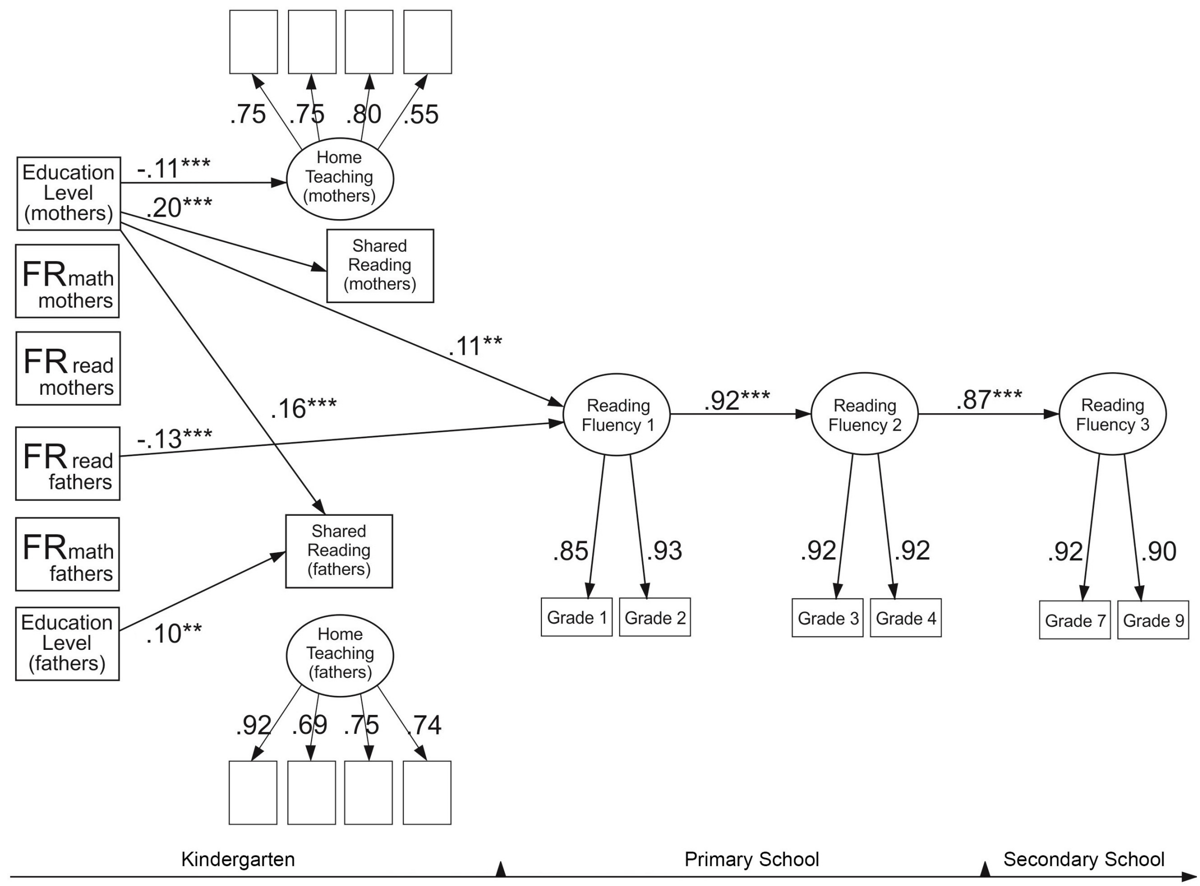

FIGURE 2 | Reading fluency model. The model shows only significant standardized paths. Familial risk (FR for reading and mathematical difficulties of mothers and fathers). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. Two significant residual correlations were included in the model: between the mothers' and fathers' teaching factor (0.27**) and between the mothers' and fathers' shared reading variables (0.47**).

mathematical skills, each explaining 1% of the variance. Mothers' and fathers' levels of education were also significant predictors of children's arithmetic fluency, with fathers' education explaining 1% of the variance at the first time point and mothers' education explaining 1% of the variance at the second time point. No significant effects of any home environment factors for predicting children's arithmetic fluency were observed. Higher levels of education among mothers predicted less time spent on teaching activities and more time spent on shared reading. Higher levels of education among mothers and fathers predicted more shared reading with fathers. This model did not reveal any significant indirect associations. Similarly to reading skills, arithmetic fluency demonstrated very high stability across time. The first time point explained 81% of the variance in mathematics skills at the second time point, which then explained 77% of the variance at the third time point.

DISCUSSION

In this study, our main goal was to gain more understanding of the basis of reading and mathematical comorbidity by examining the transmission of parental reading and mathematical difficulties (FR) onto children's reading and mathematical skills. We examined both direct effects of FR on children's skill development and indirect effects of FR via formal and informal home learning activities. To provide insights into the underpinning processes of the frequently occurring comorbidity of reading and mathematical difficulties, our analysis included mathematical and reading skills, FR for reading and mathematical difficulties coming from both parents, as well as home environment measures for both literacy and numeracy activities. Parental educational level was included as a control measure. Our findings indicated the direct effects of FR on children's skills but no indirect effects via the home environment. Indeed, neither mathematical nor reading difficulties of the parents predicted the frequency of shared reading and parental teaching activities. Higher levels of parental education, on the contrary, predicted more frequent shared reading with both parents and less frequent teaching activities with mothers. In addition, we found that parental mathematical difficulties predicted not only children's mathematical skills but also their reading comprehension, whereas parental reading difficulties predicted only children's reading fluency. This suggests that the mathematical difficulties

TABLE 5 | All regression paths and residual correlations in the three models.

Path estimates	Model for reading fluency: estimate (s.e.)	Model for reading comprehension (s.e.): estimate (s.e.)	Model for arithmetic fluency: estimate (s.e.)
FR for reading, mothers → home teaching, mothers	−0.05 (0.03)	−0.05 (0.03)	−0.05 (0.03)
FR for reading, mothers → shared reading, mothers	−0.04 (0.03)	−0.04 (0.03)	−0.04 (0.03)
FR for math, mothers → home teaching, mothers	−0.06 (0.05)	−0.06 (0.05)	−0.06 (0.05)
FR for math, mothers → shared reading, mothers	0.02 (0.03)	0.02 (0.03)	0.02 (0.03)
FR for reading, mothers→ skills at Time Point 1	−0.05 (0.03)	−0.06 (0.04)	−0.00 (0.03)
FR for math, mothers→ skills at Time Point 1	−0.06 (0.03)	−0.10* (0.04)	−0.11** (0.03)
Education level, mothers → skills at Time Point 1	0.11** (0.04)	0.13** (0.04)	0.06 (0.04)
Education level, mothers → skills at Time Point 2			0.09*** (0.02)
Education level, mothers → home teaching, mothers	−0.11*** (0.03)	−0.11*** (0.03)	−0.11*** (0.03)
Education level, mothers → shared reading, mothers	0.20*** (0.03)	0.20*** (0.03)	0.20*** (0.03)
Shared reading, mothers → skills at Time Point 1	−0.01 (0.04)	0.05 (0.04)	−0.01 (0.04)
Shared reading, mothers → skills at Time Point 2		0.13*** (0.03)	
At-home teaching, mother → skills at Time Point 1	−0.02 (0.04)	0.02 (0.04)	−0.01 (0.04)
FR for reading, fathers → home teaching, fathers	0.01 (0.03)	0.01 (0.03)	0.01 (0.03)
FR for reading, fathers → shared reading, fathers	0.01 (0.03)	0.01 (0.03)	0.01 (0.03)
FR for math, fathers → home teaching, fathers	−0.07 (0.04)	−0.07 (0.04)	−0.07 (0.04)
FR for math, fathers → shared reading, fathers	−0.01 (0.03)	−-0.01 (0.03)	−0.01 (0.03)
FR for reading, fathers → skills at Time Point 1	−0.13*** (0.04)	−0.07 (0.04)	−0.04 (0.04)
FR for math, fathers → skills at Time Point 1	−0.05 (0.04)	−0.10* (0.04)	−0.11** (0.04)
Education level, fathers → skills at Time Point 1	0.06 (0.04)	0.14** (0.04)	0.10** (0.04)
Education level, fathers → home teaching, fathers	−0.01 (0.03)	−0.01 (0.03)	−0.01 (0.03)
Education level, fathers → shared reading, fathers	0.10** (0.03)	0.10** (0.03)	0.10** (0.03)
Shared reading, fathers → skills at Time Point 1	0.02 (0.04)	0.10* (0.04)	0.01 (0.04)
At-home teaching, fathers → skills at Time Point 1	−0.04 (0.04)	−0.02 (0.04)	0.00 (0.03)
Skills at Time Point 1 → Skills at Time Point 2	0.92*** (0.01)	0.85*** (0.03)	0.90*** (0.01)
Skills at Time Point 2 → Skills at Time Point 3	0.87*** (0.02)	0.93*** (0.03)	0.88*** (0.02)
Education level, mothers → Shared reading, fathers	0.16*** (0.03)	0.16*** (0.03)	0.16*** (0.03)
Residual covariances			
Home teaching, mothers with home teaching, fathers	0.25*** (0.04)	0.25*** (0.04)	0.25*** (0.04)
Shared reading, mothers with home teaching, mothers	0.15***(0.03)	0.15*** (0.03)	0.15*** (0.03)
Shared reading, mothers with home teaching, fathers	0.13*** (0.03)	0.13*** (0.03)	0.13*** (0.03)
Shared reading, fathers with home teaching, fathers	0.26*** (0.03)	0.26*** (0.03)	0.26*** (0.03)
Shared reading, fathers with shared reading, mothers	0.44*** (0.03)	0.44*** (0.03)	0.44*** (0.03)

**p < 0.05, **p < 0.01, ***p < 0.001. Some regression and correlation paths were not initially hypothesized but were later added based on the modification indices.*

of parents increase their children's liability for developing not only mathematical difficulties but also reading comprehension difficulties. Finally, of the home environment measures, shared reading predicted reading comprehension in Grades 1 and 2 as well as faster development of comprehension skills from Grades 1 and 2 to Grades 3 and 4, whereas more literacy and numeracy teaching activities did not predict skills. These findings suggest that children's learning difficulties arise from a complex interaction of multiple risk factors (inherited deficits and environmental influences).

Familial Risk as a Predictor of Reading and Mathematical Skills

The results suggested significant within-domain effects of parental skills on children's skills, particularly for parental mathematical difficulties. Both mothers' and fathers' mathematical difficulties predicted poorer performance in arithmetic fluency among their children. Furthermore, fathers' reading difficulties predicted their children's reading fluency. Mothers' reading difficulties, however, were not predictive of any of the children's skills. These findings are consistent with those of previous studies showing significant FR effects for mathematics (Shalev and Gross-Tsur, 2001; Soares et al., 2018) and reading (Elbro et al., 1998; Torppa et al., 2011, 2015; van Bergen et al., 2014a; Hulme et al., 2015; Esmaeeli et al., 2019). However, the effect sizes were modest, with FR (coming from each parent) predicting approximately 1% of children's skills in Grades 1 and 2. Nevertheless, this effect size is comparable to that in earlier studies in which FR was self-reported and not tested. Recently, Esmaeeli et al. (2019) reported that in their study, FR explained 3% of the variance in children's reading skills. However, Torppa et al. (2011) and van Bergen et al. (2014a) estimated that 8–16% and 11% of children's reading skills, respectively, can be predicted by FR when it is identified with parental skill assessments. Undoubtedly, parental testing is

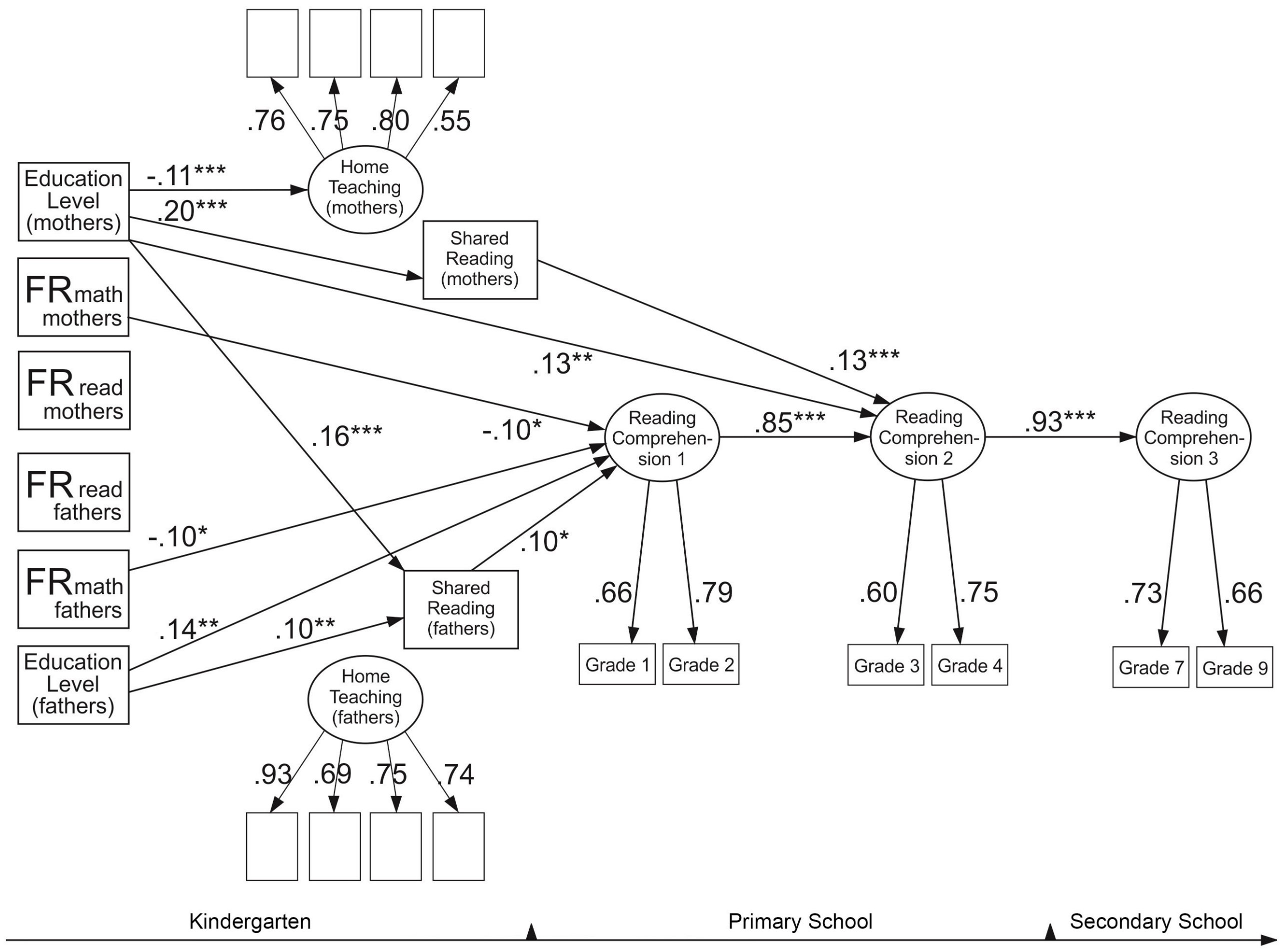

FIGURE 3 | Reading comprehension model. The model shows only significant standardized paths. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. Familial risk (FR for reading and mathematical difficulties of mothers and fathers). Two significant residual correlations were included in the model: between the mother's and father's teaching factor (0.27**) and between the shared reading variables (0.47**).

a more reliable measure to detect FR than self-reports, although the correlation between formally tested reading skills and self-reported difficulties has been reported to be as high as 0.80 (van Bergen et al., 2014a).

In line with the previous FR studies, the results of our models revealed significant differences in children's skills between groups with and without FR. For some skill measures, the results further suggested a stepwise pattern wherein the group with one parent FR had stronger skills than the group with FR owing to two parents. This evidence suggests that the dual parent learning difficulty constitutes an aggravated risk for children's skill development. This finding is in line with the MDM and fits with the suggestions of the continuous liability distribution of FR (Snowling et al., 2003; Pennington, 2006; van Bergen et al., 2012). The pattern was present for parental mathematical difficulties in four arithmetic assessments, two reading fluency assessments, and one reading comprehension assessment. However, for parental reading difficulties, the pattern was present only for the reading fluency of children in Grades 1 and 4.

Significant cross-domain effects of FR on children's skills were also identified but only for parental mathematical difficulties. Both mothers' and fathers' mathematical difficulties predicted children's reading comprehension but not reading fluency. Moreover, children's mathematical skills did not appear to be associated with FR for reading difficulties. These paths from FR to mathematical difficulties lend support to the argument that reading and mathematical difficulties have both common and distinct underpinnings (Landerl and Moll, 2010; Carvalho and Haase, 2019) and point to an intergenerational transmission of multiple deficits, as posited by Pennington's MDM. The findings support those of earlier studies indicating that mathematical difficulties more often co-occur with reading difficulties than the other way around (Landerl and Moll, 2010; Carvalho and Haase, 2019). The findings do not, however, explain the comorbidity of reading and mathematical difficulties that is often found using fluency-based assessments (Moll et al., 2019). The processes underlying the specific link between children's reading comprehension and parental mathematical difficulties need to be

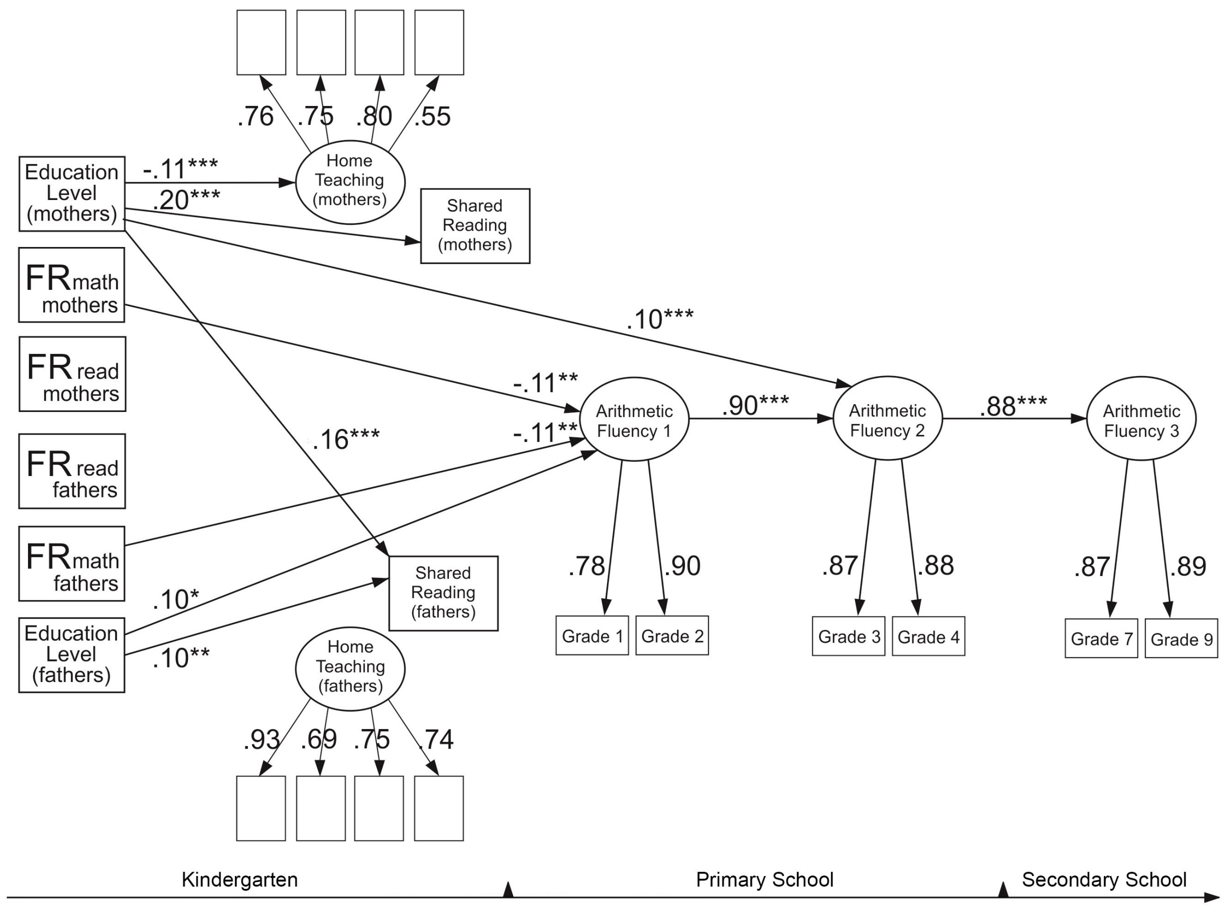

FIGURE 4 | Arithmetic fluency model. The model shows only significant standardized paths. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. FR, familial risk (FR for reading and mathematical difficulties of mothers and fathers). Two significant residual correlations were included in the model: between the mother's and father's teaching factor (0.27**) and between the shared reading variables (0.47**).

examined further. Some research has indicated that the genetic correlations of mathematical skills with reading comprehension are significantly higher than those with decoding (Harlaar et al., 2012). Furthermore, a strong association has been found between children's reading comprehension and mathematical reasoning (Pimperton and Nation, 2010), which may in part explain why we found parental mathematical difficulties predicting children's reading comprehension.

Home Learning Environment as a Predictor of Children's Reading and Arithmetic Skills

At-home teaching activities seemed to have neither direct nor indirect effects on children's skills, which stands in contrast with our hypothesis and earlier research (Martini and Sénéchal, 2012; Sénéchal and Lefevre, 2014; Skwarchuk et al., 2014; Sénéchal, 2015; Puglisi et al., 2017; Napoli and Purpura, 2018). Our findings are in line with some other research (Missall et al., 2015; Zippert and Rittle-Johnson, 2020) and could be viewed as supportive evidence for the argument that gains from formal home activities tend to be negligibly small and short-term in the context of transparent languages and fade away once children enter school (Manolitsis et al., 2013; Silinskas et al., 2020). Indeed, highly regular orthographies speed up the process of reading acquisition allowing children to reach good reading levels with the support of high-quality phonics teaching at school (Aro, 2017), which explains why providing early reading instruction at home does not ensure any long-term advantage. It is also important to stress that Finland has succeeded in promoting educational equality by creating a welfare state, which provides early educational support in schools to every child reducing the need for home teaching and the extent to which a family's socioeconomic background affects their child's development (e.g., Reinikainen, 2012).

At the same time, as expected, shared reading organized by both mothers and fathers had significant direct effects on children's reading comprehension in lower grades, which is in line with earlier findings pointing to the influence of informal literacy inputs on beginners' reading comprehension (Foy and Mann, 2003; Sénéchal, 2006, 2015; Torppa et al., 2007; Martini and Sénéchal, 2012; Manolitsis et al., 2013; Sénéchal and Lefevre, 2014; Hamilton et al., 2016; Puglisi et al., 2017). However, no effects of shared reading were found for arithmetic or reading fluency, which is consistent with the findings of earlier studies that investigated the effects of informal meaning-related home activities on children's decoding skills, symbolic number knowledge, and non-symbolic arithmetic skills (Sénéchal et al., 2008; Martini and Sénéchal, 2012; Sénéchal and Lefevre, 2014; Napoli and Purpura, 2018; Esmaeeli et al., 2019). The reason for reading comprehension being associated with shared reading is typically explained by its impact on oral language (Torppa et al., 2007; Sénéchal et al., 2008; Martini and Sénéchal, 2012; Sénéchal and Lefevre, 2014; Hamilton et al., 2016; Silinskas et al., 2020). Similar to the predictive effects of FR, the effects of shared reading on children's comprehension were rather small—less than 2%. The modest variance explained by informal learning likely stems from the same reasons listed above in regards to the predictive role of formal activities at home. In addition, Puglisi et al. (2017) reported that the relationship between informal literacy learning activities and children's skills is mostly accounted for by parental skills and might reflect a gene-environment correlation. Interestingly, however, this study found that shared reading with mothers was predictive of the reading comprehension of children in Grades 3 and 4 even with the inclusion of FR, as well as over and above the autoregressor, suggesting that the improvement in reading comprehension during the early school years was partially predicted by shared reading.

Familial Risk and the Home Learning Environment

The models indicated that FR for neither reading nor mathematical difficulties predicted at-home teaching or shared reading—parents with difficulties read with their children and taught academic skills in the same way as the parents without difficulties. This is in line with previous research (Elbro et al., 1998; Laakso et al., 1999; Torppa et al., 2007; Hamilton et al., 2016) suggesting that parental reading and mathematical difficulties are not transmitted to their children via the home environment. Intriguingly, higher levels of education among mothers predicted significantly less time spent on teaching activities and more time spent on shared reading. In other words, FR predicted neither formal nor informal home environment activities whereas maternal education predicted both. In the more educated homes, fathers also spent more time reading with their children. It is possible that parents with lower levels of education are more inclined to expect their children's possible school failure or, alternatively, that they increase the volume of home teaching activities when their children display early signs of difficulties (Blevins-Knabe and Musun-Miller, 1996; Silinskas et al., 2010; Sénéchal and Lefevre, 2014).

In addition, and contrary to our hypothesis, we did not find FR having a significant indirect effect on children's skills via the home environment. This negative finding is in line with Esmaeeli et al. (2019), who despite their hypothesis also failed to find significant indirect paths from FR for reading difficulties to children's skill. That said, however, it is important to not completely discard the influence of FR on the home environment. Indeed, Esmaeeli et al. (2018) made a reasonable argument that FR might be negatively affecting the home environment both directly and indirectly through parental education because the FR status is likely to be a contributing factor to lower parental education, as was previously reported both in Finland and in other countries (McLaughlin et al., 2014; Aro et al., 2019). Interestingly, some studies (Scarborough et al., 1991; Bus et al., 1995; Elbro et al., 1998; Snowling, 2000; Leinonen et al., 2001; Torppa et al., 2007)

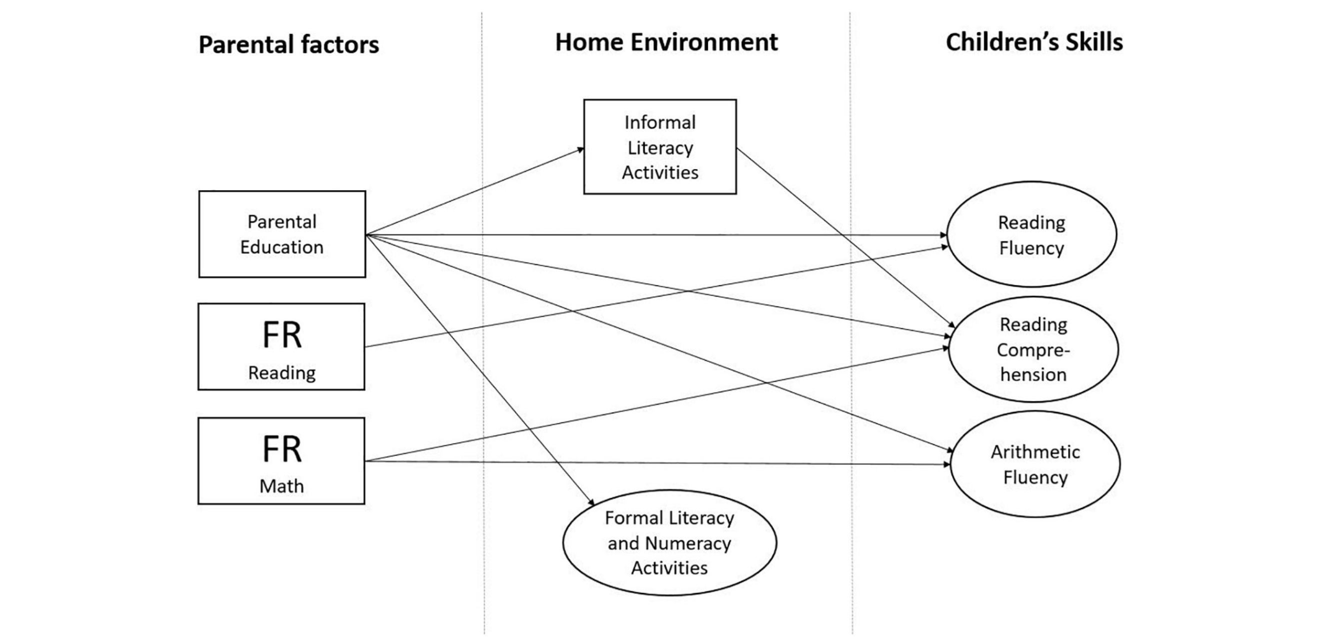

FIGURE 5 | Visual summary. The figure shows all significant paths found in this study.

showed that parents with learning difficulties read less than their control counterparts and thus may provide less positive parental models.

Limitations and Future Research

The present study has limitations in regard to the measures employed. First, similarly to previous investigations (e.g., Silinskas et al., 2010; Esmaeeli et al., 2018, 2019), this study deployed parental self-reports of HLE and HNE, which are liable to social desirability bias. Moreover, the measures mostly focused on assessing the formal activities of the home environment and had only one question assessing informal HLE and no questions tapping into informal HNE. Therefore, an important goal for future research is to incorporate a wider range of assessment measures for HLE and HNE which, in combination with longitudinal study designs, render an essentially more reliable prediction than cross-sectional studies alone. However, even well-founded longitudinal associations are far from being interpreted causally. Thus, randomized controlled trials testing various HLE and HNE interventions are needed to aid in the understanding of causal effects. Second, the quality of at-home learning can vary significantly and could be an additional predictor (Siraj-Blatchford, 2010; Kluczniok et al., 2013). The lack of measures capturing the quality of home teaching could be one of the reasons behind the small amount of variance explained by the home environment activities, and future studies should take this into account. Third, future research would benefit from using a more comprehensive assessment of the FR status. The self-report measure for parents used in the present study was short and simple. Nevertheless, this study revealed significant FR effects on children's reading and mathematical skills that are comparable to those found in previous FR studies (Silinskas et al., 2010; Esmaeeli et al., 2018, 2019).

In this study, we were particularly interested in arithmetic fluency as it starts to develop in early grades and forms the foundation not only for more complex arithmetic skills (Carr and Alexeev, 2011) but also for mathematical reasoning (Powell et al., 2016). The defining feature of specific mathematical difficulty in the primary grades is a poorly developed subtraction and addition fluency (e.g., Jordan et al., 2003). However, a desirable goal is making the mathematical assessment more comprehensive by including, for example, a mathematical reasoning measure. The link between reading comprehension and mathematical reasoning has been previously reported (Pimperton and Nation, 2010) suggesting that the possible intergenerational connection of these skills could to be another avenue for future research. Finally, it is important to assess not only the quantity but also the quality of home learning activities, which represents a serious challenge but could be achieved in future research with the use of qualitative case studies (Siraj-Blatchford, 2010).

CONCLUSION

We have summarized visually the results of this study in **Figure 5**. The key finding is that FR for both reading and mathematical difficulties had direct effects on children's skills—the difference between groups with and without FR became apparent in the early grades and remained stable till the last time point of assessment in Grade 9. More specifically, FR for mathematical difficulties predicted both mathematical and reading comprehension difficulties in children, whereas FR for reading difficulties was predictive of children's reading fluency difficulties only. However, there were no indirect effects of FR via the home environment. Moreover, we failed to detect any effect of the FR status on the home environment. Another important finding is that shared reading was the only component of the home environment that predicted faster development of children's skills: more specifically, the reading comprehension in Grades 3 and 4. At the same time, more educated mothers and fathers spent more time reading with their children, whereas mothers with lower levels of education were more likely to focus on at-home teaching. These findings might appear somewhat counterintuitive and therefore call for more nuanced research of learning milieus at home. In particular, more attention needs to be paid on how to support the home learning activities of academically under-privileged parents who are trying their best to give their children a head start.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethical Committee of the University of Jyväskylä in 2006. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

DK drafted the first version of the current manuscript. MP, MT, and DK contributed to the data analysis. GS, M-KL, PN, A-MP, and MT were responsible for the data collection and commented on the manuscript. All authors contributed to the manuscript drafting, and read and approved the submitted version.

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Comorbid Learning Difficulties in Reading and Mathematics: The Role of Intelligence and In-Class Attentive Behavior

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The goal was to identify the domain-general cognitive abilities and academic attitudes that are common and unique to reading and mathematics learning difficulties that in turn will have implications for intervention development. Across seventh and eighth grade, 315 (155 boys) adolescents (*M* age = 12.75 years) were administered intelligence, verbal short-term and working memory, and visuospatial memory, attention, and ability measures, along with measures of English and mathematics attitudes and mathematics anxiety. Teachers reported on students' in-class attentive behavior. A combination of Bayesian and multi-level models revealed that intelligence and in-class attentive behavior were common predictors of reading accuracy, reading fluency, and mathematics achievement. Verbal short-term memory was more critical for reading accuracy and fluency, whereas spatial ability and mathematics self-efficacy were more critical for mathematics achievement. The combination of intelligence and in-class attentive behavior discriminated typically achieving students from students with comorbid (D = 2.44) or mathematics (D = 1.59) learning difficulties, whereas intelligence, visuospatial attention, and verbal short-term memory discriminated typically achieving students from students with reading disability (D = 1.08). The combination of in-class attentive behavior, verbal short-term memory, and mathematics self-efficacy discriminated students with mathematics difficulties from their peers with reading difficulties (D = 1.16). Given the consistent importance of in-class attentive behavior, we conducted *post hoc* follow-up analyses. The results suggested that students with poor in-class attentive behavior were disengaging from academic learning which in turn contributed to their risk of learning difficulties.

Keywords: learning difficulties, adolescence, reading achievement, mathematics achievement, cognition, attention, learning, memory

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INTRODUCTION

Academic competencies at the end of secondary school contribute to individuals' employability, wages, and the ability to pursue further education (Rivera-Batiz, 1992; Bynner, 1997; Ritchie and Bates, 2013; Stoet and Geary, 2020). Individuals with deficits in core academic domains, especially reading and mathematics, will face long-term hardships in many areas of life (Richmond-Rakerd et al., 2020). Interventions that reduce risk of academic difficulties thus have the potential for long-term benefits for at-risk individuals and the communities in which they will eventually reside. Fuchs et al. (2013, 2019) demonstrated that students' responsiveness to such interventions is influenced by their preexisting domain-general abilities, such as working memory, and that more effective interventions can be developed with the inclusion of supports that address any domain-general weaknesses (Fuchs et al., 2020). As an example, speeded (timed) practice of just-learned number knowledge benefited students with weak non-verbal reasoning abilities, whereas non-speeded practice did not.

More generally, individual differences in academic achievement, achievement growth, and grade-point average are related to domain-general cognitive abilities (e.g., working memory; Geary et al., 2017; Peng et al., 2019) and to non-cognitive factors, such as mathematics self-efficacy (Marsh and Yeung, 1998; Eccles and Wang, 2016; Semeraro et al., 2020). However, most of the learning difficulties research has focused on cognitive factors, such as poor working memory (Geary, 1993, 2004; Swanson et al., 2009a; Peng and Fuchs, 2016; Koponen et al., 2017), although non-cognitive factors are sometimes considered (Cirino et al., 2018; Devine et al., 2018). Even fewer studies have assessed the joint relations between domain-general cognitive abilities and non-cognitive factors and learning difficulties. We provided such an assessment for middle-school students and sought to determine the best combinations of domain-general cognitive and non-cognitive factors that characterize learning difficulties in mathematics, reading, and their comorbidity.

Learning Difficulties

In the United States, about 5% of students have school-identified specific learning disabilities (Grigorenko et al., 2020), but the percentage of at-risk students is much higher. This is because many students fail to achieve grade-level learning benchmarks for key subject areas. The U.S. National Assessment of Educational Progress, for instance, identifies 'basic' achievement levels as *partial* mastery of grade-level knowledge and skills.[1] The most recent assessments revealed that 27% and 28% of United States students were below basic levels of achievement in reading in 8th and 12th grade, respectively. For mathematics, 31% and 38% of students were below basic levels of achievement in 8th and 12th grade, respectively (United States Center for Educational Statistics, 2020).

Many students with below-basic academic competencies are not identified as having a specific learning disability and many of them might not meet the multiple criteria for diagnosis of such a disability (Grigorenko et al., 2020). Nevertheless, students with below basic levels of reading and mathematical competencies are at high risk of long-term difficulties in the labor market and in other areas of life (Berlin and Sum, 1988; Rivera-Batiz, 1992; Hanushek and Woessmann, 2008; Ritchie and Bates, 2013). In the study of the factors contributing to learning difficulties in mathematics, a commonly used cutoff is at or below the 25th percentile on a standardized achievement test (Geary et al., 2007; Murphy et al., 2007). A cutoff at this percentile is consistent with the percentage of United States students with below-basic academic competencies, and thus we adopted it for our analyses of reading, mathematics, and comorbid learning difficulties.

However, performance on achievement tests is continuous and generally normally distributed (Geary et al., 2012; Grigorenko et al., 2020), and thus cutoffs at any percentile are arbitrary, albeit useful for the identification and study of at-risk students. For this reason, we also use an individual differences approach to identify the domain-general cognitive and non-cognitive factors that are common and unique to reading and mathematics achievement.

Domain-General Cognitive Abilities

Individual differences in reading and mathematics achievement, as well as achievement growth, are related to intelligence and executive functions (Deary et al., 2007; Peng et al., 2018, 2019). Working memory–holding information in mind while engaged in other processes (Miyake et al., 2000)–is an important component of executive functions and is consistently related to academic learning (Paas and Ayres, 2014; Lee and Bull, 2016; Geary et al., 2017). Although the diagnosis of a specific learning disability typically involves the exclusion of students with very low IQ scores (Grigorenko et al., 2020), students with persistent learning difficulties often have modestly lower IQ scores than their typically achieving peers. Although IQ may contribute to their learning difficulties, it is not in and of itself a sufficient explanation (Stuebing et al., 2002; Murphy et al., 2007). Deficits in executive functions and especially working memory appear to be an additional contributing factor in both reading difficulties and mathematics difficulties (Swanson et al., 2009b; Geary et al., 2012).

There are also cognitive abilities that are relatively more important for reading or for mathematics achievement. Short-term verbal memory and verbal working memory contribute to various aspects of reading competence–assessed in individual differences and learning disability studies–and are more important than visuospatial memory (Carretti et al., 2009; Swanson et al., 2009b; Giofrè et al., 2018; Peng et al., 2018). Verbal short-term and working memory can contribute to some aspects of early number and arithmetic learning (Krajewski and Schneider, 2009; Allen et al., 2020), but these become relatively less important for mathematics learning in later grades. As the mathematics that students are expected to learn becomes more complex, visuospatial memory (Li and Geary, 2013, 2017) and more complex spatial abilities become increasingly important (Casey et al., 1997; Kyttälä and Lehto, 2008). The latter includes the ability to generate and manipulate visual images and is consistently correlated with mathematics achievement (Casey et al., 1997). The ability to control visuospatial attention is related to some aspects of number processing (Longo and Lourenco, 2007) and may also contribute to word reading (Friedrich et al., 1985).

Non-cognitive

Several non-cognitive measures were considered in this study, including academic attitudes, mathematics anxiety, and in-class

[1] https://nces.ed.gov/nationsreportcard/

attentive behavior. The attitudes included self-efficacy or confidence about one's abilities in English and mathematics, as well as beliefs about the future usefulness or utility of competence in English and mathematics (Eccles and Wigfield, 2002; Eccles and Wang, 2016). The relation between these attitudes and academic outcomes is typically bidirectional for older students and adults (Valentine et al., 2004; Talsma et al., 2018), but the relations are less certain across elementary and middle school students (Giofrè et al., 2017; Gunderson et al., 2018; Geary et al., 2019; Toste et al., 2020). Whatever the direction of the relations during schooling, in the long-term these attitudes can influence later occupational choices (Lauermann et al., 2017).

Mathematics anxiety is another factor that has been linked to variation in mathematics outcomes, although cause-and-effect relations are not yet fully understood (Ashcraft and Kirk, 2001; Ma and Xu, 2004; Dowker et al., 2016); unfortunately, we did not have a parallel measure for reading anxiety. Byrnes and Miller-Cotto (2016) recently found that internalizing problems, which includes anxiety, were associated with slower mathematics growth across the third- and eighth-grade academic years, controlling many other factors. Higher mathematics anxiety is also thought to result in an avoidance of mathematics coursework and math-intensive careers (Hembree, 1990; Meece et al., 1990).

On the basis of these findings, we might expect that students with learning difficulties would show lower academic self-efficacy and those with mathematics difficulties would show higher mathematics anxiety than their typically achieving peers, but this is not always the case. The academic self-efficacy of many students with learning difficulties (in any area) is overly optimistic relative to their actual achievement (Klassen, 2002). Devine et al. (2018) found that relative to typically achieving students, about twice as many students with mathematics learning difficulties showed high levels of mathematics anxiety. However, most of the students with difficulties did not show higher than average levels of mathematics anxiety and many of the anxious students had average or better mathematics achievement levels.

A final non-cognitive factor that contributes to academic achievement is in-class attention. Teacher ratings of students' in-class attentive behavior is consistently related to concurrent and longitudinal gains in mathematical achievement and is sometimes related to gains in reading achievement (Fuchs et al., 2006, 2016; Geary et al., 2013). The associated behaviors include sustained attention and attention to details during school activities, and distractibility in the classroom (Swanson et al., 2012). In-class attentive behavior is likely influenced by cognitive competencies, such as executive functions, but we included it as a non-cognitive measure because it captures aspects of students' behavioral engagement in the classroom that are not fully captured by cognitive measures of attentional control and working memory.

Attentional deficits and issues with behavioral self-control are common among students with reading, mathematics, and comorbid learning difficulties (Willcutt et al., 2013), and have long-term consequences. In a large-scale longitudinal study, Smart et al. (2017) found that the combination of learning difficulties and comorbid attentional and behavioral deficits resulted in a 16-fold increase in the odds of dropping out of school and a 2-fold increase in the odds of employment difficulties in early adulthood.

Current Study

The current study provides a broad assessment of the domain-general cognitive, as well as the non-cognitive factors, that are common and unique to individual differences in reading and mathematics achievement and in the prediction of comorbid learning difficulties. As noted, identifying the domain-general cognitive abilities that contribute to mathematics and reading achievement will have implications for the development of interventions for students who are at-risk for academic difficulties (Fuchs et al., 2013, 2019, 2020). The inclusion of non-cognitive factors greatly broadens the study of these at-risk students and could have implications for understanding their long-term engagement in the domain. For instance, above-average levels of mathematics anxiety could result in an avoidance of mathematics that over time will exacerbate knowledge-deficits in this domain (Hembree, 1990; Meece et al., 1990).

On the basis of prior studies, we anticipated that IQ and one or several measures of working memory (e.g., N-back) would emerge as common contributors to reading and mathematics achievement, and to comorbid learning difficulties. We also anticipated that one or several of the verbal short-term or working memory measures would be unique (or at least relatively more important) to reading achievement and difficulties, and that one or several of the visuospatial measures would be unique to mathematics achievement and difficulties. Among the non-cognitive measures, we anticipated in-class attentive behavior would emerge as important to mathematics and perhaps reading achievement but were less certain about the attitudes and anxiety measures, given the mixed findings in prior studies.

MATERIALS AND METHODS

Participants

The participants were 315 (155 boys) students enrolled in an on-going longitudinal study conducted in collaboration with the Columbia Public Schools in Columbia, MO, United States. They were recruited across two cohorts from a larger group of 1,926 students who participated in an assessment of sixth-grade mathematical competencies (see Geary et al., 2019). All 1,926 students were invited to join the longitudinal component of the study and 342 of them and their parents did so. The 315 students included here completed all of the seventh- and eighth-grade assessment sessions.

Demographic information was obtained through a parent survey. For the group of 315 students, 88% of them were non-Hispanic, 6% were Hispanic or Latino, and the ethnic status of the remaining students was unknown. The racial composition was 71% White, 14% Black, 3% Asian, 1% Native American, 10% multiracial, with the remaining unknown. As a comparison, students in the school district from which the participants were recruited were 61% white, 20% black, 5% Asian, 7% Hispanic, and 6% multiracial. For the current participants, parent-reported annual household income was distributed as follows: \$0–\$24,999

(9%); $25,000–$49,999 (15%); $50,000–$74,999 (9%); $75,000–$99,999 (19%); $100,000–$149,999 (17%); and $150,000+ (15%). Sixty-three percent of the students had at least one parent with a college degree. Fifteen percent of the families received food assistance, and five percent received housing assistance.

Materials

Standardized Measures

Intelligence

Full scale IQ was estimated using the Vocabulary and Matrix Reasoning subtests of the *Wechsler Abbreviated Scale of Intelligence* (WASI; Wechsler, 1999), following procedures detailed in the manual.

Achievement and disability groups

Mathematics and reading achievement were assessed using the Numerical Operations and Oral Reading Fluency subtests from the *Wechsler Individual Achievement Test–Third Edition* (Wechsler, 2009), respectively. The Numerical Operations items for students of this age included basic arithmetic and continued through fractions, algebra, geometry and calculus, solved with pencil and paper. For Oral Reading Fluency, the student read two passages (one at a time) under a time limit. Reading errors (added words, misstated words) were recorded by the experimenter and independently verified by review of an audio-recording of the read passages. The scores were reading accuracy [total word count − (total addition errors + total other errors)] and oral reading fluency [(total word count − total other errors)/total completion time]*60, which were highly correlated ($r = 0.68$, $p < 0.001$).

To identify groups with and without learning difficulties, we first examined the distribution of achievement scores for the current sample, focusing on the 25th percentile (Geary et al., 2007; Murphy et al., 2007). For Numerical Operations, students at the 25th percentile of the current sample were at the 18th percentile based on national norms. Students at or below this cutoff were considered to have mathematics difficulties ($N = 84$). Using the same 18th percentile cutoff based on national norms, 95 students were identified as having reading difficulties based on reading accuracy scores. Only 26 students scored at or below this cutoff for reading fluency and 25 of them were included in the reading difficulties group based on reading accuracy. Thus, the reading difficulties group was determined based solely on reading accuracy, although we still conducted individual differences analyses for Oral Reading Fluency scores.

Forty-six students fell into both groups and were classified as having comorbid learning difficulties [National Percentile Ranks = 6.60 ($SD = 4.70$) and 8.18 ($SD = 5.46$) for mathematics and reading, respectively]. Forty-nine students fell into the reading but not mathematics group and were classified as having reading difficulties [National Percentile Ranks = 47.45 ($SD = 21.91$) and 9.06 ($SD = 5.38$) for mathematics and reading, respectively]. Thirty-eight students fell into the mathematics but not reading group and were classified as having mathematics difficulties [National Percentile Ranks = 10.58 ($SD = 5.37$) and 40.53 ($SD = 17.55$) for mathematics and reading, respectively]. As a comparison group, we used the 182 students who did not fall into any of the difficulties groups [National Percentile Ranks = 64.60 ($SD = 26.31$) and 48.35 ($SD = 18.65$) for mathematics and reading, respectively].

Cognitive Measures

All of the tasks are standard measures of short-term and working memory, verbal memory, and various aspects of spatial ability. Most of the tasks were administered on iPads using customized programs developed through Inquisit by Millisecond.[2] The verbal memory task was administered using a customized program developed in Qualtrics;[3] manuals are available on OSF.[4] With the exception of N-back which was only administered in seventh grade (due to time constraints), all tasks were administered in seventh and eighth grade. The score was the mean across the two grades, which should provide a more stable estimate of their abilities in these areas than will scores for any single grade. We estimated the reliabilities (ρ) of these summary scores using the Spearman–Brown Prophecy formula applied to the test–retest correlations across grades.

The assessment of verbal short-term memory included a measure of passive memory for strings of words, as well as the more standard forward digit span measure, whereas the assessment of visuospatial memory included a forward spatial span task (Gathercole et al., 2004). The working memory measures involved the active retention of information, while processing other information and included the standard backward digit span measure and N-back. The latter engages brain regions typically associated with working memory but are not identical to those engaged in the digit span task (Yaple and Arsalidou, 2018). The inclusion of both measures thus provided a broader assessment of working memory than the inclusion of only one of them. The broad assessment of working memory is potentially important because it is more consistently related to outcomes in mathematics than are other executive functions (e.g., inhibition; Bull and Lee, 2014). The spatial ability measures assessed visuospatial attention and the ability to generate and manipulate images (Hegarty, 2018), and these too are predictive of outcomes in mathematics (Casey et al., 1997; Kyttälä and Lehto, 2008).

Digit span

The students hear a sequence of digits presented at 1 s intervals, starting with three digits for the forward assessment and two digits for the backward assessment. The task is to recall the digit list in order (in either a forward or backward manner, respectively) by tapping the digits on a circle of digits displayed on the iPad screen. If the response is correct, the student moves up to the next level. If the response is incorrect, the same level is presented a second time. If a consecutive error occurs, the student moves down to a lower level. Each direction (forward and then backward) ends after 14 trials. The score was the highest digit span correctly recalled before making two consecutive errors

[2]https://www.millisecond.com
[3]https://www.qualtrics.com
[4]https://osf.io/qwfk6/

at the same span length. Estimated reliabilities for the current sample were adequate for both forward ($\rho = 0.68$) and backward ($\rho = 0.73$) digit span.

Verbal memory

The verbal memory measure was taken from a longer proactive inhibition task. The student listens to a recording of a set of four animal words, presented in 1-s intervals using the iPad speakers. To prevent rehearsal, the student immediately names colors from a sheet with rows of different colors for 10 s. After 10 s, a tone prompts the student to recall the words, in order. Responses are recorded by the experimenter using Qualtrics on the iPad. The process is repeated with two new sets of four animal words, and finally with a set of four fruit words. Items were taken from Paivio et al. (1968) and Gilhooly and Logie (1980). The words were chosen based on Imagery (I) and Concreteness (C) ratings (1 to 7 scale), with all scores > 6. The one exception was 'lime' (imagery of 5.7), which was included because it was the closest (to 6.0) available one-syllable fruit word. Each quartet included one moderate to high frequency word and three low frequency words ($<$10/million), and three 1-syllable and one 2-syllable words. All within-list words started with different letters and presentation orders were initially randomized, and subsequently presented in the same order to all students. We used percent correct on the first quartet of words as a measure of short-term verbal memory ($\rho = 0.40$ for the current sample). The ρ is low but the internal consistency of the measure, based on the eight trials across grades, is adequate ($\alpha = 0.66$).

We did not use performance on the three other quartets of words because there were (as expected) memory interference effects for these quartets and thus they did not provide measures of basic verbal memory.

N-back

Following Jaeggi et al. (2010), students completed an adaptive version of a single N-back task. The student is shown a "target" letter and then a sequence of 20 randomly determined stimulus letters (all consonants; 6 are target; 14 are not) and asked to indicate whether the currently presented letter is a target by tapping a key, or is not a target by not responding. The target letter could be the first stimuli presented ($N = 0$) or could be the same as the one that preceded it ($N = 1$) or the same as one presented in the 2 ($N = 2$) or 3 ($N = 3$) trials that preceded it.

For each trial a letter is presented for 500 ms, followed by a 2,500 ms blank screen, and then by the next letter in the sequence. Students have the entire 3,000 ms to respond by tapping a key if they detect a target. After three 10-item practice blocks for levels $N = 0$ to $N = 2$, all participants start on level $N = 0$. Depending on performance, they move up, stay on the current level, or move down a level for five total blocks ($<$3 errors – move up; 3–5 errors – repeat level; $>$5 errors – move down). Performance feedback (percent correct) is displayed after each block. Hits (H), Misses, False Alarms (FA), and Correct Rejections are recorded and summarized by block. The score is (H – FA)/(total blocks). The estimated split-half reliability for the current sample was 0.74.

Spatial span

Spatial span was assessed using the forward Corsi Block Tapping Task (Kessels et al., 2000). Students are presented with a display of nine squares that appear to be randomly arranged. The squares "light up" in a pre-determined sequence, and the task is to tap on the squares in the same order they were lit. The sequence length starts at two squares and could increase to up to nine squares. Students have two attempts at each sequence length. If one of the sequences is recalled correctly, the next sequence level begins; if both sequences at the same level are recalled incorrectly, the task is terminated. The score is the total number of correctly recalled sequences across the whole task ($\rho = 0.67$ for the current sample).

Spatial ability

Judgment of Line Angle and Position Test (JLAP) was the first spatial measure (Collaer et al., 2007), and assesses visuospatial attention (Benton et al., 1978). The task requires students to match the angle of the single presented line to 1 of 15-line options in an array at the bottom center of the iPad screen. The 20 test items are presented one at a time, and the student uses the touch screen to select the matching angle. Each stimulus is presented for up to 10 s, and when a selection is made, a reaction time is recorded, and the next stimulus is immediately presented. The outcome is the number correct ($\rho = 0.71$ for the current sample).

The Mental Rotation Task (MRT-A; Peters et al., 1995) was the second spatial measure, and assesses the ability to generate and manipulate images (Hegarty, 2018). On each trial, the student views images of 3D drawings of 10 connected cubes. For each trial, there is one target and four choice options, and the task is to select the two options that are rotations of the target figure. After four self-paced practice problems, students are presented with 24 problems in two blocks of 12 problems each (3 min per block). The score is the number of problems on which the student chose both correct options ($\rho = 0.83$ for the current sample).

Non-cognitive Measures

Due to assessment delays related to the Covid-19 pandemic, we only have attitudes and anxiety data for seventh grade.

Academic attitudes

Mathematics and English attitudes were assessed using measures from the Michigan Study of Adolescent and Adult Transitions.[5] The measures are designed to assess students' self-efficacy in and their beliefs about the long-term utility of these areas (Meece et al., 1990; Eccles and Wigfield, 2002). The mathematics measure included seven items on a 1-to-7 Likert scale; e.g., "How much do you like doing math?" rated from 1 (a little) to 7 (a lot), with the six English items being similar.

Previous analyses using an exploratory principle components factor analysis (EFA), as well as parallel and MAP analyses (R Core Team, 2017), indicated that the mathematics items defined two factors and the English items one factor (Geary et al., 2020). For mathematics attitudes, the loadings of individual items on their respective factors were consistent with distinct utility (Items 1 to 4, inclusive) and self-efficacy (Items 5 to 7) dimensions. The

[5] http://garp.education.uci.edu/msalt.html

scores were the sum of the corresponding items (α = 0.71 for utility, and 0.78 for self-efficacy). The English attitudes score was the mean of the six items (α = 0.83).

Mathematics anxiety

The 10 items were adapted from Hopko et al. (2003). Each item (e.g., "Taking an examination in a math course") was rated on a 1 (low anxiety) to 5 (high anxiety) scale (Geary et al., 2019). All three analyses (i.e., EFA, MAP, parallel) indicated two factors. The first included five items that involved learning mathematics (e.g., "Watching a teacher work an algebraic equation on the board"; items 1, 3, 6, 7, 9) and the second four items that involved some type of evaluation (e.g., "Taking an examination in a math course"; items 2, 4, 5, 8), and the final item (i.e., "In general, how anxious are you about math?"). Composite scores were based on the mean of the five learning anxiety items (α = 0.77) and the five evaluation anxiety items (α = 0.86). The two core factors identified here are consistent with previous findings (Baloglu and Koçak, 2006).

In-class attentive behavior

In-class attentive behavior was assessed using the Strength and Weaknesses of ADHD-Symptoms and Normal-Behavior (SWAN) measure (Swanson et al., 2012). The items assess attentional deficits and hyperactivity, but the scores are normally distributed and based on the behavior of a typical student. The nine item (e.g., "Gives close attention to detail and avoids careless mistakes") attention subscale was distributed to the students' seventh-grade and eighth-grade mathematics and English language arts teachers who were asked to rate the behavior of the student relative to other students of the same age on a 1 (far below) to 7 (far above) scale. Ratings were consistent across items (αs = 0.98), mathematics and language arts teachers within grades (*r*s = 0.69 to 0.73), and across grades (*r*s = 0.67 to 0.88). Given this consistency, we calculated one in-class attentive behavior score based on mean ratings across teachers and grades (α = 0.92).

Procedure

In seventh grade, the students were administered the intelligence, achievement, attitudes, anxiety, and cognitive measures individually at a quiet location in their school across three 45-min assessments. As shown in **Table 1**, with the exception of the verbal memory task (due to time constraints), the cognitive measures were administered during the first semester of seventh grade, and the remaining measures during the second semester. In eighth grade, all of the cognitive tasks were assessed in the fall semester and the achievement measures in the spring. In the spring of both grades, students competed the attitudes and anxiety measures and teachers completed the in-class attentive behavior survey.

Parents provided informed written consent, and assent was obtained from adolescents for all assessments. The University of Missouri Institutional Review Board (IRB; Project 2002634, "Algebraic Learning and Cognition") approved all methods included in this study.

TABLE 1 | Age of administration and timing of assessments.

Task name	Seventh grade		Eighth grade	
	Fall	**Spring**	**Fall**	**Spring**
Mean age at test	153	156	164	168
Digit span forward	x		x	
Digit span backward	x		x	
N-back	x			
Spatial span	x		x	
Judgment of Line Angle and Position	x		x	
Mental Rotations Test	x		x	
Verbal memory		x	x	
Intelligence		x		
Oral Reading Fluency				x
Numerical Operations				x
In-class attentive behavior		x		x
Mathematics efficacy		x		x
Mathematics utility		x		x
English attitudes		x		x
Mathematics anxiety for learning		x		x
Mathematics anxiety for evaluation		x		x

Age is in months, SDs range between 4.47 and 4.96 months.

Analyses

The first goal was to identify common and unique predictors of individual differences in reading and mathematics achievement. To do so, we first used Bayesian regressions to identify the best set of cognitive and non-cognitive predictors of achievement (Gallistel, 2009; Rouder and Morey, 2012). For this we used the *BayesFactor* package in R (v0.9.12-4.2; Morey and Rouder, 2015) with default prior scales for standardized slopes (r_{scale} = 1/2). Bayes Factors provide information regarding whether the inclusion of specific predictors improves model fit above and beyond other predictors simultaneously considered in the model. This method is more robust than standard linear regression with correlated variables. Bayes Factors are higher when one of two highly correlated variables are included in relation to models containing both or none, providing the ability to compare the relative contribution of individual predictors. In separate analyses, we selected the best combination of cognitive and then non-cognitive predictors of standardized eighth-grade Oral Reading Fluency and Numerical Operations scores. The variables identified from each of these analyses were subsequently used in a follow-up analysis to identify the best combination of cognitive and non-cognitive predictors of these achievement scores. The sequence of analyses provides structured, step-by-step information on the best set of cognitive, non-cognitive, and combined predictors of individual differences in achievement. The results are identical to those that would emerge if all variables were considered simultaneously, but the approach used here provides more information regarding the relative importance of different combinations of cognitive and non-cognitive variables.

The first set of Bayes Factors are noted as MC_m, where m = the specific set of cognitive (C) predictors in the model (M) and comparisons as BC_{mn}, with B representing the comparison ratio of Bayes Factors between models m and n. BC_{m0} represents a contrast of the selected model to a null model with no predictors. These analyses assess the likelihood of the data for alternative models. For the cognitive measures, the initial analysis included digit span forward, digit span backward, N-back, Corsi, JLAP, MRT, verbal memory, and IQ as potential predictors. The first model identified the most probable subset of these variables as predictors of the achievement outcome. For the non-cognitive measures, we included all of the English and math attitudes and math anxiety variables in the prediction of both math and reading achievement as a way to assess the convergent and discriminant validity of these variables. That is to determine if students are making subject-specific discriminations in their self-reports (they were, below).

For instance, the full model (including all selected cognitive predictors from the first regression) MC_1 for the prediction of Oral Reading Accuracy included digit span forward, JLAP, verbal memory, and IQ. Each of these predictors were then dropped one-by-one and change in the odds of the model was evaluated. Dropping IQ resulted in model MC_2 and the comparison to the full model as BC_{21}. The latter resulted in a Bayes Factor ratio of 5.17×10^6, meaning the model without IQ was <1% as probable as the model with it. Dropping verbal memory resulted in a model that was 32.35% as probable (MC_{31}) or stated differently the model including verbal memory was preferred 3.09 times to 1 over the model without it. Here, lower Bayes Factors indicate greater evidence for a predictor. As a rule of thumb, models that are less than 33% as probable without the variable provide evidence for retaining it, and models that are less than 10% as probable provide strong evidence for retaining it (Jeffreys, 1961; Raftery, 1995). We used the 33% criterion for variable retention, corresponding to a commonly used cutoff for positive evidence (e.g., Bayes factor of three, Kass and Raftery, 1995); stated differently, to be retained the model with the variable had to be preferred at least 3 to 1 over the model without it.

Once the best set of predictors was identified, we used multi-level models to estimate the relative importance of the common and unique predictors of Oral Reading Accuracy and Numerical Operations and Oral Reading Fluency and Numerical Operations scores using Proc Mixed (SAS Institute, 2014). Students were distributed among six schools and there were small but significant school differences for Oral Reading Accuracy, $F(5,309) = 3.84$, $p = 0.002$, $r^2 = 0.06$, and Numerical Operations, $F(5,309) = 5.42$, $p < 0.001$, $r^2 = 0.08$. To model these effects, students were assigned as level 1 units and schools as level 2 units in the multi-level models, which allowed intercepts to vary randomly for schools. Achievement scores and predictor variables were centered ($M = 0$, $SD = 1$) and Oral Reading Accuracy (or Fluency) and Numerical Operations scores were nested in an overall achievement variable. Differences across reading and mathematics achievement were estimated with test by predictor interactions. Initially, all variables identified in the Bayesian analyses were included as fixed effects, along with the interactions with test. Non-significant interactions were dropped and changes in model fit were assessed using the Bayesian Information Criterion (smaller values indicate better fit) and negative log likelihood estimate. For nested models, values for the latter can be evaluated using a χ^2 statistic (Wilks, 1938).

Next, logistic regressions were used to predict inclusion or not in each of the three learning difficulties groups (i.e., comorbid difficulties, reading difficulties, mathematics difficulties) relative to the group of typically achieving students, and inclusion in the mathematics difficulties as compared to the reading difficulties group. The variables used in each regression were based on the results from the Bayesian and multi-level models. These sets of variables provide the best estimate of the combination of factors that predict different forms of learning difficulty and a means to estimate the relative importance of each individual predictor. Moreover, the Cohen's *d* of the log odds of group membership is identical to the multivariate Mahalanobis distance (i.e., multivariate *d*) and thus provides a multivariate estimate of the magnitude of the differences across the students in the learning difficulties groups and students in the typically achieving group.

RESULTS

Mean scores across measures are shown in **Table 2** for the entire sample and the samples of typically achieving and learning difficulty groups. Whole-sample correlations among the measures are shown in **Figure 1**.

Bayesian Regressions

Oral Reading Accuracy

As noted, the best set of cognitive predictors of Oral Reading Accuracy scores were digit span forward, JLAP, verbal memory, and IQ (see **Table 3**). The BC_{m0} is very large for this first model and all alternative models, providing strong evidence for some combination of cognitive predictors of Oral Reading Accuracy relative to the null. Dropping IQ and digit span forward resulted in models that were <1% as probable as the models without them. Dropping verbal memory and JLAP resulted in models that were 32.35% (MC_{31}) or 14.05% (MC_{41}) as probable as the models with them; or stated otherwise, the models including verbal memory and JLAP were preferred 3.09 and 7.12 times to 1 relative to models without them. On the basis of these results, all four variables were retained for the combined analyses.

The second section of **Table 3** indicates that the best set of non-cognitive predictors of Oral Reading Accuracy included mathematics anxiety for learning, English attitudes, and in-class attentive behavior. Dropping the latter resulted in a model (MNC_2) that was <1% as probable as the model with it. However, dropping mathematics anxiety and English attitudes resulted in models that were 59.46% (MNC_3) and 83.27% (MNC_4), respectively, as probable as the models with them respectively; or stated otherwise, the models including mathematics anxiety and English attitudes were preferred 1.68 and 1.20 times to 1 relative to models without them. The two latter results indicate that inclusion of these variables does not add substantively to the prediction of Oral Reading Accuracy and thus only in-class attentive behavior was retained for the combined analyses.

TABLE 2 | Means for cognitive and non-cognitive measures.

Measure	Overall (*N* = 315) *M* (*SD*)	Typically achieving (*N* = 182) *M* (*SD*)	Comorbid difficulty (*N* = 46) *M* (*SD*)	*d*	Reading difficulty (*N* = 49) *M* (*SD*)	*d*	Math difficulty (*N* = 38) *M* (*SD*)	*d*
Achievement								
Oral Reading Accuracy	92.71 (12.52)	99.65 (8.49)	77.35 (6.73)	1.78	78.47 (5.96)	1.69	96.42 (7.91)	0.26
Oral Reading Fluency	103.58 (11.79)	108.59 (8.49)	89.93 (10.84)	1.58	96.08 (10.04)	1.06	105.76 (10.87)	0.24
Numerical Operations	98.85 (18.22)	108.64 (14.81)	75.20 (7.16)	1.84	99.37 (9.44)	0.51	79.95 (5.77)	1.57
Cognitive								
Intelligence	105.07 (13.09)	110.77 (10.70)	90.33 (10.43)	1.56	102.27 (11.28)	0.65	99.21 (11.01)	0.88
N-back	3.80 (0.76)	3.95 (0.76)	3.38 (0.71)	0.75	3.72 (0.72)	0.30	3.68 (0.66)	0.36
Digit span forward	5.86 (0.99)	6.16 (0.97)	5.14 (0.76)	1.03	5.46 (0.82)	0.71	5.83 (0.90)	0.33
Digit span backward	4.72 (1.12)	5.14 (1.07)	3.78 (0.80)	1.21	4.30 (0.78)	0.75	4.38 (1.06)	0.68
Verbal memory	0.68 (0.23)	0.74 (0.20)	0.53 (0.25)	0.91	0.61 (0.21)	0.57	0.65 (0.24)	0.39
Spatial span	8.83 (1.96)	9.26 (1.91)	7.61 (1.94)	0.84	8.76 (1.65)	0.26	8.34 (1.91)	0.47
Judgment of Line Angle	13.57 (2.86)	14.45 (2.70)	11.74 (2.48)	0.95	12.74 (2.95)	0.59	12.63 (2.32)	0.64
Mental Rotation Test	9.88 (4.31)	11.00 (4.27)	6.41 (2.60)	1.06	9.85 (3.95)	0.27	8.76 (4.17)	0.52
Non-cognitive								
In-class attentive behavior	4.90 (1.35)	5.49 (1.07)	3.32 (1.15)	1.61	4.89 (1.03)	0.44	3.97 (1.12)	1.13
Math utility	5.25 (0.97)	5.36 (0.96)	4.89 (0.93)	0.48	5.48 (0.82)	−0.12	4.89 (1.09)	0.48
Math efficacy	5.02 (1.02)	5.23 (0.87)	4.38 (1.01)	0.83	5.18 (0.94)	0.05	4.48 (1.27)	0.74
English attitudes	5.06 (1.11)	5.19 (1.00)	4.88 (1.22)	0.28	4.85 (1.10)	0.31	4.92 (1.38)	0.24
Math anxiety for evaluation	2.61 (0.96)	2.54 (0.95)	2.80 (0.96)	−0.27	2.55 (0.94)	−0.01	2.81 (1.02)	−0.28
Math anxiety for learning	1.71 (0.65)	1.58 (0.55)	2.07 (0.73)	−0.75	1.70 (0.69)	−0.18	1.91 (0.76)	−0.51

$d = (M_{Typical} - M_{Difficulty})$/pooled SD. The achievement and intelligence scores are standardized based on national norms (M = 100, SD = 15). Raw scores are presented for all other variables.

The combined analysis included digit span forward, JLAP, verbal memory, IQ, and in-class attentive behavior. As shown in **Table 3**, the best model included all five predictors. However, dropping verbal memory resulted a model that was 66.06% (MA_4) as probable as the model with it, and thus this variable was dropped. The other models provide evidence for the retention of the remaining variables.

Oral Reading Fluency

The bottom sections of **Table 3** show the Bayesian results for the prediction of Oral Reading Fluency scores. The best set of cognitive predictors included digit span forward, verbal memory, and IQ. The BC_{m0} is very large for this first model and all alternative models, providing strong evidence for some combination of cognitive predictors of Oral Reading Fluency. As can be seen, there is strong evidence for the retention of each of these variables.

The next section of **Table 3** shows that the top set of non-cognitive predictors of Oral Reading Fluency included mathematics utility, English Attitudes, mathematics anxiety for evaluation, and in-class attentive behavior. Dropping each of these variables in turn resulted in models that were <12.76% as probable as the model with them, or models with each of these predictors are preferred at least 7.84 to 1 over models without them. Thus, all were retained for the combined analysis.

The combined analyses included digit span forward, verbal memory, IQ, mathematics utility, English Attitudes, mathematics anxiety for evaluation, and in-class attentive behavior. As shown in the final section of **Table 3**, all of these predictors were in the best model, except for mathematics utility and mathematics anxiety for evaluation. Dropping each of the remaining predictors in turn resulted in models that were <32.17% as probable as the models with them; or stated otherwise, the models with each of these predictors were preferred at least 3.11 to 1 over the models without them.

In all, digit span forward, IQ, and in-class attentive behavior were common predictors of Oral Reading Accuracy and Oral Reading Fluency, whereas JLAP was unique to the former and Verbal Memory and English Attitudes to the latter.

Numerical Operations

A summary of the Bayesian models for the prediction of Numerical Operations scores is presented in **Table 4**. The first of these sections shows that the best set of cognitive predictors included digit span forward, JLAP, MRT, verbal memory, and IQ. Dropping IQ resulted in a substantive reduction in model fit (<1% as probable as the model with it). Dropping verbal memory (55.09% as probable, or the model with it is preferred 1.82 to 1 relative to the model without it) and digit span forward (79.40% as probable, or the model with it is preferred 1.26 to 1 relative to the model without it) resulted in models that were not substantively different than the models with them. There was positive evidence for the retention of MRT (19.09% as probable, or the model with it is preferred 5.24 to 1 to the model without it) and JLAP (10.31% as probable, or the model with it is preferred 9.7 to 1 to the model without it). On the basis of these findings, JLAP, MRT, and IQ were retained for the final analyses.

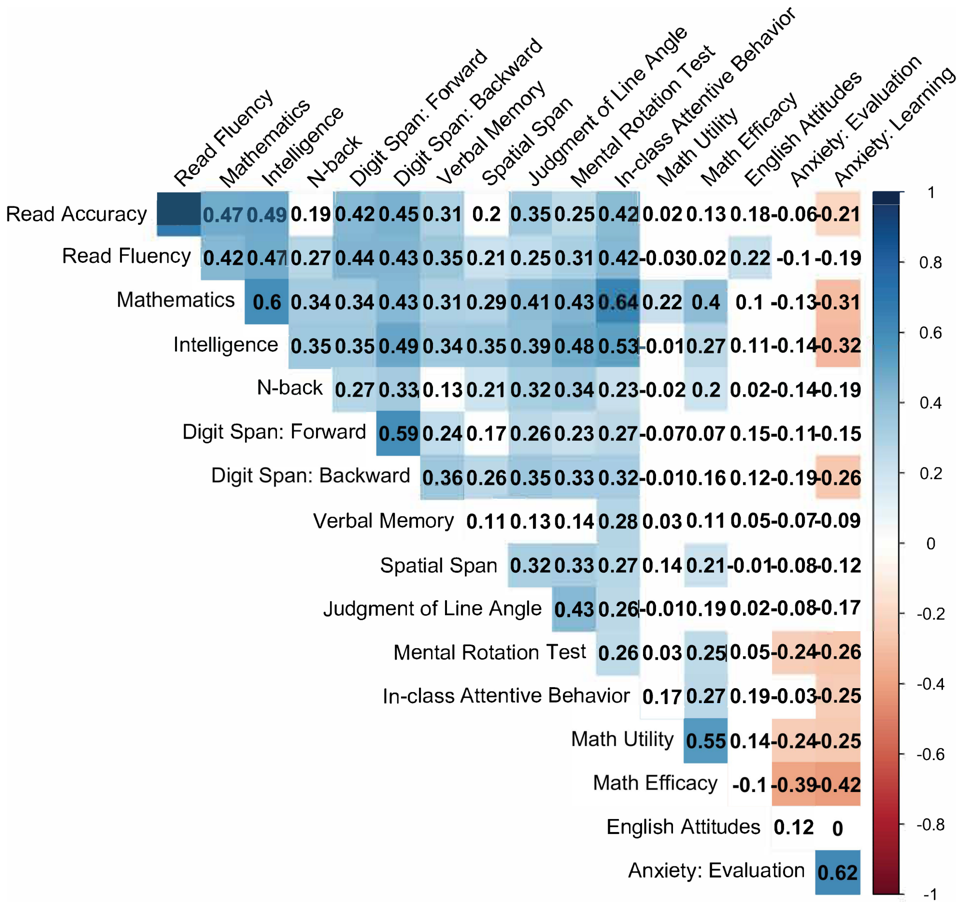

FIGURE 1 | Correlations among predictors and reading and mathematics achievement.

As shown in **Table 4**, there was strong evidence for the inclusion of mathematics self-efficacy and in-class attentive behavior among the non-cognitive predictors of Numerical Operations scores. Thus, the final combined analyses included JLAP, MRT, IQ, mathematics self-efficacy, and in-class attentive behavior. The best model included all of these variables. Dropping each of the predictors resulted in models that were less than 26.57% as probable as models with them; in other words, the models with them were preferred at least 3.76 to 1 over the models without them.

Intelligence and Working Memory

On the basis of prior research, we anticipated one or several of the working memory measures would emerge as predictors of reading and mathematics achievement (Swanson et al., 2009b; Lee and Bull, 2016; Geary et al., 2017). This was the case for Oral Reading Fluency but not for Oral Reading Accuracy or Numerical Operations scores. One possibility is that inclusion of IQ in the analyses obscured any relation between working memory and these outcomes, given the correlation between performance on IQ and working memory measures (Ackerman et al., 2005). To assess this possibility, we conducted *post hoc* analyses for Oral Reading Accuracy and Numerical Operations, dropping IQ.

For Oral Reading Accuracy, dropping IQ resulted in the identification of digit span backward as a predictor, along with digit span forward, JLAP and in-class attentive behavior as in the original analyses. Similarly, there was no change in the best model for predicting Numerical Operations scores, except that digit span backward replaced IQ.

Multi-Level Models

Oral Reading Accuracy and Numerical Operations

The Bayesian analyses identified IQ, in-class attentive behavior, and JLAP as common predictors of Oral Reading Accuracy and Numerical Operations scores, and digit span forward as unique to reading achievement and MRT and mathematics self-efficacy as unique to mathematics achievement. These six variables along with achievement test (reading = 0, mathematics = 1) and test by variable interactions were included in the multi-level models.

The full model revealed non-significant interactions between test and IQ ($p = 0.391$) and test and JLAP ($p = 0.599$). Dropping these two interactions did not substantively change overall model fit [ΔBIC = 2.4, $\chi^2(2) = 1.1$, $p = 0.577$]. The estimates associated with the model that did not include these interactions are shown in **Table 5**. The highly significant main effects,

TABLE 3 | Bayes factor analyses of predictors of oral reading achievement.

Oral Reading Accuracy			
Model: Top Cognitive Predictors	**BC_{m0}**	**Excluded**	**BC_{m1}**
MC_1 DSF + JLAP + Verbal memory + IQ	6.92×10^{23}	–	1
MC_2 DSF + JLAP + Verbal memory	3.58×10^{18}	IQ	0.0000
MC_3 DSF + JLAP + IQ	2.24×10^{23}	Verbal memory	0.3235
MC_4 DSF + Verbal memory + IQ	9.72×10^{22}	JLAP	0.1405
MC_5 + JLAP + Verbal memory + IQ	4.76×10^{19}	DSF	0.0000
Model: Top Non-cognitive Predictors	**BNC_{m0}**	**Excluded**	**BNC_{m1}**
MNC_1 English attitudes + MAnxLearn + Attentive behavior	1.01×10^{12}	–	1
MNC_2 English attitudes + MAnxLearn	2.49×10^{3}	Attentive behavior	0.0000
MNC_3 English attitudes + Attentive behavior	5.98×10^{11}	MAnxLearn	0.5946
MNC_4 MAnxLearn + Attentive behavior	8.38×10^{11}	English attitudes	0.8327
Model: Top Combined Predictors	**BA_{m0}**	**Excluded**	**BA_{m1}**
MA_1 DSF + JLAP + Verbal memory + IQ + Attentive behavior	1.37×10^{25}	–	1
MA_2 DSF + JLAP + Verbal memory + IQ	6.92×10^{23}	Attentive behavior	0.0504
MA_3 DSF + JLAP + Verbal memory + Attentive behavior	1.03×10^{23}	IQ	0.0075
MA_4 DSF + JLAP + IQ + Attentive behavior	9.07×10^{24}	Verbal memory	0.6606
MA_5 DSF + Verbal memory + IQ + Attentive behavior	2.67×10^{24}	JLAP	0.1948
MA_6 JLAP + Verbal memory + IQ + Attentive behavior	2.07×10^{21}	DSF	0.0002
Oral Reading Fluency			
Model: Top Cognitive Predictors	**BC_{m0}**	**Excluded**	**BC_{m1}**
MC_1 DSF + Verbal memory + IQ	2.66×10^{24}	–	1
MC_2 DSF + Verbal memory	7.03×10^{17}	IQ	0.0000
MC_3 DSF + IQ	4.57×10^{22}	Verbal memory	0.0172
MC_4 Verbal memory + IQ	4.45×10^{18}	DSF	0.0000
Model: Top Non-cognitive Predictors	**BC_{m0}**	**Excluded**	**BC_{m1}**
MNC_1 MUtility + English attitudes + MAnxEval + Attentive behavior	1.22×10^{14}	–	1
MNC_2 MUtility + English attitudes + MAnxEval	4.10×10^{2}	Attentive behavior	0.0000
MNC_3 MUtility + English attitudes + Attentive behavior	1.56×10^{13}	MAnxEval	0.1276
MNC_4 MUtility + MAnxEval + Attentive behavior	1.86×10^{12}	English attitudes	0.0152
MNC_5 English attitudes + MAnxEval + Attentive behavior	9.21×10^{12}	MUtility	0.0752
Model: Top Combined Predictors	**BA_{m0}**	**Excluded**	**BA_{m1}**
MA_1 DSF + Verbal memory + IQ + English attitudes + Attentive behavior	3.30×10^{26}	–	1
MA_2 DSF + Verbal memory + IQ + English attitudes	2.40×10^{25}	Attentive behavior	0.0727
MA_3 DSF + Verbal memory + IQ + Attentive behavior	1.06×10^{26}	English Attitudes	0.3217
MA_4 DSF + Verbal memory + English attitudes + Attentive behavior	8.01×10^{23}	IQ	0.0024
MA_5 DSF + IQ + English attitudes + Attentive behavior	2.21×10^{25}	Verbal memory	0.0366
MA_6 Verbal memory + IQ + English attitudes + Attentive behavior	5.42×10^{21}	DSF	0.0000

DSF, Digit Span Forward; JLAP, Judgment of Line Angle and Position Test; MRT, Mental Rotation Test; MAnxLearn, Mathematics Anxiety for Learning; MAnxEval, Mathematics Anxiety for Evaluation; MUtility, Mathematics Utility; MC, Models for cognitive variables; MNC, Models for non-cognitive variables; MA, Models for all, that is, top cognitive and non-cognitive variables.

without significant interactions for IQ and JLAP ($ps < 0.001$), confirm the importance of these variables in the prediction of overall achievement, that is, achievement across reading and mathematics.

The significant interactions indicate that the relative importance of the predictor varies across reading and mathematics achievement, with positive estimates indicating larger effects in the prediction of reading achievement and negative estimates indicating larger effects in the prediction of mathematics achievement. The interactions are consistent with the Bayesian analyses, with digit span forward being relatively more important for the prediction of reading accuracy and MRT and mathematics self-efficacy for mathematics achievement. In-class attentive behavior predicts reading and mathematics

TABLE 4 | Bayes factor analyses of predictors of mathematics achievement.

Numerical Operations			
Model: Top Cognitive Predictors	**BC_{m0}**	**Excluded**	**BC_{m1}**
MC_1 DSF + JLAP + MRT + Verbal memory + IQ	1.80×10^{32}	–	1
MC_2 DSF + JLAP + MRT + Verbal memory	3.08×10^{22}	IQ	0.0000
MC_3 DSF + JLAP + MRT + IQ	9.94×10^{31}	Verbal memory	0.5509
MC_4 DSF + JLAP + Verbal memory + IQ	3.45×10^{31}	MRT	0.1909
MC_5 DSF + MRT + Verbal memory + IQ	1.86×10^{31}	JLAP	0.1031
MC_6 JLAP + MRT + Verbal memory + IQ	1.43×10^{32}	DSF	0.7940
Model: Top Non-cognitive Predictors	**BC_{m0}**	**Excluded**	**BC_{m1}**
MNC_1 Math efficacy + Attentive behavior	3.23×10^{40}	–	1
MNC_2 Math efficacy	7.32×10^{10}	Attentive behavior	0.0000
MNC_3 Attentive behavior	4.17×10^{34}	Math efficacy	0.0000
Model: Top Combined Predictors	**BA_{m0}**	**Excluded**	**BA_{m1}**
MA_1 JLAP + MRT + IQ + Math Efficacy + Attentive behavior	7.81×10^{51}	–	1
MA_2 JLAP + MRT + IQ + Math efficacy	3.12×10^{36}	Attentive behavior	0.0000
MA_3 JLAP + MRT + IQ + Attentive behavior	3.54×10^{48}	Math efficacy	0.0005
MA_4 JLAP + MRT + Math efficacy + Attentive behavior	3.72×10^{48}	IQ	0.0005
MA_5 JLAP + IQ + Math efficacy + Attentive behavior	2.07×10^{51}	MRT	0.2657
MA_6 MRT + IQ + Math efficacy + Attentive behavior	1.16×10^{51}	JLAP	0.1485

DSF, Digit Span Forward; JLAP, Judgment of Line Angle and Position Test; MRT, Mental Rotation Test; MC, Models for cognitive variables; MNC, Models for non-cognitive variables; MA, Models for all, that is, top cognitive and non-cognitive variables.

achievement, but the interaction reveals that it is relatively more important for mathematics.

Oral Reading Fluency and Numerical Operations

The Bayesian analyses identified IQ and in-class attentive behavior as common predictors of Oral Reading Fluency and Numerical Operations scores. Digit span forward, verbal memory, and English Attitudes were unique to reading fluency, whereas JLAP, MRT and mathematics self-efficacy were unique to mathematics achievement. These eight variables along with achievement test (reading = 0, mathematics = 1) and test by variable interactions were included in the multi-level models.

TABLE 5 | Estimates from multi-level model for Oral Reading Accuracy and Numerical Operations.

Effect	**Estimate (*se*)**	***t*-Test**	***p***
Fixed effects			
Intercept	−0.012 (0.06)	−0.18	0.867
Intelligence	0.234 (0.04)	5.71	0.000
In-class attentive behavior	0.390 (0.05)	8.26	0.000
JLAP	0.134 (0.04)	3.81	0.000
Digit span forward	0.078 (0.04)	1.78	0.077
Mental Rotation Test (MRT)	0.100 (0.05)	2.14	0.033
Mathematics efficacy	0.171 (0.04)	3.93	0.000
Test by in-class attentive behavior	−0.184 (0.06)	−3.13	0.002
Test by digit span forward	0.176 (0.06)	3.09	0.002
Test by MRT	−0.121 (0.06)	2.09	0.037
Test by mathematics efficacy	−0.205 (0.06)	−3.58	0.000
Random effects			
Intercepts: Schools	0.015 (0.01)	1.11	0.133
Intercepts: Students in schools	0.061 (0.03)	2.07	0.019
Residual	0.459 (0.04)	12.55	0.000

JLAP, Judgment of Line Angle and Position.

The full model revealed non-significant interactions between test and IQ ($p = 0.877$) and test and MRT ($p = 0.953$). Dropping these two interactions did not substantively change overall model fit [$\Delta BIC = 1.8$, $\chi^2(2) < 1$, $p < 0.001$]. The estimates associated with the model that did not include these interactions are shown in **Table 6**. The highly significant main effects, without significant interactions for IQ and MRT (ps < 0.001), indicate that these variables predicted achievement in both domains.

Again, the significant interactions indicate that the relative importance of the predictor varies across reading and mathematics achievement, with positive estimates indicating larger effects in the prediction of reading fluency and negative estimates indicating larger effects in the prediction of mathematics achievement. The interactions indicate stronger relations between in-class attentive behavior, JLAP, and mathematics efficacy and mathematics achievement than reading fluency. In contrast, digit span forward, verbal memory, and English attitudes were more strongly related to reading fluency than to mathematics achievement.

Logistic Regressions

Comorbid Learning Difficulties

The first logistic regression included the common predictors of reading and mathematics achievement, that is, IQ, in-class

TABLE 6 | Estimates from multi-level model for Oral Reading Fluency and Numerical Operations.

Effect	Estimate (*se*)	*t*-Test	*p*
Fixed effects			
Intercept	−0.007 (0.05)	−0.14	0.893
Intelligence	0.193 (0.04)	4.82	0.000
In-class attentive behavior	0.391 (0.05)	8.21	0.000
Digit span forward	0.077 (0.04)	1.76	0.079
Verbal memory	0.059 (0.04)	1.38	0.167
English attitudes	0.006 (0.04)	0.15	0.881
JLAP	0.116 (0.04)	2.61	0.010
Mental Rotation Test (MRT)	0.119 (0.04)	3.38	0.001
Mathematics efficacy	0.179 (0.04)	4.18	0.000
Test by in-class attentive behavior	−0.198 (0.06)	−3.20	0.002
Test by digit span forward	0.164 (0.06)	2.77	0.006
Test by verbal memory	0.107 (0.06)	1.84	0.067
Test by English attitudes	0.099 (0.06)	1.75	0.080
Test by JLAP	−0.106 (0.06)	−1.82	0.070
Test by mathematics efficacy	−0.321 (0.06)	−5.55	0.000
Random effects			
Intercepts: Schools	0.007 (0.01)	0.89	0.186
Intercepts: Students in schools	0.033 (0.03)	1.17	0.121
Residual	0.468 (0.04)	12.55	0.000

JLAP, Judgment of Line Angle and Position.

attentive behavior, and JLAP. The overall model was highly significant, Wald $\chi^2(3) = 48.01$, $p < 0.001$, and correctly classified 95.5% of the students as having comorbid learning difficulties or not. However, the estimate for JLAP was not significant ($p = 0.070$) and thus the regression was rerun with only IQ and in-class attentive behavior.

The resulting model was highly significant, Wald $\chi^2(2) = 48.32$, $p < 0.001$, as were the effects for IQ and in-class attentive behavior (ps < 0.001). One *SD* increases in IQ and in-class attentive behavior resulted in 4.6-fold [95% confidence interval (CI) = 2.4, 8.7] and 4.7-fold [CI = 2.5, 9.0] increases in the odds of being in the typically achieving group, respectively. The combination correctly classified 94.6% of students as having comorbid learning difficulties or not, which is equivalent to a very large multivariate effect, $D = 2.44$ [CI = 2.03, 2.85]. As a comparison, the univariate effect sizes for IQ ($d = 1.56$) and in-class attentive behavior ($d = 1.61$) were large, as shown in **Table 2**, but smaller than the combined effect.

Reading Difficulties

The first logistic regression included the best predictors of reading achievement identified in the prior analyses, that is, IQ, in-class attentive behavior, JLAP, and digit span forward. The overall model was highly significant, Wald $\chi^2(4) = 32.52$, $p < 0.001$, and correctly classified 79% of the students as having reading difficulties or not. However, the estimate for in-class attentive behavior was not significant ($p = 0.077$) and thus the regression was rerun with only IQ, JLAP, and digit span forward.

The resulting model was highly significant, Wald $\chi^2(3) = 30.78$, $p < 0.001$, as were the individual effects (ps < 0.05). One *SD* increases in IQ, JLAP, and digit span forward resulted in 1.9-fold [CI = 1.2, 2.9], 1.5-fold [CI = 1.0, 2.2], and 2-fold [CI = 1.3, 3.0] increases in the odds of being in the typically achieving group, respectively. The combination correctly classified 78% of students as having reading difficulties or not, which is equivalent to a large multivariate effect $D = 1.08$ [CI = 0.74, 1.41]. As a comparison, the univariate effect sizes for IQ ($d = 0.65$), JLAP ($d = 0.59$), and digit span forward ($d = 0.71$) were moderate and smaller than the combined effect.

Mathematics Difficulties

The first logistic regression included the best predictors of mathematics achievement identified in the prior analyses, that is, IQ, in-class attentive behavior, JLAP, MRT, and mathematics self-efficacy. The overall model was highly significant, Wald $\chi^2(5) = 39.80$, $p < 0.001$, and correctly classified 87.7% of the students as having mathematics difficulties or not. However, the estimates for JLAP ($p = 0.107$) and MRT ($p = 0.772$) were not significant.

Dropping MRT resulted in a significant effect for JLAP ($p = 0.044$), but a substantive decrease in the percentage (79%) of students who were correctly classified. Dropping other individual variables indicated that the most parsimonious model only included IQ and in-class attentive behavior, Wald $\chi^2(2) = 38.57$, $p < 0.001$. One *SD* increases in IQ and in-class attentive behavior resulted in 2.2-fold [CI = 1.4, 3.7] and 3.6-fold [CI = 2.1, 6.2] increases in the odds of being in the typically achieving group. The combination correctly classified 86.8% of students as having mathematics difficulties or not, which is equivalent to a large multivariate effect, $D = 1.59$ [CI = 1.20, 1.97]. As a comparison, the univariate effect sizes for IQ ($d = 0.88$) and in-class attentive behavior ($d = 1.13$) were large, but smaller than the combined effect.

Mathematics Versus Reading Difficulties

The first logistic regression included the best predictors of mathematics or reading achievement identified in prior analyses, that is, IQ, in-class attentive behavior, forward digit span, JLAP, MRT, and mathematics self-efficacy. The overall model was significant, Wald $\chi^2(6) = 17.58$, $p = 0.007$, and correctly classified 79.1% of the students as having mathematics rather than reading difficulties. However, the estimates for IQ ($p = 0.794$), JLAP ($p = 0.657$) and MRT ($p = 0.566$) were not significant and thus dropped.

The follow-up regression was significant, Wald $\chi^2(3) = 17.19$, $p < 0.001$. The individual estimates for in-class attentive behavior ($p < 0.001$) and mathematics self-efficacy ($p = 0.041$) were significant and the estimate for forward digit span was a trend ($p = 0.065$). One *SD* increases in in-class attentive behavior and mathematics self-efficacy resulted in 2.7-fold [CI = 1.5, 4.8] and 1.7-fold [CI = 1.02, 2.93) decreases, respectively, in the odds of being in the mathematics difficulties group. A 1 *SD* increase in forward digit span, in contrast, resulted in a 1.6-fold [CI = 0.97, 2.7] decrease in the odds of being in the reading difficulties group. The combination correctly classified 78.5% of students as having mathematics or reading difficulties, which is equivalent to a large multivariate effect, $D = 1.16$ [CI = 0.66, 1.65].

In-Class Attentive Behavior

The above analyses indicated that in-class attentive behavior is an important predictor of individual differences in academic achievement and contributes to comorbid and mathematics learning difficulties. In a *post hoc* analyses, we used Bayesian regressions to identify the best set of cognitive and non-cognitive predictors of in-class attentive behavior, which allowed for inferences about the factors that might contribute to students' disengagement in classroom learning.

As shown in **Table 6**, the top cognitive model included verbal memory and IQ, but dropping the former resulted in little change in model fit. The model without verbal memory was 86.09% as probable as the one with it, or the model with it was preferred only 1.16 to 1 over the model without it. The top non-cognitive predictors included mathematics self-efficacy, English attitudes, mathematics anxiety for evaluation, and mathematics anxiety for learning. Dropping each of these variables in turn resulted in models that were less than 5% as probable as the models with them, and thus all of them were kept for the combined analyses.

The combined analysis included mathematics self-efficacy, English attitudes, mathematics anxiety for evaluation, mathematics anxiety for learning, and IQ, and the best model included all of them. However, as shown in **Table 7**, the inclusion of mathematics anxiety for learning did not add substantively to the prediction of in-class attentive behavior and thus was dropped.

A follow-up regression revealed that these four variables explained 33% of the variance in in-class attentive behavior, $F(4,310) = 37.35$, $p < 0.001$. The largest effect was for IQ, $\beta = 0.47$, $t_{(310)} = 9.68$, $p < 0.001$, followed by mathematics self-efficacy, $\beta = 0.19$, $t_{(310)} = 3.62$, $p < 0.001$, English attitudes, $\beta = 0.14$, $t_{(310)} = 3.03$, $p = 0.003$, and mathematics anxiety for evaluation, $\beta = 0.09$, $t_{(310)} = 1.84$, $p = 0.068$. IQ alone explained 28% of the variance, $F(1,313) = 120.93$, $p < 0.001$, whereas the combination of the three non-cognitive variables (without IQ) explained 12% of the variance in in-class attentive behavior, $F(3,311) = 14.29$, $p < 0.001$.

Overall, students with higher intelligence and mathematics self-efficacy, along with more positive attitudes toward English or language arts and more concern about their performance on mathematics evaluations were more attentive in classrooms.

DISCUSSION

The current study provided a comprehensive analysis of the common and unique predictors of individual differences in reading and mathematics achievement and learning difficulties in these domains. The results indicate that there are common domain-general cognitive abilities and non-cognitive factors that contribute to individual and group differences in reading and mathematics achievement, as well as factors that are unique to each of them. We discuss the details and implications of these results in terms of individual differences in achievement and with respect to students with learning difficulties.

Individual Differences in Achievement

The finding that intelligence emerged as a common predictor of reading accuracy, reading fluency, and mathematics achievement is not surprising, given previous findings (Deary et al., 2007; Peng et al., 2019). As noted, on the basis of these findings we anticipated that one or several of the commonly used working memory measures (e.g., backward digit span) would emerge as predictors of both reading and mathematics achievement (Swanson et al., 2009a; Lee and Bull, 2016; Geary et al., 2017), but this was not the case. One potential reason is the well-documented correlation between performance on intelligence and working memory measures (Ackerman et al., 2005). Indeed, dropping IQ resulted in the emergence of working memory (i.e., digit span backward) as a predictor of both reading accuracy and mathematics achievement. In other words, working memory contributes to variation in reading and mathematics achievement, as found in many previous studies, but the associated variance is captured by intelligence. The results confirm that the combination of strong working memory abilities and intelligence indexes the ease of learning academic material (Cattell, 1963; Geary, 2005, 2008).

In keeping with prior studies, in-class attentive behavior also emerged as an important predictor of achievement but more so for mathematics than for reading accuracy or reading fluency (Geary et al., 2013; Fuchs et al., 2016). The pattern likely follows from the importance of attending to classroom lectures for learning mathematical content. In other words, the mathematics achievement measure assessed knowledge that is imparted, at least in part, in the context of classroom instruction and inattention in the classroom is related to slower learning of mathematics (Stigler et al., 1987). The reading achievement measure, in contrast, assessed oral reading that is likely not as dependent on day-to-day attention in classroom settings. Even so, teacher-rated in-class attentive behavior was predictive of individual differences in oral reading accuracy. If the in-attentive behavior reported by teachers is expressed during oral reading, then we would expect less fluent reading and more reading errors, as we found. Interventions that focus students' attention on each grapheme in words as they read are helpful for reducing such errors (McCandliss et al., 2003).

We also anticipated that one or several of the spatial measures would emerge as stronger predictors of mathematics than reading achievement, and the Bayesian analyses showed that this was the case for the Mental Rotation Test (Casey et al., 1997; Kyttälä and Lehto, 2008). Among other things, the MRT assesses ease of generating mental images (Hegarty, 2018) that in turn could facilitate comprehension of certain types of mathematics (e.g., slopes, number line, parallel lines) and might also contribute to the ability to use spatial strategies during mathematical problem solving (Johnson, 1984). Any such relations would be more important for some types of mathematics than others (Kyttälä and Lehto, 2008), but our mathematics achievement measure does not allow for this type of fine-grain assessment.

TABLE 7 | Bayes factor analyses of predictors of in-class attentive behavior.

Model: Top Cognitive Predictors	BC_{m0}	Excluded	BC_{m1}
MC_1 Verbal memory + IQ	6.91×10^{20}	–	1
MC_2 Verbal memory	3.13×10^{4}	IQ	0.0000
MC_3 IQ	5.95×10^{20}	Verbal memory	0.8609
Model: Top Non-cognitive Predictors	BNC_{m0}	**Excluded**	BNC_{m1}
MNC_1 Math efficacy + EngAtt + MAnxEval + MAnxLearn	3.10×10^{8}	–	1
MNC_2 Math efficacy + EngAtt + MAnxEval	9.40×10^{5}	MAnxLearn	0.0030
MNC_3 Math efficacy + EngAtt + MAnxLearn	1.35×10^{7}	MAnxEval	0.0436
MNC_4 Math efficacy + MAnxEval + MAnxLearn	4.54×10^{6}	EngAtt	0.0146
MNC_5 EngAtt + MAnxEval + MAnxLearn	2.18×10^{5}	Math efficacy	0.0007
Model: Top Combined Predictors	BA_{m0}	**Excluded**	BA_{m1}
MA_1 Math efficacy + EngAtt + MAnxEval + MAnxLearn + IQ	3.99×10^{22}	–	1
MA_2 Math efficacy + EngAtt + MAnxEval + MAnxLearn	3.10×10^{8}	IQ	0.0000
MA_3 Math efficacy + EngAtt + MAnxEval + + IQ	2.58×10^{22}	MAnxLearn	0.6464
MA_4 Math efficacy + EngAtt + + MAnxLearn + IQ	6.80×10^{21}	MAnxEval	0.1705
MA_5 Math efficacy + + MAnxEval + MAnxLearn + IQ	5.13×10^{21}	EngAtt	0.1286
MA_6 + EngAtt + MAnxEval + MAnxLearn + IQ	2.22×10^{21}	Math efficacy	0.0556

MAnxLearn, Mathematics Anxiety for Learning; EngAtt, English Attitudes; MAnxEval, Mathematics Anxiety for Evaluation. MC, Models for cognitive variables; MNC, Models for non-cognitive variables; MA, Models for all, that is, top cognitive and non-cognitive variables.

Performance on the Judgment of Line Angle and Position Test (Collaer et al., 2007), a measure of visuospatial attention (Tranel et al., 2009), also emerged as a predictor of individual differences in mathematics achievement. Consistent with this finding, prior studies indicate that the visuospatial abilities assessed by this measure are important for discriminating the relative magnitudes of numerals and for positioning them on the number line (Longo and Lourenco, 2007; Zorzi et al., 2012).

However, performance on the JLAP was just as important in predicting oral reading accuracy as mathematics achievement, indicating that visuospatial attention is not uniquely related to mathematics learning. Indeed, prior studies have found that deficits in visuospatial attention contribute to reading difficulties, including word reading errors (Friedrich et al., 1985; Valdois et al., 2019). Valdois et al.'s (2019) study suggests that the deficits are associated with the top-down control of visual attention. Deficits in control of visual attention would hamper the processing of visually and sequentially presented details, which would make accurate reading and many aspects of mathematics (e.g., processing an equation) error prone. At the same time, oral reading fluency was not related to JLAP performance, indicating the students who committed reading errors were still able to appear to fluently read, although they often generated words that were not actually in the text.

In addition to the Mental Rotation Test, mathematics self-efficacy was more important in the prediction of mathematics than reading achievement, and English attitudes were more strongly related to reading fluency than to mathematics achievement or reading accuracy The pattern indicates that students were differentiating between their competencies in mathematics and reading, and that perceived effort during the act of reading (i.e., fluency) might be more important in shaping associated attitudes than reading accuracy. The cause-effect relation between attitudes and achievement cannot, however, be determined from these results. On the basis of prior results, it is likely that the relation emerged because students are aware of their relative performance in mathematics and reading and this in turn influenced their attitudes in these areas (Talsma et al., 2018; Geary et al., 2019).

Verbal short-term memory, as measured by forward digit span, was the only measure that was important for reading accuracy and fluency but not mathematics achievement, while passive verbal memory contributed to oral reading fluency but not reading accuracy. While these findings are generally consistent with many previous studies (Swanson et al., 2009b; Peng et al., 2018), they also provide nuance. The critical difference is that the use of verbal memory strategies (e.g., rehearsal) is possible with the digit span but not the verbal memory task. In other words, the ability to engage in top-down manipulation of verbal material was relatively more important for oral reading accuracy than was passive short-term retention of words, while the passive retention of verbal information also contributed to fluency.

Finally, our *post hoc* analyses of individual differences in in-class attentive behavior is unique (to the best of our knowledge) to this study and suggests that a combination of cognitive ability and academic attitudes contribute to engagement in middle-school classrooms. One possibility is that lower-ability students find academic learning more difficult than their higher-ability peers and over time this leads to less positive academic attitudes and less investment in academic learning. The long-term result would be disengagement in classroom settings and with schooling more generally. If correct, then longitudinal studies should show a cross-grade decline in in-class attentive behavior that is mediated by intelligence and academic attitudes. If so, then interventions associated with improving engagement in the classroom might prove useful for these students.

Learning Difficulties

As noted, individual differences in achievement are continuous and thus cutoffs for learning difficulties are necessarily arbitrary to some extent (Grigorenko et al., 2020). Nevertheless, on the basis of the relation between various outcomes in adulthood and actual academic competencies at different levels of achievement, the 25th percentile is a reasonable cutoff for identifying adolescents who are at risk for long-term educational and occupational issues (Rivera-Batiz, 1992; Ritchie and Bates, 2013; Richmond-Rakerd et al., 2020).

Students with difficulties in both reading and mathematics are at significantly higher long-term risk than are students with difficulties in only one domain. The focus on these students added to the individual differences analyses by identifying the core factors contributing to group membership. The combination of low-average intelligence (M = 90, **Table 2**) and poor in-class attentive behavior was a potent predictor of whether a student fell into the comorbid learning difficulty or typically achieving group (D = 2.44). The use of a typically achieving group with high-average intelligence and mathematics achievement likely inflated the size of the multivariate effect. Nevertheless, in comparison with the overall sample (**Table 2**), the students with comorbid learning difficulties were still about 1 *SD* below average on both intelligence (d = 1.13) and in-class attentive behavior (d = 1.17), indicating the combination would remain a substantive discriminator of difficulty status relative to students with average intelligence and achievement.

The identification of intelligence and in-class attentive behavior as contributors to learning difficulties confirms prior results (Geary et al., 2012; Willcutt et al., 2013; Peng et al., 2019). The unique contribution here is the identification of their combined contributions to achievement difficulties. Although the logistic regression indicated that they contributed equally to group membership, the finding that intelligence is a strong predictor of attentive behavior suggests a more dynamic relationship, as noted above.

As with comorbid learning difficulties, the combination of intelligence and in-class attentive behavior also discriminated students with mathematics learning difficulties from their typically achieving peers (Willcutt et al., 2013). The difference was that in-class attentive behavior was a stronger predictor of mathematics difficulties than was intelligence, relative to equal contributions for students with comorbid difficulties. As noted, it is possible that low-average intelligence contributes to student disengagement from and less positive attitudes toward academic learning. In this situation, interventions that incorporate components of self-regulation (Wang et al., 2019), enhance academic attitudes (Sisk et al., 2018), or enhance classroom management strategies (Korpershoek et al., 2016) might be particularly helpful for students with both comorbid and mathematics learning difficulties.

Intelligence also contributed to risk of reading difficulties. However, in contrast to students with comorbid or mathematics difficulties, in-class attentive behavior did not emerge as a core discriminator of these students from their typically achieving peers. Rather, the combination of relatively low visuospatial attention and verbal short-term memory, along with intelligence, discriminated them. The finding for verbal short-term memory (Helland and Asbjørnsen, 2004) and visuospatial attention (Friedrich et al., 1985) is in keeping with prior results and demonstrates that their combined effect is more important than either effect in isolation. The null result for in-class attentive behavior is surprising, given the individual differences results and Willcutt et al.'s (2013) finding of increased rates of attention-deficit disorder among students with reading disability. The differences are likely related to the multiple factors that can disrupt reading achievement and the heterogeneity of reading difficulties groups across studies. The reading difficulty group here appears to have circumscribed deficits in the top-down control of visual attention and in verbal short-term memory.

Limitations

The correlational nature of the data is the primary limitation and precludes strong causal statements. We assessed a broader array of domain-general cognitive and non-cognitive predictors of reading and mathematics achievement than is typical for this type of study, but this does not preclude the contributions of other factors that we did not assess. The inclusion of other factors, such as the contributions of the home environment and other known predictors of academic achievement (e.g., rapid automatic naming), might change the relative importance of the factors that we identified, although this remains to be determined. Moreover, the emergence of in-class attentive behavior as a predictor of academic outcomes should not be interpreted as an indicator of attentional deficits, as the participants' classroom behavior could simply reflect disengagement from schooling rather than attentional deficits *per se*. Despite these limitations, our broad assessments and analytic approaches enabled a thorough evaluation of the cognitive and non-cognitive factors that are common to mathematics and reading achievement and learning difficulties, as well as factors that disproportionately contribute to achievement in one domain or the other. The combination has implications for the identification of at-risk students and for the development of interventions to reduce these risks.

DATA AVAILABILITY STATEMENT

The data and R code used in these analyses are available in Open Science Framework, https://osf.io/cuvs5/.

ETHICS STATEMENT

The study was reviewed and approved by the University of Missouri Institutional Review Board (IRB; Project 2002634, "Algebraic Learning and Cognition"). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

DG drafted the manuscript and completed most of the analyses. JS completed some analyses. MH and LN managed data collection and quality control. All authors contributed to the writing of the final manuscript.

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Testing the Specificity of Predictors of Reading, Spelling and Maths: A New Model of the Association Among Learning Skills Based on Competence, Performance and Acquisition

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In a previous study (Zoccolotti et al., 2020) we examined reading, spelling, and maths skills in an unselected group of 129 Italian children attending fifth grade by testing various cognitive predictors; results showed a high degree of predictors' selectivity for each of these three behaviors. In the present study, we focused on the specificity of the predictors by performing cross-analyses on the same dataset; i.e., we predicted spelling and maths skills based on reading predictors, reading based on maths predictors and so on. Results indicated that some predictors, such as the Orthographic Decision and the Arithmetic Facts tests, predicted reading, spelling and maths skills in similar ways, while others predicted different behaviors but only for a specific parameter, such as fluency but not accuracy (as in the case of RAN), and still others were specific for a single behavior (e.g., Visual-auditory Pseudo-word Matching test predicted only spelling skills). To interpret these results, we propose a novel model of learning skills separately considering factors in terms of competence, performance and acquisition (automatization). Reading, spelling and calculation skills would depend on the development of discrete and different abstract competences (accounting for the partial dissociations among learning disorders reported in the literature). By contrast, overlap among behaviors would be accounted for by defective acquisition in automatized responses to individual "instances"; this latter skill is item specific but domain independent. Finally, performance factors implied in task's characteristics (such as time pressure) may contribute to the partial association among learning skills. It is proposed that this new model may provide a useful base for interpreting the diffuse presence of comorbidities among learning disorders.

Keywords: comorbidity, reading, spelling, maths, proximal predictors, learning disabilities, dyslexia, acquisition of instances

INTRODUCTION

Developmental disorders in reading, spelling and maths tend to be partially associated, a phenomenon known as comorbidity (e.g., Landerl and Moll, 2010). Comorbidity poses an important challenge to classical cognitive models as they are typically focused on accounting for the presence of deficits in a single domain, i.e., reading, spelling or maths (Pennington, 2006). Historically, an impetus to the development of cognitive models (such as the dual route cascade model or DRC in the case of reading; Coltheart et al., 2001) has come from the detailed analysis of selective deficits in reading (spelling or maths) in patients with focal brain lesions. Co-presence of acquired symptoms in patients is common but it can be easily accommodated by positing that the brain lesion has impaired processing in more than a single, distinct brain area (i.e., in terms of anatomical overlap), making associations in the case of acquired problems not particularly interesting. Unlike the case of acquired symptomatology, association among symptoms in the developmental domain is considerably more interesting although difficult to account for.

In a breakthrough analysis of comorbidity, Pennington (2006) has proposed that comorbidity among developmental disorders is to be expected because multiple factors are responsible for developmental disorders, such as dyslexia or ADHD, as they appear at the clinical level, i.e., in terms of "complex behavior disorders". Importantly, developmental deficits are framed in a multiple level perspective, including the behavioral level (complex behavior disorders), as well the cognitive, the neural and etiological levels. One does not expect 1:1 correspondence between genes, neural structures and cognitive factors, but there are interactions both within and between levels. Thus, a complex behavioral disorder would result from interaction of multiple cognitive factors and comorbidity of behavioral disorders can be explained by such interactions. Albeit quite broad, the multiple level model of Pennington (2006) represents an important reference to frame developmental disorders, in particular since it has the potential to account for both dissociated and associated symptoms.

Indeed, in recent years there has been increasing research aimed to pinpoint the multiple factors underlying the co-presence of developmental disorders. Pennington and colleagues focused on the comorbidity between reading impairment and ADHD. Evidence indicates that children with dyslexia tend to be impaired in phonological tasks while children with ADHD in tasks of inhibition control; however, both groups are also impaired in speed of processing which thus appears as a factor present in both disorders (e.g., Willcutt et al., 2005, 2010). In the same vein, some studies have tried to identify the independent and conjunct factors accounting for the partial overlap between reading and language impairments (Bishop et al., 2009), while others for that between reading and maths (e.g., Slot et al., 2016). Information coming from these studies seems still insufficient to draw definite conclusions. For example, in the case of reading and maths, several different alternatives have been proposed: Slot et al. (2016) proposed that comorbidity is accounted for by phonological processing while Wilson et al. (2015) found common deficits in rapid naming and verbal short-term memory (Wilson et al., 2015). More recently, it was found that children with comorbid dyslexia and dyscalculia presented deficits in visual perception (Cheng et al., 2018). Overall, it seems that up until now studies have failed to converge on a unitary framework (for a discussion on this point, see Astle and Fletcher-Watson, 2020).

It may be observed that research on the cognitive antecedents of comorbidity, such as those above briefly reported, have been largely developed outside the traditional models of cognitive models of reading spelling and maths. Indeed, as stated above, cognitive architectures postulated by cognitivist models (extended to developmental disorders, but originally derived from studies in patients with acquired symptoms) seem to offer limited information to explain comorbidity of learning disorders as they are typically focused in explaining single behaviors (e.g., reading or maths).

So, one can draw a fairly clear distinction between studies that tried to isolate the cognitive antecedents of the co-morbidity of two (or more) developmental disorders which typically only loosely referred to the existing cognitive models for these disorders and studies, framed within the cognitivist tradition, that typically aimed to account for deficits within a single deficit perspective (e.g., reading or maths), generally selecting participants to the studies according to a single-deficit category (Peters and Ansari, 2019). It should be noted that there is some overlap in the cognitive processes these two lines of research refer to. So, for example, phonological processes are invoked both within the co-morbidity approach in accounting for the presence of dyslexia (along with perceptual speed, Willcutt et al., 2005, 2010) and within cognitive models of reading (such as the triangle model, Plaut et al., 1996) to account for at least some proportion of the deficits in reading. Still, the perspective in which cognitive processes are referred to is quite different in the tradition of cognitive architectures and in the recent comorbidity studies focusing on the overlap between cognitive processes. In the first case, there is an explicit attempt to express the nature of the relationship between the cognitive process and the target behavior within a given architecture (e.g., the cognitive model of reading, spelling, or maths). Thus, a cognitive architecture is a complex model in which all the interactions between the involved processes, necessary to account for a given target behavior, are made explicit. In this perspective, cognitive predictors may be described as the "proximal" factors accounting for the performance (as well as different forms of impairment) in a given behavior (Coltheart, 2015). By contrast, cognitive processes have been referred to as "distal" if some relationship between the process and the target behavior is expected (and empirically proven), but its nature is not made explicit as well as its relationships with the other cognitive processes contributing to predict a given behavior. Coltheart (2015) describes distal factors by stating that they affect behavior indirectly by influencing the proximal factors in the model. In this vein, one can easily see that short-term memory, attention and the like are important for efficient reading but their action would influence the target behavior by modulating the activity of the proximal factors envisaged by the model (e.g., memory may modulate the application of phoneme-grapheme rules in the example provided by Coltheart, 2015). Note that cognitive skills are neither proximal nor distal as such; rather, this distinction refers to the way in which one looks at a given cognitive factor (for a thorough discussion see Coltheart, 2015). Overall, research on the cognitive antecedents of comorbidity has moved away from referring to cognitive models as they are typically focused in explaining single behaviors (i.e., reading, spelling or maths) and, with few exceptions (see below), offer no explicit base to develop predictions for explaining the widespread presence of comorbidity among developmental disorders.

There is another, critical reason why research on comorbidity is difficult to frame within cognitive architectures. Cognitive models typically aim to account for behaviors (e.g., reading or maths) seen in highly abstract forms. For example, the DRC (Coltheart et al., 2001) spells out the processes for reading aloud single mono-syllabic words in English. It is only by extrapolation that this model may be used to account for the performance in actual, common reading tasks, such as silently reading a text. In other terms, models such as the DRC aim to account for the competence that is hypothesized to underlie the ability (as well as the derangement) in a given domain, not the actual behavior in naturalistic conditions (for a discussion see Bishop, 1997). So, cognitive models generally fail to describe (or leave largely underspecified) the processing factors through which actual performance can be explained (Bishop, 1997). In Chomsky (1966) terms, cognitive architectures describe "competence" factors but are silent as to the "performance" factors involved. By contrast, in the example of reading, it is likely that naturalistic conditions (such as the presence of multiple words and lines in the text; the necessity of moving the eyes from a word to the next; the memory load involved when fixating and processing the next word while pronouncing the preceding word) involve performance factors which are not the same of those in reading single short words. Attention to performance factors is consistent with Pennington (2006) view that proposes that comorbidity occurs among "complex behavioral disorders". Accordingly, an analysis focusing only on "competence" factors may indeed fail to provide a full account for the actual behavioral disorders.

However, we propose that the approach based on cognitive architectures may be adjusted to account for the presence of comorbidities among developmental disorders. Indeed, in a few cases, this has been done. For example, it has been proposed that reading and spelling may rely on the same lexicon (Allport and Funnell, 1981; Coltheart and Funnell, 1987; Behrmann and Bub, 1992; Angelelli et al., 2010a). Even though this proposal is controversial and alternative options based on the idea of multiple lexica have been proposed (for a discussion, see Hillis and Rapp, 2004), this case provides an interesting demonstration that, in principle, cognitive architectures may be developed which explicitly consider more than a single behavior.

AIM OF THE STUDY

In the present report, as well as a previous companion one (Zoccolotti et al., 2020), we aimed to develop a unitary model to uncover the unique and shared influences of predictors for reading, spelling and maths skills. To this aim, we examined these performances in an unselected group of fifth grade Italian children. It is well known that performances in reading (spelling or maths) can be described on a continuum such that so-called pathological performances merely reflect low points on a continuous distribution (e.g., Protopapas and Parrila, 2018). So, we considered as an appropriate starting point to examine performances within an unselected sample of children, though the ultimate goal of this work is to develop a model able to account for the comorbidities of learning disorders, and in particular for both the presence of associations and dissociations among them.

The present report is strictly linked to a previous one based on the same dataset (Zoccolotti et al., 2020), which presented the following main features. First, as target dependent behaviors we selected ecological tasks, such as reading a text passage, spelling a passage under dictation, and making calculations. Second, we used a "proximal" approach, that is we formulated explicit causal relationships between predictors (i.e., cognitive antecedent of the specific behavior under scrutiny) and target dependent measures (i.e., reading, spelling or maths). Third, based on the relevant literature, predictors of reading, spelling and maths were selected pointing to both efficacy and parsimony (details of such a selection are given in Zoccolotti et al., 2020). Fourth, as a control, we tested the possible predictive power of general cognitive dimensions (i.e., measures of short-term memory, phonemic verbal fluency, visual perceptual speed, and non-verbal intelligence). These can be seen as "distal" predictors in the sense that some relationships with the dependent measures are expected but the nature of these relationships is not specified, and they may occur through complex interrelationships with the cognitive proximal predictors.

Based on communality analyses, presented analytically in Zoccolotti et al. (2020), we developed separate models to account for the abilities to read, spell and do maths. All these models explained a sizeable amount of variance (ranging from 27.5% in the case of calculation accuracy to 48.7% of reading fluency). The only exception was reading accuracy for which the models based on specific and general factors yielded similarly limited results (for this reason, reading accuracy will not be considered in the present report). **Figure 1** synthesizes the conclusions of the previous study, and is the starting point of the present one. **Figure 1** presents schematically these models illustrating the cognitive dimensions used as predictors and the target behaviors (as well as the tasks used to measure both). Models based on general cognitive factors also accounted for some variance (ranging from 6.5% in the case of writing to 19.5% in the case of reading fluency) but this was appreciably less than that explained by models based on the hypothesized proximal predictors. Furthermore, when general predictors were added one by one to models based on specific predictors, in most cases they did not add unique variance while they accounted for some shared variance with other variables, and the overall increase in explained variance was in most cases very small (for these analyses please refer to **Supplementary Table 2** in the **Supplementary Materials**, Zoccolotti et al., 2020[1]).

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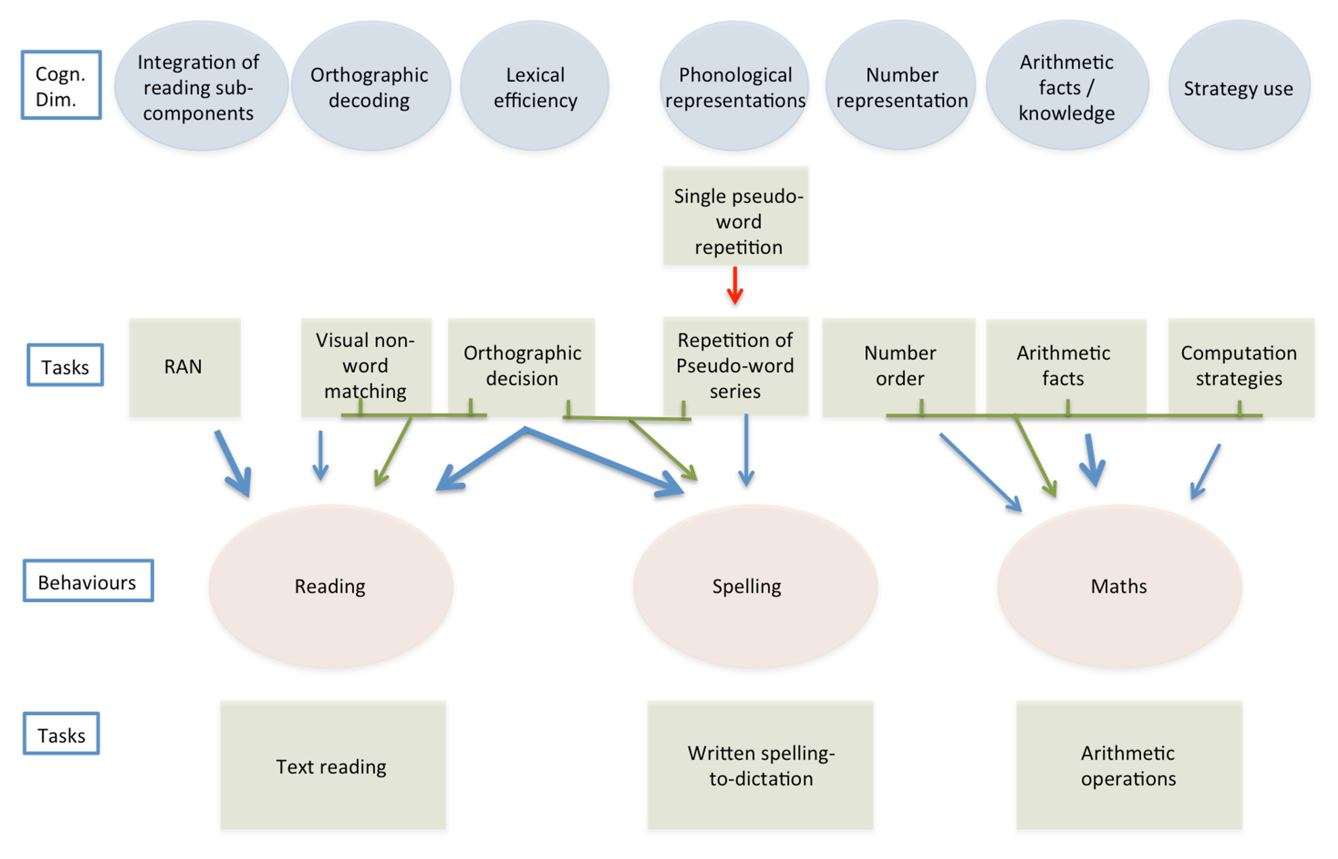

FIGURE 1 | Predictors of reading, spelling, and doing maths (based on the results from Zoccolotti et al., 2020). The figure presents the main links observed between tasks, used as predictors, and reading (fluency), spelling, and maths (accuracy) measures. Both direct links (in blue) and links expressing communalities (green arrows coming from green lines connecting square boxes) between predictors are reported (for the sake of presentation only communalities with beta of ca.05 or more are reported). The "heavier" blue arrows indicate "strong" influences (i.e., beta of ca.10 or more). The red arrow under the Single pseudo-word repetition box indicates a suppressive effect.

Overall, the models of reading, spelling and maths proposed in Zoccolotti et al. (2020) and summarized here in **Figure 1** can be considered "specific" because, using sets of predictors which mark different putative dimensions for different behaviors, they explained a relevant amount of variance in each of these behaviors. Furthermore, they showed greater efficacy than models based on general cognitive factors (i.e., distal predictors in Coltheart's terms). Still, only a limited amount of variance was explained by shared factors. The Orthographic Decision test (see Zoccolotti et al., 2020) worked as a predictor of both reading and spelling, a finding consistent with the literature, which indicates that a single orthographic lexicon may account for performance in reading and spelling (Allport and Funnell, 1981; Coltheart and Funnell, 1987; Behrmann and Bub, 1992; Angelelli et al., 2010a). However, apart from this, models for different skills were based on different factors. In particular, the factors selected to predict maths were entirely separate from those of reading and spelling. This selectivity is not surprising as, up until now, it has proven difficult to pinpoint the factors which account for the co-morbidity between reading and calculation disorders (e.g., Wilson et al., 2015; Slot et al., 2016; Cheng et al., 2018). One proposal that has been advanced is that phonological skills may account for such co-morbidity (Slot et al., 2016). Our original analyses did not offer much support to this proposal; in fact, phonological skills provided a relevant contribution only to predict spelling (Zoccolotti et al., 2020).

In the present report, we submit to a more stringent test the conclusion that the models of reading, spelling and maths reported by Zoccolotti et al. (2020) are indeed "specific". This was done by using predictors in a cross-over manner, that is evaluating whether predictors of a "target" behavior (e.g., skill in arithmetical facts predicting maths) also had an influence on "non-target" behaviors (e.g., skill in arithmetical facts predicting spelling or reading). Our working hypothesis was that, if models are specific, predictors used in such a cross-over manner should fail to make effective predictions. Thus, for example, one should expect that the set of predictors in the model of reading fluency would not predict spelling or maths or, possibly, that they would predict such behaviors in ways that cannot be distinguished by the model based on general cognitive abilities. Conversely, one should expect that predictors in the model of maths would not predict reading and spelling and so on. The results of the present study were used to develop a model aimed to account for both the overlap and the dissociation between learning skills (and deficits).

MATERIALS AND METHODS

Participants

An unselected sample of 129 (65 male, 64 female) Italian children (mean age = 10.7 years; SD = 0.3; range = 10.1-11.3 years) participated in the study. These participants are the same as in Zoccolotti et al., 2020. All children attended fifth grade in two schools in Rome and three in Latina in low-middle social class environments. Children from a total of 14 classes participated in the study. All children had an adequate performance to the Raven CPM (Pruneti et al., 1996).

Parents were informed about the screening activities and authorized their child's participation by signing the appropriate informed consent paperwork. The study was carried out in accordance with the principles of the Helsinki Declaration and was approved by the ethical committee of the IRCSS Fondazione Santa Lucia and by the school authorities.

Materials

Following is a brief description of the tests used, divided between dependent measures, putatively specific predictors and general cognitive predictors (for a more in-depth description of the test materials, please refer to Zoccolotti et al., 2020).

Dependent Measures for Reading, Spelling, and Maths

MT reading test (Cornoldi and Colpo, 1998)

The child reads a text passage aloud with a 4-min time limit; reading time (in seconds per syllable) and accuracy (number of errors) are scored.

"Nonna Concetta" spelling-to-dictation (Marinelli et al., 2016a)

The child has to spell a text dictated by an examiner, including both consistent and inconsistent words. Therefore, the task cannot be solved exclusively through sub-lexical phoneme-to-grapheme mapping, but requires the retrieval of lexical representation also in a consistent orthography such as Italian. The total number of elements for which a mistake is present is scored.

Mental and written arithmetic calculations subtests (from the test AC-MT 6-11; Cornoldi et al., 2002)

As to mental calculations, the child performs three sums and three subtractions of two two-digit numbers in the mind as quickly and as accurately as possible. The percentage of errors is scored. The time to perform the task is scored only to stop the task if 30" per calculation are elapsed. As to written calculations, the child performs two calculations for each of the four basic number operations, based on two numbers. The percentage of errors is calculated. An "*accuracy score*" derived from both the mental and written arithmetic calculations and a "*time score*," derived only by the written calculation test, were used as dependent measures.

Specific Cognitive Predictors

RAN (De Luca et al., 2005)

The child is shown matrices of colored squares or digits and is requested to name each stimulus as quickly and accurately as possible. The time to complete the task is measured (in seconds per item).

Orthographic decoding (Visual-auditory pseudo-word matching test)

In this test (specifically devised for this project on comorbidity), the child has to say whether or not two pseudo-words presented in the visual modality, in a mixed visual-auditory modality or in the auditory-auditory presentation are the same or not. Accuracy is measured as percentage of errors. The *Visual-visual and Auditory-auditory* presentations were used in the original report but are not presented here as they did not enter in the original models.

Orthographic decision

In this test (specifically devised for this project), the child has to silently read a list of high- and low-frequency inconsistently spelled words (and corresponding derived pseudo-homophones, homophonic to the original words but orthographically incorrect for the presence of a phonological plausible error) and to indicate whether or not they are correctly spelled. Then the task taps the retrieval of the orthographic representation thought lexical reading. The percentage of errors in judging both correct words and pseudo-homophones is scored.

Single pseudo-word repetition and phonemic segmentation

In this test (specifically devised for this project), thirty long pseudo-words were presented in the auditory modality. The child has to repeat each stimulus and, then, segment it by phonemes. The percentages of correct repetitions and correct segmentations were scored. Only data relative to the Single Pseudo-word Repetition part of the test are used in the present report.

Repetition of pseudo-word series (Marinelli et al., 2020b)

The child is asked to listen to 10 series of triplets of pseudo-words and repeat the items of each series in the same order immediately after the acoustic warning. The percentage of correct repetitions was used in the analysis.

Number order test (from the AC-MT 6-11 battery; Cornoldi et al., 2002)

The child has to order 10 series of 4 numbers. The percentage of wrong series was entered into the analyses.

Arithmetic facts test (from the developmental dyscalculia battery; Biancardi and Nicoletti, 2004)

The child has to say the result of a series of multiplications as rapidly as possible. The percentage of incorrect responses (taking into consideration incorrect response as well as response given beyond time limit or attempts based on the use of a mental calculation) is scored.

Computation strategies test (from the AC-MT 11-14 battery; Cornoldi and Cazzola, 2003)

The child must determine the result of arithmetic operations without actually calculating them, but reasoning on the base of similar complete calculations that are shown beside. The percentage of computations performed correctly within the time limit was used in the analyses.

The following tests (maths domain) were also administered but they did not enter in the original models and they are not referred to in the present report: Computation Procedures (Tabulation and carry); Backward Counting (from the AC-MT battery; Cornoldi et al., 2002); Dictation of Numbers (from the AC-MT battery; Cornoldi et al., 2002); Arabic Number Reading test (from the Developmental Dyscalculia Battery; Biancardi and Nicoletti, 2004).

General Cognitive Predictors

Performance in the following general cognitive tests was considered for the control models. The putative target dimension is presented in brackets:

Symbol search subtest (subtest from the WISC-R; Wechsler, 1986) (cognitive speed)

The child has to mark a box if a string of symbols contains one or both of the symbols presented on the left of the string, working as rapidly as possible. The percentage of correct responses out of the trials performed within 2 minutes was used.

Raven's colored progressive matrices (non-verbal intelligence)

The percentage of correct responses was scored and used for the analyses.

Forward and backward span of numbers (from the BVN battery; Bisiacchi et al., 2005) (verbal short-term memory)

The forward task requires the immediate serial recall of a sequence of digits. The span corresponds to the last length for which at least two sequences were correctly recalled. In the backward task the child has to recall each sequence in backward order. The forward and backward spans were measured.

Verbal phonemic fluency test (from the BVN battery, Bisiacchi et al., 2005) (verbal fluency)

The child has to generate as many words as possible from the initial letters C, S, and P in a minute. The number of correct items is scored.

Procedure

Children were tested in a quiet room in their schools. Three examiners examined approximately a third of the sample each. To insure homogeneity of administration, examiners participated to an intensive training before the study with the supervision of one of the authors, MDL).

Most tests were performed individually, while a few (*Written Arithmetic Calculations, Number Order and Raven's Colored Progressive Matrices*) were collectively administered to small groups of children. About three hours of testing were necessary to complete the battery. Most children completed testing in 3 sessions.

Order of tests was fixed and was the following (in brackets are tests which were administered but are not considered in the present report): MT reading test, RAN test, "Nonna Concetta" Spelling-to-dictation test, Verbal Phonemic Fluency test, Mental Calculation, (Backward Counting), (Dictation of Numbers), Forward and Backward Span of Numbers, Raven's Colored Progressive Matrices, Number Order test, Written Arithmetic Calculations, Symbol Search subtest, Repetition of Pseudo-word Series, (Arabic Number Reading test), Orthographic Decision test, Arithmetic Facts test, Single Pseudo-word Repetition and Phonemic Segmentation tests, Computation Strategies test, (Computation Procedures, Tabulation and carry test), Orthographic decoding: (Visual-visual), Visual-auditory Pseudo-word Matching test (Auditory-auditory).

Data Analysis

Descriptive statistics (N, mean, SD, coefficient of variation, min and max values observed, maximum values maximum possible score - only in the case of closed scales -, and reliability values) are presented in **Supplementary Table 1** in the **Supplementary Materials**. Furthermore, **Supplementary Table 2** in the **Supplementary Materials** reports the Pearson intercorrelations among all variables.

The results are based on the commonality analysis, a method of variance partitioning designed to identify proportions of variance in the dependent variable that can be attributed uniquely to each of the independent variables, and proportions of variance that are attributed to various combinations of independent variables (Pedhazur, 1982; Nimon, 2010). Notably, some of these interactions might also reveal suppressive effects, i.e., in the cases in which the predictor shares variance with another predictor and this variance does not contribute directly to performance on the dependent measure.

Communality analysis is a powerful analysis that is most effective in the case of a limited set of predictors. This feature is useful here since our general aim is to build models of performance characterized by both effectiveness (in terms of total variance explained) and parsimony (in terms of number of predictors used).

In our first report (Zoccolotti et al., 2020), communality analyses were used for identifying the most effective models of reading, spelling and maths. Here, our focus was in testing the specificity of the models originally developed for reading, spelling and maths. If the original models were indeed specific, testing predictors over non-target behaviors should fail to effectively predict target behaviors. These hypotheses were tested by switching predictors over dependent measures; thus, we checked to what extent the predictors of reading accounted for spelling and calculation and so on.

To anticipate, these analyses indicated that set of predictors exerted a significant influence also over non-target behaviors. To further understand these patterns we examined the relative efficacy of each specific predictor over both target and "non-target" behaviors, also by separately adding them into each of the original models. An analytic description of this procedure is provided in the section "RESULTS."

RESULTS

First, we present an overview of the communality analyses run on non-target behaviors and how they compare in terms of general explanation (R^2) to the original models of reading, spelling and maths as well as to the model based on general cognitive predictors (for more information on how these models were devised and tested please refer to Zoccolotti et al., 2020). The outcome of these analyses is summarized in **Table 1** which presents the total variance accounted for by using the predictors in the models of reading, spelling, and maths when applied to the target as well as all non-target behaviors (the list of predictors used in the original analyses is also reported in Part A of the table). Inspection of the table shows that each set of "specific" predictors always yields the highest estimate on the target behavior (i.e., direct models). Thus, reading fluency is best accounted for by the predictors in the reading model (Orthographic Decision, RAN, and Visual-auditory Pseudo-word Matching) and the same holds true for spelling (predictors: Orthographic Decision, Single Pseudo-word Repetition and Repetition of Pseudo-word Series) and calculation, both speed and accuracy (predictors: Number Order, Arithmetic Facts, and Computation Strategies).

However, inspection of the table also clearly illustrates that putatively specific models predict much more than one would expect (and much more than what accounted for by general cognitive predictors) of the other "non-target" dependent behaviors. Thus, the predictors of the reading model account for 21.1% of the total variance in spelling, 31.9% of the variance in calculation (speed) and 19.4% of that in calculation (accuracy). Much the same occurs when using predictors of spelling and calculation. In fact, some of the values are particularly high. For example, the predictors in the model of calculation account for 38.8% of the variance in reading fluency, a value only slightly inferior to the variance predicted by the model of reading itself (48.7%) and even higher than the two specific models of calculation (which accounted for 37.9% and 27.5% of variance for time and accuracy, respectively; see **Table 1**).

Notably, all values for predictions over non-target behaviors are appreciably higher than those of the model based on general cognitive factors (i.e., predictors: Raven, Symbol Search, Backward Span, Verbal Phonemic Fluency; see last column of **Table 1**). A further test on the possible role of the general predictors was carried out by replicating the communality analyses using as dependent variables the standardized residuals once the effect of the general cognitive factors was partialled out (based on multiple regression analyses). These results are summarized in **Supplementary Table 3** in the **Supplementary Materials**. Even with this stringent test, the described pattern holds although partially attenuated; thus, for example, the predictors of the reading model account for 38.9% of the model of reading but also 18.0% of the variance in spelling, 25.2% of the variance in calculation (speed) and 12.9% of that in calculation (accuracy).

The absolute level of variance differs somewhat among behaviors. Some of these differences may be due to different levels of reliability of the dependent measures. Thus, reliability values tend to be generally higher for reading fluency than for the other measures. To normalize data with respect to this critical aspect, in **Table 2**, values of total explained variance are expressed in terms of "true" score variances, i.e., the product of observed score variance and reliability of the test (but see Kang and MacDonald, 2010, for limitations on this procedure).

After correction for reliability differences among dependent measures, values of total true variances are somewhat less different from each other. Still, it is clear that putatively "specific" predictors tend to have strong influences across different learning processes, well beyond the values observed in the case of general cognitive predictors.

The communality analyses are presented more extensively in **Table 3** in terms of both coefficients and percentage of explained variance for each factor separately and in common with the others in the model. We also examined the 95% confidence limits of the coefficients; these estimates were obtained as accelerated bootstrap confidence intervals produced

TABLE 1 | Part A) Predictors in the original models of reading, spelling, and maths and in the general cognitive factors model (from Zoccolotti et al., 2020). Part B) Percentage of total variance explained by different models.

PART A					
	Original models	**Reading fluency model**	**Spelling accuracy model**	**Calculation (fluency and accuracy) model**	**General cognitive factors model**
	Predictors	- Orthographic Decision - RAN - Visual-auditory Pseudo-word Matching	- Orthographic Decision - Single Pseudo-word Repetition - Repetition of Pseudo-word Series	- Number Order - Arithmetic Facts - Computation Strategies	- Raven - Symbol Search - Backward Span - Verbal Phonemic Fluency
PART B					
Dependent measures	Reading fluency	**48.7**	34.9	38.8	19.5
	Spelling accuracy	21.1	**29.2**	18.6	6.5
	Calculation speed	31.9	18.1	**37.9**	12.8
	Calculation accuracy	19.4	20.2	**27.5**	12.8

In particular, each specific set of predictors is used to predict the target behavior as well as all the other non-target behaviors. The variances explained by the "specific" predictions (i.e., reading predicted by predictors in the reading fluency model etc.) are marked in bold. For comparison, the variances accounted for by the general cognitive factors model are also presented.

TABLE 2 | Percentage of "true variance" explained by models based on different sets of predictors i.e., total variance values adjusted for the reliability values of the four dependent measures.

		Predictors			
		Reading fluency model	**Spelling accuracy model**	**Calculation (fluency and accuracy) model**	**Cognitive abilities model**
Dependent measures	Reading fluency	**57.3**	41.1	45.6	22.9
	Spelling accuracy	28.1	**38.9**	24.8	8.7
	Calculation speed	40.9	23.2	**48.6**	16.4
	Calculation accuracy	38.8	40.4	**55.0**	25.6

The reliability values were the following: Reading fluency: r = 0.85; Spelling accuracy: r = 0.75; Calculation speed = 0.78; calculation accuracy = 0.50. The true variance explained by the "specific" predictions (i.e., reading dependent measure predicted by reading predictors etc.) are marked in bold.

over 1,000 iterations (Nimon and Oswald, 2013). These analyses are graphically presented in **Supplementary Figures 1–4** of the **Supplementary Materials**.

Table 3 allows examining the efficacy of each predictor (singly and/or in common with others) in contributing to the cross-over tests. It may be noted that some of the predictors show a very high efficacy in the cross-over tests while others show a more selective influence. Below we describe the influence of each predictor analyzing the breadth of its impact across different behaviors. We also note whenever different predictors appear to have overlapping influences across target and non-target behaviors.

Orthographic Decision and Arithmetic Facts Tests

Inspection of **Table 3** shows that performance in the Orthographic Decision test does not only predict performance in reading and in spelling, but also strongly enters in the prediction of calculation skills. Indeed, it accounts for 39.3% of the unique variance in the case of calculation speed with a β of.12 and 59.8% of the unique variance in the case of calculation accuracy with a β of.12. A very similar pattern is observed in the case of the Arithmetic Facts test. This latter is a strong predictor of calculation skills (particularly in the case of calculation speed) but it is also a strong predictor of reading fluency (β = 0.16, 40.3% of accounted variance) and also, although to a lesser extent, of spelling (β = 0.03, 15.0% of explained variance). It seems that the variance accounted for by these two tests (Orthographic Decision and Arithmetic Facts) is similar. To directly check this impression, we run analyses in which we added only the Arithmetic facts test to the original "Reading" and "Spelling" models. These results are illustrated in **Table 4**; the table also presents similar analyses carried out with all the other predictors considered (results are illustrated below).

The total variance accounted in reading fluency changes minimally when the Arithmetic Facts test is added to the predictors of the original Reading model (passing from 48.7% to 48.9%, **Table 4**). This is actually a general finding as this occurs for all variables included in **Table 4** but one (which will be commented later); thus, this result will not be repeated in the text for each variable. The Arithmetic Facts test contributes minimally in terms of unique variance (β = 0.003, 0.6% of accounted variance) but substantially in terms of shared variance (β = 0.29), most of which was with the Orthographic Decision test (see last column of **Table 4** which reports the predictor(s) with which the added predictor shared at least 10% of variance). As stated above, the total percentage of R^2 provides an estimate of its overall influence summing its unique contribution and that shared with other variables. Overall, the Arithmetic Facts test contributes for a quite substantial amount of the explained variance of the model of reading fluency (R^2 = 59.7%).

Results are similar in the analysis on spelling. When the Arithmetic Facts test is added to the predictors in original spelling model, it contributes little in terms of unique variance (β = 0.02, 5.7% of accounted variance) but more substantially in terms of shared variance (β = 0.08), most of which was with the Orthographic Decision test (see last column of **Table 4**). Overall, the Arithmetic Facts test contributes appreciably to the explained variance of the model (R^2 = 32.7%).

Then, we carried out a similar analysis with the Orthographic Decision test on the calculation skills; namely, we added this test to the predictors in the original models of "calculation speed" and "calculation accuracy". In the former case (**Table 4**), the Orthographic Decision test does not account for unique variance (β = 0.004, 1.0% of accounted variance) but it appreciably contributes to shared variance (β = 0.16) much of which was with the Arithmetic Facts test (see last column of **Table 4**). Overall, the Orthographic Decision test contributes appreciably to the explained variance of the model of calculation speed (R^2 = 43.4%). Similar results were obtained when adding the Orthographic Decision test to the predictors for calculation accuracy (**Table 4**). The Orthographic Decision test contributes minimally in terms of unique variance (β = 0.01, 4.7% of accounted variance) but much more so in terms of common variance (β = 0.16), shared with the Arithmetic Facts, the Number Order and Computation Strategies tests. Overall, the Arithmetic Facts test contributes substantially to the explained variance of the model of calculation accuracy (R^2 = 60.2%).

Overall, these data indicate that, in spite of their surface differences, the Orthographic Decision and the Arithmetic Facts tests exert similar influences across reading, spelling and maths.

RAN Test

Other predictors show a pattern of both associations and dissociations. In the original models (Zoccolotti et al., 2020), the RAN test was a strong predictor of reading fluency (but not accuracy) contributing with both unique and shared variance to the overall prediction; by contrast, RAN did not contribute to the model of spelling. Thus, there was an indication that RAN contributed to measures of time but not accuracy. Much the same occurs when the RAN task is

TABLE 3 | Cross-analyses carried out by switching predictors over dependent measures: predictors in the models of reading, spelling, and calculation are used to test whether they also predict non-target behaviors.

	A. Reading (fluency)		B. Spelling		C. Calculation (speed)		D. Calculation (accuracy)	
	Coeff.	**% R^2**	**Coeff.**	**% R^2**	**Coeff.**	**% R^2**	**Coeff.**	**% R^2**
Predictors in the Reading fluency model								
Unique to RAN	**0.12**	**24.5**	0	0.3	0.13	40.6	0	0.0
Unique to Orthographic Decision (OD)	**0.19**	**39.3**	0.2	95.4	0.13	39.3	0.12	59.8
Unique to Visual-auditory Pseudo-word Matching (V-ApwM)	**0.03**	**6.9**	0.01	2.5	0	1.3	0.02	9.9
Common to OD and RAN	**−0.02**	**−4.2**	0	1.3	−0.02	−5.4	0	0.3
Common to V-ApwM and RAN	**0.04**	**8.3**	0	0.6	0.02	6.1	0	0.6
Common to OD and V-ApwM	**0.10**	**19.9**	0	1.5	0.04	11.5	0.06	29.5
Common to OD and RAN and V-ApwM	**0.03**	**5.3**	0	−1.5	0.02	6.6	0	−0.1
Total	**0.487**		0.211		0.319		0.194	
Predictors in the Spelling model								
Unique to Orthographic Decision (OD)	0.16	45.0	**0.12**	**41.3**	0.13	71.1	0.1	48.0
Unique to Single Pseudo-word Repetition (SpwR)	0.01	1.5	**0.06**	**19.5**	0.01	7.9	0	1.0
Unique to Repetition of Pseudo-word Series (RpwS)	0.03	8.5	**0.07**	**23.6**	0	0.7	0.03	14.0
Common to OD and SpwR	0	0.7	**−0.01**	**−2.2**	0	2.1	0	−0.5
Common to OD and RpwS	0.08	23.6	**0.1**	**34.7**	0.01	4.7	0.06	30.0
Common to RpwS and SpwR	0.02	6.1	**−0.04**	**−12.9**	0	−0.5	0	−0.5
Common to OD and SpwR and RpwS	0.05	14.6	**−0.01**	**−4.1**	0.03	14.1	0.02	7.9
Total	0.349		**0.292**		0.181		0.202	
Predictors in the Calculation model								
Unique to Number Order (NO)	0	0.5	0.05	27.8	**0.00**	**0.0**	**0.03**	**9.7**
Unique to Arithmetic facts (AF)	0.16	40.3	0.03	15.0	**0.19**	**49.4**	**0.04**	**15.4**
Unique to Computation strategies (CS)	0.09	23.9	0.01	6.0	**0.05**	**12.6**	**0.06**	**22.1**
Common to NO and AF	0	0.6	0.03	14.5	**0.02**	**4.3**	**0.02**	**8.6**
Common to NO and CS	0	0.2	0.02	11.7	**0.01**	**1.7**	**0.04**	**12.7**
Common to CS and AF	0.08	20.5	0.01	6.3	**0.07**	**17.1**	**0.03**	**12.1**
Common to NO and AF and CS	0.05	14.0	0.03	18.7	**0.056**	**14.8**	**0.054**	**19.5**
Total	0.388		0.186		**0.379**		**0.275**	

For each predictor, the overall standardized β coefficient and percentage of variance explained in the communality analysis (% R^2 = Total/R^2) are reported. Results for model predictions over target behaviors (i.e., set of predictors of reading predicting reading fluency etc.) are reported in bold.

used in the present study as a predictor of calculation skills (see **Table 3**). It is a strong predictor of unique variance in the case in which time is measured (β = 0.13, 40.6% of explained variance) while it does not contribute at all (β = 0.00) in the case in which calculation accuracy is considered (**Table 3**).

When the RAN test is added to the model of calculation speed (see **Table 4**), it does not account for much unique variance (β = 0.02, 5.8% of accounted variance) but it appreciably contributes to shared variance (β = 0.13) much of which was with the Arithmetic Facts test (see last column of **Table 4**). Overall, the RAN test contributes substantially to the explained variance of the model of calculation speed (R^2 = 38.0%). By contrast, the contribution of RAN to the model of calculation accuracy is minimal both in terms of unique variance (β = 0.02, 5.4%) as well as shared variance (β = −0.01) and the overall contribution to the variance of the model was negligible (R^2 = 0.6%). Also in the case of spelling, no increase of explained variance was present when the RAN test was added to predictors, and the contribution of this variable was negligible both in terms of unique and common variance.

Overall, these data indicate that the RAN task contributes to the prediction in the case of dependent measures based on time but not in the case of dependent measures based on accuracy.

Computation Strategies Test

The Computation Strategies test also shows an interesting pattern of co-associations (see **Table 3**). In particular, it entered in both models of calculation speed and accuracy. However, it also strongly predicted unique variance in reading fluency (β = 0.09, 23.9% of explained variance) and, to a lesser extent, in spelling accuracy (β = 0.01, 6.0% of explained variance).

To understand the possible relationship between performance in this test and the other reading markers we added the Computation Strategies test to the predictors of the original Reading model (Zoccolotti et al., 2020). The results of this analysis (see **Table 4**) are quite surprising. Indeed, adding the Computation Strategies test appreciably increases the total power of the model passing from the original 48.7% to 53.4%, indicating a total increase in explanatory power of 4.7%. The Computation strategies test contributes both unique (β = 0.05; 8.9% of the total variance accounted for by the model) and

TABLE 4 | Changes to various original models (from Zoccolotti et al., 2020) when a new predictor is added.

Added predictor	Original Model	% R^2 original model	% R^2 with the added predictor	Un.	Com.	Tot.	% R^2 Tot	% R^2 Un.	Variance shared with
Arithmetic Facts (AF)	Reading (fluency)	48.7	48.9	0.003	0.29	0.29	59.7	0.6	OD (14%); OD and V-ApwM (16%)
	Spelling	29.2	30.9	0.02	0.08	0.10	32.7	5.7	OD (18%); OD and SpwR (16%)
Orthographic Decision (OD)	Calculation (speed)	37.9	38.2	0.004	0.16	0.17	43.4	1.0	AF (12%)
	Calculation (accuracy)	27.5	28.9	0.01	0.16	0.17	60.2	4.7	NO and AF and CS (16%)
RAN	Calculation (speed)	37.9	40.2	0.02	0.13	0.15	38.0	5.8	AF (23%)
	Calculation (accuracy)	27.5	29.1	0.02	−0.01	0.002	0.6	5.4	–
	Spelling	29.2	29.2	0.000	0.001	0.001	0.5	0.03	–
Computation Strategies (CS)	Reading (fluency)	48.7	53.4	0.05	0.18	0.23	42.6	8.9	OD (18%)
	Spelling	29.2	29.6	0.004	0.08	0.08	26.9	1.2	OD (10%); OD and SpwR (15%)
Repetition of Pseudo-word Series (RpwS)	Reading (fluency)	48.7	50.1	0.01	0.17	0.18	36.8	2.8	OD (10%)
	Calculation (speed)	37.9	38.5	0.01	0.03	0.03	8.9	1.6	–
	Calculation (accuracy)	27.5	28.6	0.01	0.09	0.10	36.6	3.6	NO and AF and CS (11%)
Visual-auditory Pseudo-word Matching (V-ApwM)	Calculation (speed)	37.9	37.9	0.000	0.08	0.08	21.5	0.1	AF (11%)
	Calculation (accuracy)	27.5	28.6	0.01	0.07	0.08	27.0	4.0	–
	Spelling	29.2	29.6	0.004	0.007	0.01	2.2	1.2	–
Number Order (NO)	Reading (fluency)	48.7	48.8	0.001	0.06	0.06	12.1	0.3	–
	Spelling	29.2	30.8	0.02	0.12	0.14	43.8	5.3	OD (16%); OD and SpwR (21%)
Single Pseudo-word Repetition (SpwR)	Reading (fluency)	48.7	48.8	0.001	0.08	0.08	16.4	0.03	–
	Calculation (speed)	37.9	37.9	0.000	0.04	0.04	11.2	0.000	–
	Calculation (accuracy)	27.5	27.6	0.001	0.02	0.02	5.9	0.02	–

The first column indicates the added predictor; the second the original model; next, the total percentage of variance (R^2) explained by the original model is presented (from Zoccolotti et al., 2020), followed by the indication of the total variance (R^2) explained by the same model after the addition of the predictor. Then, unique, common and total contributions of each added predictor are presented (as raw beta coefficients). The next columns report the% of total and unique variances (R^2) accounted by the added predictor with respect to the total variance explained by the model. The last column reports the list of predictor(s) with which the added predictor shared variance (in excess of 10%).

common variance (β = 0.18) with the three other predictors, and in particular with the Orthographic Decision test (see last column of **Table 4**). Overall, the Computation Strategies test contributes appreciably to the explained variance of the original model (R^2 = 42.6%). Note that the contribution of the Computation Strategies test to the reading fluency model is a different finding from the above reported contributions of the Orthographic Decision and Arithmetic Facts tests, because it explains additional variance to that explained by the original model; thus, this predictor accounts for variance that is not captured by any of the predictors in the original reading model. Possible interpretations of this unexpected finding are presented in the section "DISCUSSION."

When the Computation Strategies test is added to the model of spelling accuracy (see **Table 4**), its contribution is negligible in terms of unique variance (β = 0.004, 1.2% of the total variance explained) but more substantial in terms of shared variance (β = 0.08), most of which with the Orthographic Decision and Single Pseudo-word Repetition tests (see last column of **Table 4**). Overall, the Computation Strategies test contributes to the explained variance of the model with R^2 = 26.9%.

Repetition of Pseudo-Word Series Test

The Repetition of Pseudo-word Series test plays a moderate contribution to reading fluency and calculation accuracy (see **Table 3**). Thus, it accounts for 8.5% of the unique variance in the case of reading (fluency) with a β of.03 and 14.0% of the unique variance in the case of calculation (accuracy) with a β of.03. In both analyses, it also contributes in these models in terms of shared variance. By contrast, it does not appreciably contribute to the calculation speed model.

When the Repetition of Pseudo-word Series test was added to the original models (**Table 4**), this predictor plays a marginal unique contribution in all the analyses. However, it shares a large quote of variance with predictors in the model of Reading speed (β = 0.17), in particular with the Orthographic Decision test. It also shares variance (β = 0.10) with predictors of calculation accuracy (in this case the shared variance is with all the predictors in the model; see last column of **Table 4**), while its shared contribution with the predictors of calculation speed is limited (β = 0.03). The overall contribution of the Repetition of Pseudo-word Series test is moderate in the case of reading fluency (R^2 = 36.8%) and calculation accuracy (R^2 = 36.6%) and minimal in the case of calculation speed (R^2 = 8.9%).

Orthographic Decoding: Visual-Auditory Pseudo-Word Matching Test

Finally, there are predictors that exert an influence mainly (or only) on a specific behavior. Performance in the Visual-auditory Pseudo-word Matching test is a predictor of reading fluency, but does not appreciably account for unique variance in the case of calculation speed (β = 0, 1.3% of the total variance explained by the model) or calculation accuracy (β = 0.02, 9.9% of the total variance explained by the model) and also contributes little, although not zero, to common variance (see **Table 3**). Interestingly, the Visual-auditory Pseudo-word Matching test also does not contribute to the prediction of spelling either in terms of unique variance (β = 0.01, 2.5% of the total variance explained by the model) or shared variance (see **Table 3**).

When the performance in this test is added to the original reading and calculation models (**Table 4**), it does not contribute in terms of unique variance (β = 0 in all models) but only in terms of shared variance and only for calculation speed (β = 0.08) and accuracy (β = 0.07). In particular, this task shares variance with the Arithmetic Facts test (see last column of **Table 4**). Overall, the contribution of the Visual-auditory Pseudo-word Matching test in these analyses is limited (ranging R^2 = 2.2 to 27.0%).

Number Order Test

A partially similar pattern is present in the case of the Number Order test. While it contributes to the models of calculation, its predictive power in the case of reading and spelling is limited. In the case of reading, it contributes little in terms of unique variance (β = 0, 0.5% of the total variance explained by the model) as well as shared variance (see **Table 3**). In the case of spelling, it moderately contributes in terms of unique variance (β = 0.05, 27.8% of the total variance explained by the model which is, however, rather low).

As reported in **Table 4**, when this task is added to the predictors of reading, the explained variance of the model does not increase: in fact, the unique contribution is null and the shared variance is moderate (0.06) and without a detectable pattern of association with other tasks. The overall contribution of the Number Order test in this analysis is limited (R^2 = 12.1%). In the case of the original spelling model, the explained variance passes from 29.2% to 30.8% due to the moderate unique contribution of this task to the model (β = 0.02) and the large quote of shared variance (β = 0.12; 39% of the overall variance) shared especially with the Orthographic Decision test and with the Orthographic Decision jointly with the Pseudo-word Repetition test. The overall contribution of the Number Order test in this analysis is moderate (R^2 = 43.8%).

Single Pseudo-Word Repetition Test

As reported in **Table 3**, the Single Pseudo-word Repetition test contributes to the model of spelling but does not appreciably account for unique variance in the case of reading (β = 0.01, 1.5% of the total variance explained by the model). It also does not contribute much unique variance to calculation accuracy (β = 0, 1% of the total variance explained by the model), while it moderately contributes to calculation speed (β = 0.01, 7.9% of the total variance explained by the model).

Finally, when performance on the Single Pseudo-word Repetition test is added to the other models (**Table 4**), in each case the unique variance is nil and the shared variance is moderate. Overall, the Single Pseudo-word Repetition test contribution in these analyses is limited (ranging R^2 = 5.9 to 16.4%). Thus, by and large this ability predicts only the spelling behavior.

DISCUSSION

The Discussion is organized in three parts: (A) first, we illustrate and comment the results of the present analyses; (B) then we exploit a theoretical proposal to frame our results; and (C) we present a novel model of the association between learning skills as a first step in the development of a model of comorbidity of learning disorders.

A. Interpreting Results of Cross-Predictor Analyses

The pattern of results for the cross-over analyses would be indeed surprising from the standpoint of putatively specific learning disturbances. Several, though not all, predictors show strong influences not only on their target behavior but also on putatively non-target behaviors. Below we illustrate possible interpretations of some of these relationships. Clearly, this is a data-driven process but one that may have the potential of understanding the breadth of the influence of factors more than in the typical case in which a given factor is tested only within a single, specific domain. Note that no attempt is made to yield an entirely exhaustive interpretation of every single factor (in all possible combinations) across all behaviors. The aim is rather that of using these results for their potential heuristic role in generating hypotheses on the association of learning skills and eventually on the co-morbidity of disorders of learning behaviors.

Memory Retrieval and the Ability to Automatize Instances

A particularly striking pattern is that pointing to an association between the Orthographic Decision and the Arithmetic Facts tests. Both tests are "strong" predictors of a target behavior (reading/spelling and calculation, respectively), but also of the other non-target behaviors (calculation and reading/spelling, respectively). What could be the reason for this pattern?

In spite of their surface characteristics, it should be noted that the Orthographic Decision and the Arithmetic Facts tests share the requirement of calling a specific trace from memory. In the case of maths, children first learn to make computations by applying an algorithm; then, by repetitive exposure to the solution of a given simple operation (such as ”3 times 8”), they learn to directly access the solution of the operation (i.e., 24) without application of the algorithm. The Arithmetic Facts test measures this latter ability. In a similar vein, at least in a regular orthography such as Italian, children first learn to apply grapheme-to-phoneme (and phoneme-to grapheme) conversion rules to read (and spell) words. Through repetitive exposure to print, they slowly learn to directly access the target word (i.e., reading by “sight”) without passing for the conversion of graphemes into phonemes (e.g., Marinelli et al., 2015, 2016b, 2020a). Within the dual route tradition, it is generally believed that access to the orthographic input lexicon facilitates reading and spelling of all words and ensure reading speed; however, this effect is clearest in the case in which the word cannot be read and spell through the sub-lexical conversion routine, as is the case of irregular words. The Orthographic Decision test ensures that the reader uses the orthographic lexicon also in a consistent orthography, such as Italian, by requiring the child to judge the orthographic correctness of a pseudo-word homophone to a real (inconsistent) word, a task that can be solved only through reliance on acquired orthographic representations not on sub-lexical mapping. Then, both in solving arithmetical facts and in carrying out orthographic decisions on inconsistent words, with increasing experience and practice children progressively pass from the application of an effortful and serial algorithm to a less demanding process based on the fast and automatic retrieval of a memory trace. Thus, the Orthographic Decision and the Arithmetic Facts tests share the requirement *to retrieve a trace in memory*, not to apply a specific algorithm.

A theory that formalizes the ability to retrieve quickly and automatically a specific memory trace is the “*Instance theory of automaticity*” proposed by Logan (1988, 1992). According to this learning theory, automatization is acquired through repetitive presentation of a stimulus: in this way, the “instance representation” of an individual object or event is stored in memory (“obligatory encoding”) and, the more repetitions, the more information becomes directly available (“obligatory retrieval”). In the course of learning, the individual’s responses to the item are progressively faster, the pace of learning being described by a power function (as originally proposed by Newell and Rosenbloom, 1981). This indicates that initial learning is fast and rate of improvement is progressively slower over target repetitions, although the function does not clearly reach a plateau (mathematically, the power function goes to zero at infinite). Still, the nearly asymptotic portion of the curve expresses a very fast and nearly constant performance, as typical of automated tasks characterized by “obligatory retrieval”.

Based on the present finding that the Orthographic Decision and the Arithmetic Facts tests are strong predictors of both the target and non-target behaviors, we propose that they both capture (at least in part) the degree of automatization characterizing an individual (e.g., how consolidated and easy to retrieve is the information that $3 \times 8 = 24$; or that QUOCO is not a correct spelling). Thus, the individual level of *ability to automatize instances* can offer a basis for this finding.

Using Contextual Information in Different Domains

Another test that showed crossed influences was the Computation Strategies test. This did not only explain variance in the two calculation models but actually increased the overall power of the model of reading by a substantial amount. This test accounts for a proportion of variance that is actually additional to that of all the predictors considered in the original reading model.

Several interpretations can be advanced to understand this unexpected finding. Here, we focus on only one based on an analysis of the characteristics of the Computation Strategies test. This explicitly requires the child to use the available information to solve the task instead of computing. Thus, knowing that $13 + 148 = 161$ (presented on the left side of a sheet of paper) can be used to speed up an operation such as $14 + 149 = \ldots\ldots$ (presented on the right side) over and above the knowledge of arithmetic facts, calculation properties and abstract number representations. In other terms, the context provides information that can be used for the processing of the ongoing stimulus, greatly facilitating the computation task. Similarly, it seems possible that the same ability is useful in reading meaningful texts, i.e., the task used in the present study to measure reading performance.

Thus, to the extent to which the Computation Strategies test captures variance in a factor that can be defined as “use of contextual information”, this may account for its contribution to the model of reading. Indeed, it is well known that contextual information optimizes reading fluency (e.g., Perfetti et al., 1979; Stanovich and West, 1979; Becker, 1980; Simpson et al., 1989). Our original model of Reading fluency did not consider processing of contextual information, but the crossed influence of the Computation Strategies test suggests that a model of reading could be enriched by considering this fourth factor. Clearly, this is a *post hoc* interpretation but one that can be subjected to empirical test. In particular, if the above speculation is correct, one would expect that performance on the Computation Strategies test would not contribute to variance in reading lists of unrelated words (a test not included in the present study).

Role of the Ability to Integrate Task Subcomponents

Some factors exerted an influence that was selective for a specific parameter across behaviors. In particular, RAN contributed in explaining variance to both reading fluency and calculation speed but did not contribute in explaining variance across measures of accuracy (both in the case of spelling and calculation). The RAN task requires the child to integrate the processing necessary for selecting the landing point of the next fixation with processing of the actual target and identification, as well as access the name of the visual object, its maintenance into short-term memory and actual utterance. These activities have to be effectively synchronized for allowing a fluent performance across a matrix containing several different targets. When seen in the light of reading, this skill appears to mark a dimension of “integration of reading sub-components”; indeed, RAN requires all the operations typical of text reading, apart from orthographic analysis (Protopapas et al., 2013; Zoccolotti et al., 2014). This interpretation is supported by the evidence which shows that the relationship of RAN tasks to reading is diluted if the number of alternative targets is reduced and the subject has to produce a single repetitive response (Georgiou et al., 2013) or a single, discrete presentation of RAN-type stimuli (instead of multiple) is used (Georgiou et al., 2013; Zoccolotti et al., 2013). In trying to account for the influence of RAN in the case of the speed of performance in mental calculations, one may refer to a similar interpretation. Indeed, the subject has to integrate processing necessary for selecting the landing point of the next fixation with processing of the actually fixated information, as well as its maintenance into short-term memory in order to apply the required processing (sum, subtraction, etc.). Thus, one can think that RAN performance marks a cognitive dimension, which is present in both reading and calculation, concerning the "ability to integrate task sub-components" in order to achieve a fluent performance.

Predictors Specific for Single Behaviors

Finally, some variables exerted an effect that was quite specific for a single behavior. Thus, the Visual-auditory Pseudo-word Matching test was predictive of reading skill but not (or minimally) for spelling and calculation. The Single Pseudo-word Repetition only entered in the prediction for spelling and not in any non-target cross-over model. Finally, the Number Order test (which marks the cognitive dimension of "Symbolic number representation") had an influence almost only in the case of the target behavior, i.e., calculation skills. It seems that these tasks tap processes that are specific for a single behavior.

B. A Multi-Level Approach to Co-morbidity in Learning Disturbances

Overall, the results of the cross-predictor analyses indicate that some predictors have a general influence across various behaviors while others predict different behaviors but only for a specific parameter, such as fluency but not accuracy, and still others are specific for a single behavior. These findings cannot be easily fit into a framework considering a single level of explanation. Rather, it appears that predictors act at different levels of generality and such characteristic should be kept into account in trying to propose a comprehensive interpretation of association of learning skills. This in turn might help to better understand the co-morbidities across different learning disabilities.

As indicated in the Introduction, one traditional distinction is between "competence" and "performance," originally put forward by Chomsky (1966) in the discussion about language. In general, competence is referred to as the abstract, general capacity to process in a given domain (such as language in the case of Chomsky). The concept of "performance" refers to the fact that what we measure in a given individual with a given task is not a direct measure of his/her competence in the domain, but the result of an interaction between competence and the specific characteristics of the task. So, in a sense, the critical difference between competence and performance is that the former is task-independent while the latter is task-specific. In this perspective, all measures of a given behavior depend upon both the competence in a specific domain and the performance on the specific task.

The value of making such a distinction is that one may assume that deficits in a specific competence (e.g., reading) will show up pervasively across different types of tasks in the domain (such as reading meaningful texts, list of words, or pseudo-words, either printed or flashed alone on a computer screen, or presented by rapid serial visual presentation, etc.). Conversely, other defects may appear contingently to the requirements of the actual task (for instance, a child may be below the norm in reading a text but not in reading single short words; may have spelling problems under dictation but be fair in writing his/her own ideas; may have problems in maths under time pressure while being accurate if enough time is given). In all these cases "performance" components are on the foreground.

The importance of such "performance" or "processing" deficits should not be overlooked (for a discussion see Bishop, 1997). In real life, we read or do calculations under specific conditions, which need to be duly fulfilled for an effective outcome. Much the same occurs in a clinical setting where reading, spelling or maths deficits are typically investigated largely using standardized tasks similar to the typical conditions of stimulus presentation that children face during their school experience (and that are typically graded according to the number of years of school experience). It should also be kept in mind that any measure of reading, spelling or maths behaviors will depend upon both competence and performance and separating these two components is inherently difficult although it may be attempted by the use of *ad hoc* analyses.

Further, we propose that a third level of explanation should be added to fully account for the complexity of results and is related to the process of "learning" or "acquisition", and particularly to its automatization phase. By and large, acquisition occurs through the effect of practice. First of all, extended practice is critical to produce automatized responses to specific target items. This would contribute to the ability to read (or spell) words (or make multiplications) not based on grapheme to phoneme conversion (or counting digits), but on direct memory retrieval of specific target items (or "instances"; Logan, 1988, 1992). Thus, through extended practice the child learns specific items (e.g., regular frequent words, such as "house," or irregular words such as "pint," or the output of simple mathematical operations such as $3 \times 8 = 24$ or $4 + 2 = 6$). In keeping with Logan (1988, 1992) proposal, learning specific instances directly contributes to the automatization, and obligatoriness, of responses, contributing to make reading, spelling and doing maths fast and smooth processes. Learning disabilities do not refer to the complete inability of the child to learn to read, spell or to do calculations as much as *the inability to do so smoothly and efficiently*. Thus, for example children with dyslexia characteristically read in an effortful, not automatic fashion; in order to read, the child has to place all his cognitive resources on decoding the text with little residual ability left for comprehension. Thus, we propose that also the *ability to learn specific instances* should be included in a three-level framework of interpretation in explaining the acquisition of learning skills.

However, practice influences all processes of learning a skill, such as reading, spelling or maths, including the acquisition of competence and the tuning of performance skills. For example, in the case of reading, through extended practice, the child has sufficient experience with the process of converting graphemes into phonemes in a given orthography, which may be the condition to activate and form a specific reading "competence" (see further comments below). Through extended practice, the child also optimizes his/her capacity to read under the typical task format used in school (e.g., Girelli et al., 2017). Thus, in several languages, words are presented horizontally, printed in black on a white surface and the child learns to read them in a left-to-right direction, slowly acquiring the capacity to smoothly read sequences of words in a text (not only isolated targets). Thus, practice favors the emergence of a reading "competence" as well as optimizes efficiency in specific task conditions ("performance").

Some general functions and characteristics of the competence, acquisition and performance levels are summarized in **Table 5**.

C. A Model of Learning Skills Based on Competence, Performance and Acquisition (Automatization) Levels

Drawing on the distinction among competence, acquisition and performance levels it is possible to outline a unitary, multi-level model of reading, spelling and maths skills. The model is illustrated in **Figure 2**. For the sake of presentation, only some of the factors possibly affecting performance are indicated; furthermore, for maths skills, only the case of calculation speed (but not accuracy) is shown. Note that the architecture of this model is considerably more general than that presented in **Figure 1**; however, also this can still be considered as a proximal model to the extent in which it envisages explicit relationships (depicted by arrows in the figure, and made explicit in the text) between predictors and different behaviors.

The model illustrates the possible sources of associations and dissociations among reading, spelling and maths skills. In particular, it is assumed that independent competences (represented in blue in **Figure 2**) are present and specific for these three behaviors and that this may account for dissociations among learning skills (as well as disorders). On the other hand, association among learning skills may be due to an acquisition factor (green lines coming from the three acquisition boxes represented in **Figure 2**), i.e., the "ability to consolidate instances" which is responsible for automatized responses in reading, spelling and maths.

Dissociations Among Learning Behaviors

The view that specific, different competences underlie the three behaviors considered is supported by the literature, although the same literature is rich of possible alternatives on the nature of the competences involved in reading, spelling and maths.

Reading competence

In the case of reading, one line of research emphasized the role of phonological processing (e.g., Stanovich, 1988). However, a systematic theory-based test of this hypothesis indicated that both English and Hebrew individuals with dyslexia showed the expected sensitivity to general phonological contrasts, although also had moderate deficits in some (though not all) phonetic categories (Berent et al., 2013, 2016). The authors concluded that individuals with dyslexia show spared phonological competence while they may be impaired in some phonetic tasks (i.e., pointing to deficits in "performance" processes). Similarly, also Ramus and Szenkovits (2008) reported spared phonological competence with deficits in children with dyslexia associated to specific task conditions (i.e., "performance" factors).

In previous studies by our research group, we focused on a different alternative interpretation, i.e., that reading competence expresses the ability to form a pre-lexical representation of the orthographic string. To test this possibility, we examined performance of children with dyslexia across several different

TABLE 5 | Main functions and characteristics of competence, acquisition and performance levels as related to individual differences in learning skills and comorbidity of learning disorders.

	Function(s)	Characteristics	Specificity/overlap
Competence	Ability to activate a specific set of representations and processes	- Domain-dependent - Task-independent - Sensitive to practice	Dissociation of deficit may be present to the extent in which different processes rest upon different sets of representations and algorithms
Acquisition	- learning specific rules and/or regularities (*algorithms and core competence*)	- Domain-dependent	
	- learning direct memory traces (*instances*) which are automatically retrieved and coercively activated in the presence of appropriate stimulation	- item specific - Domain-independent It follows a general law a practice, characterized by a slow pacing of learning (long periods for over-learning and automatic responding)	Consolidation of instances may dissociate from learning of algorithms. Deficits in developing automaticity may lead to learning disorders across different domains (comorbidity)
	- Upon practice, the child gets accustomed to the *typical task format*, characteristic of a given behavior (e.g., reading a text in a left to right manner).	- Partially domain-dependent	
Performance	Actual performance depends on the characteristics of the task which may call into action different processes depending upon the specific competence involved or/and the characteristics of the task itself (e.g., a speed task).	- Task-dependent - Partially domain-dependent - Sensitive to practice	It may lead to both associations and dissociations of learning skills (and disabilities) depending on the degree of overlap of: task-specific processes and their interaction with specific "competence" requirements

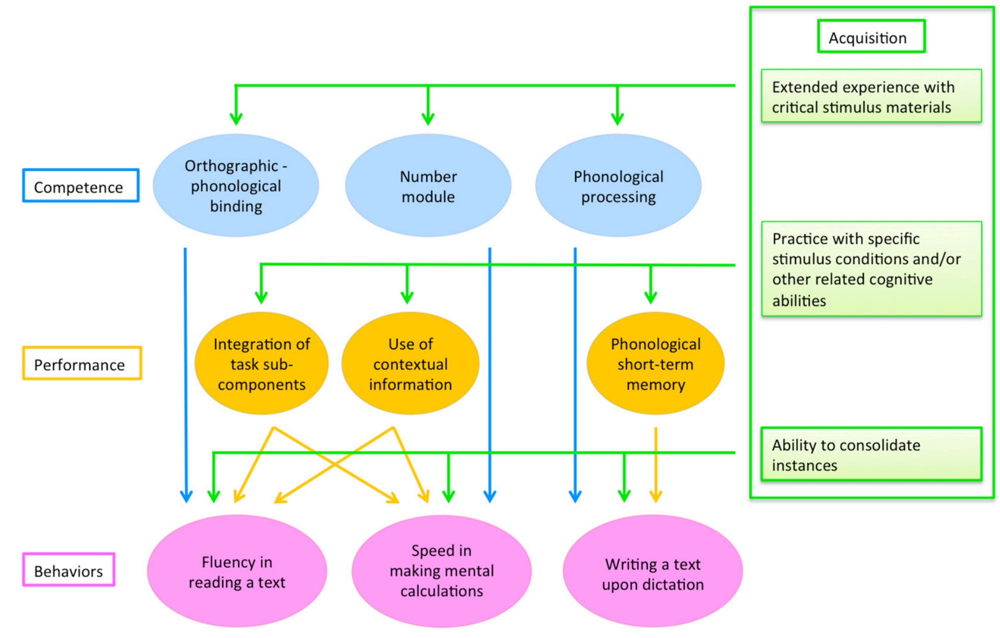

FIGURE 2 | A multi-level model of learning cognitive skills. Target behaviors are expressed in terms of task-specific exemplars. As for mathematical skills, only the case of calculation speed is shown. A description of the figure is presented in the text.

experimental conditions to cancel out the effect of performance and let emerge the non-task specific characteristics of the deficit. In a series of investigations, we adopted this approach by applying models of global performance, such as the rate and amount model (RAM; Faust et al., 1999) or the difference engine model (DEM; Myerson et al., 2003) to study reading deficits. Results indicated that the same "global" defect was present whenever a string of letters (not a single letter or bigram) was presented (De Luca et al., 2010), and whether or not it constituted a word (i.e., the same deficit was observed in the case of words, pseudo-words as well as unpronounceable non-words; Marinelli et al., 2014). Importantly, the difficulty of children with dyslexia did not extend to non-orthographic materials (such as pictures; Zoccolotti et al., 2008; De Luca et al., 2017) or responding to stimuli presented in a non-visual modality (i.e., acoustically; Marinelli et al., 2011). These results appear consistent with the idea that the basic competence involved in reading is the ability to form a pre-lexical representation of the orthographic string (also called "graphemic description" by Marsh and Hillis, 2005).

This view is consistent with a comprehensive model of the putative "competence" of reading that has been the focus of a large series of neuroimaging investigations by Dehaene and colleagues (e.g., Dehaene et al., 2005). In summarizing their studies, Dehaene et al. (2005) have proposed a local combination detectors (LCD) model. Interestingly, according to Dehaene and Cohen (2007), tuning of the VWFA represents an instance of cultural re-cycling, such that, upon appropriate exposure to a given orthography, neurons in the areas devoted to visual object recognition optimize their responses to specific stimuli, such as letter strings (bigrams, trigrams and quadrigrams). Note that, in this view, the reading competence is associated to the ability to efficiently read letter strings which are represented within the most frequent words in a given language, not necessarily the capacity to read specific words. While the LCD model by Dehaene et al. (2005) emphasizes visual processes, in several parts of their formulation they also indicate that this sensitivity must be coupled with specific phonological activation. This point has been made most cogently by Blomert (2011) who summarized a number of imaging studies pointing to the presence of specific orthographic-phonological connections (Blau et al., 2008, 2009, 2010) and refers to this pattern in terms of orthographic-phonological binding. Thus, extended practice with orthographic materials is necessary to reach a fine tuning of visual mechanisms and strong connections with language areas; the first years of schooling are crucial to this aim (Blomert, 2011) but there are children who show difficulties at these early stages, indicating a selective difficulty in the acquisition of the core reading competence.

The challenge to define the core competence that characterizes the process of reading is still open. However, based on the above quoted evidence, we propose as a working hypothesis that the key competence in reading refers to the ability to form and activate pre-lexical processes of "orthographic-phonological binding" upon the presentation of orthographic strings. Orthographic-phonological binding is represented in **Figure 1** in the oval blue. Notably, the results of the present study are well in line with this proposal. Thus, the Visual-auditory Pseudo-word Matching test entered in the prediction of reading but not in that of maths or spelling.

Maths competence

Literature on numerical skills clearly indicates a separate key competence than reading. In particular, several authors have proposed that the core competence regards the *ability to represent* *and process numerosity* (Landerl et al., 2004; Butterworth, 2005; Wilson and Dehaene, 2007). Butterworth (2005) explicitly refers to the need for this skill to be tuned through adequate exposure. In the present experiment, a measure which can putatively capture this skill is the performance in the Number Order test. Consistently, performance in this test entered in the model of numerical skills and explained an important portion of variance, but not in that of reading or spelling.

Note that authors differ in their consideration about whether this skill should be seen as general or two distinct representational systems for symbolic and non-symbolic numerosity tasks should be envisaged (e.g., Butterworth, 2005; Sasanguie et al., 2014). Here, partly because of the complexities inherent in carrying out non-symbolic numerosity tasks, we only focused on symbolic tasks. So, present data are not informative concerning this distinction and further work seems necessary.

Recently, Moll et al. (2019) reported that co-morbidity between reading and maths disorders depends upon the maths subskills considered. Thus, there was a stronger association between literacy and arithmetic than between literacy and magnitude processing (measured both as comparison among digits and perception of dots numerosity). This finding is in line with the present proposal that the core competence of representing and processing numerosity (Number module in **Figure 2**) accounts for the specificity of the maths disorder, not for its co-morbidity with other learning disabilities.

Spelling competence

It is somewhat more complex to adjudicate whether reading and spelling rest on the same or different competences. As stated above, reading competence heavily rests on the ability (made possible by specific areas in the left temporal-occipital cortex) to activate visual traces of letter strings such as bigrams, trigrams and quadrigrams. On the converse, it is generally believed that spelling closely rests on the *availability of well-defined phonological traces* (e.g., Perfetti, 1992). Therefore, we focus on such ability as the specific competence supporting spelling (see the blue oval in **Figure 2**).

The results in our previous report (Zoccolotti et al., 2020) and the present analyses are consistent with this view. While phonological markers did not appreciably contribute to the prediction of reading, they did so in the case of spelling. Notably, two phonological tests (Single Pseudo-word Repetition and the Repetition of Pseudo-word Series) contributed to the best model for spelling accuracy and they did so in a suppressive interaction from each other (Zoccolotti et al., 2020). The performance in the Repetition of pseudo-word series seems closely coupled to the specific requirements of the task. Thus, in the "Nonna Concetta" test, dictation stresses the ability of the child to maintain in short term memory a complex sequence of phonological information. Accordingly, one may propose that the Repetition of Pseudo-word Series test captures variance associated to the specific task characteristics (i.e., performance). By contrast, one may envisage that the variance of the Single Pseudo-word Repetition test may be more directly related to the core phonological competence of spelling. If this hypothesis is correct, this latter test should enter in the prediction of spelling skills independent of the specific task, i.e., as a marker of the competence in spelling.

In **Figure 2**, we tentatively point to the three above defined competences in terms of independent processing (as sketched by the three separate blue arrows pointing to the three behaviors). Core competence factors largely account for the presence of distinct components of variance in reading, spelling or maths skills and potentially for the dissociability of deficits in these learning domains. Yet, a note of caution is in order on this conclusion. In fact, it should be kept in mind that competence cannot be directly probed with a single task; thus, a thorough test of a given competence requires direct control of the role of task requirements, which in turn would require *ad hoc* investigations.

Associations Among Learning Behaviors

By contrast, associations (or co-morbidity) are mostly explained by the presence of a domain-independent factor ("ability to consolidate instances"). The direct effect of this factor on behaviors is indicated in **Figure 2** by the horizontal green line from the "Ability to consolidate instances" box pointing with three green arrows to the three target behaviors. Accordingly, individual skill in automatizing would span over reading as well as spelling and maths. We previously referred to the distinction between proximal and distal factors. In describing distal factors, frequent examples in the literature refer to domain general processes, such as short-term memory or attention. In the view proposed here, the ability to automatize is seen as domain general process but one for which an explicit relationship of its influence over the dependent measures is envisaged, i.e., it is described in proximal terms.

In particular, the ability to automatize is a factor that contributes to efficient performance. Conversely, poor ability in forming instances does not make the behavior impossible but rather has the more specific effect of preventing fast and fluid reading, efficient spelling and fast and efficient calculation. As stated above, children (and even more so adults) with dyslexia are not unable to read but their reading is cumbersome, inefficient and ultimately tiring, characteristics that indicate a controlled, voluntary mode of processing (Schneider and Chein, 2003). This contrasts with the smooth and efficient decoding of the typically developing peers, which marks their pre-attentive, automatic processing (Schneider and Chein, 2003). Thus, lack of automaticity does not necessarily indicate an impaired core reading competence (which of course may also be present), but would indicate a deficit in a component necessary for fluent reading, and one that can be a source of at least partial associations.

Thus, following our hypothesis, a lack of automaticity in reading should be associated with a deficit at maths level, in the form of difficulty to retrieve arithmetic facts. Indeed, adults with dyslexia were found defective in their ability to retrieve arithmetic facts, although their numerical representations were spared (De Smedt and Boets, 2010). Accordingly, they show an "incomplete" pattern of co-morbidity (meaning that the association is not between behaviors as such, but between sub-components of different behaviors). In this vein, one may hypothesize that other forms of incomplete co-morbidities may be present (for a discussion on this point see Moll et al., 2019). For example, children with dyscalculia including a limited capacity to retrieve arithmetic facts should show selective deficits in reading irregular words or choose among homophonic versions of orthographic strings with inconsistent transcription, even in cases in which there are no sufficient elements for a formal diagnosis of dyslexia. Further research is needed to confirm this hypothesis.

Another prediction that can be advanced is that deficits that can be ascribed to a defective ability to consolidate instances should emerge more clearly late in the course of development, when typically developing children have consolidated their knowledge of many items allowing fast and smooth reading. Findings along this line have been advanced in terms of spelling skills by Angelelli et al. (2010b). They noticed that children with dyslexia showed parallel deficits in spelling but the characteristics of the writing deficit changed as a function of age. In third grade, children showed a generalized deficit encompassing all stimulus categories while, in fifth grade, there was a clear prevalence of spelling errors for inconsistent words, i.e., words which require the retrieval from memory of the lexical representation. In a parallel study, Angelelli et al. (2010a) examined the consistency of this lexical deficit between a reading (orthographic decision) and a spelling task. Fifth grade children with dyslexia showed a parallel impairment in both tasks and, in particular, showed item consistency across reading and spelling, i.e., they were impaired in judging the orthographic correctness of the very same words with irregular transcription which they failed to spell. Thus, their lexical deficit was item specific but consistent across reading and spelling, a pattern consistent with the idea of a cross-modal defect in consolidating specific instances. Finally, Marinelli et al. (2017) recently reported that, in spite of their item-based lexical deficit in both tasks, children with dyslexia showed appropriate sensitivity to the distributional information of sound-spelling mappings at sub-lexical level and such knowledge facilitated both spelling and reading, allowing for partial compensation of their lexical deficit.

Overall, it is proposed that the putative lexical deficit shown by children with dyslexia in both reading and spelling can be ascribed to a more general defect in consolidating individual instances. Consistently with the "Instance theory of automaticity" (Logan, 1988, 1992), such deficit (a) emerges more clearly late in the course of development, when automatization is acquired in most typically developing children (Angelelli et al., 2010b; Marinelli et al., 2017) and (b) is characterized by item specificity (Angelelli et al., 2010a; Marinelli et al., 2017). Furthermore, in keeping with the idea that a deficit in the ability to consolidate instances is domain-independent, the deficit is quite consistent between reading and spelling (Angelelli et al., 2010a). Finally, the deficit is independent from a deficit in competence as such (Marinelli et al., 2017). So, these data are consistent with the idea that some children may suffer from an acquisition defect which is particularly evident in reading and spelling tasks calling for item specific knowledge of words with inconsistent mapping. Based on the present hypothesis, we would expect these children to be also selectively impaired in arithmetic fact retrieval, a prediction that can be the object of future investigations.

Previous Studies on Automatization Deficits in Dyslexia and Difficulties Inherent to the Evaluation of This Hypothesis

The idea that the lack of automaticity may be a cause of dyslexia as well as other learning disturbances has already been advanced in the literature (Nicolson and Fawcett, 1990). Interestingly, these authors do not propose a deficit in automaticity as a single cause of dyslexia but rather they envisage an additional role for this factor, one that, however, may work for different learning disabilities, thus "*reuniting the developmental disorders*" (Nicolson and Fawcett, 2007). The position we take here is similar in this respect. However, a key distinction to the proposal by Nicolson and Fawcett is that we take a proximal approach and propose that the ability to consolidate instances is part of the multi-level model accounting for reading, spelling and doing maths. By contrast, in their original formulation, Nicolson and Fawcett (1990) rested on a distal approach. This led to experiments testing whether children with dyslexia were impaired in cerebellar-like tasks, such as balancing a rod or maintaining a posture. Perhaps, such relationships do exist, although substantial failures to replicate the original findings have been put forward (e.g., Wimmer et al., 1999; Ramus et al., 2003). At any rate, we propose that performance on these tasks only capture a long-distance relationship (in a distal perspective), while a much more specific formulation is possible within a proximal perspective. In particular, the model developed here allows specifying what should be predicted by the automaticity component, i.e., the ability to foster performance by activating direct responses to single, well-practiced items, an ability which is domain general because it holds across different learning tasks. Thus, no direct relationship is expected with reading or maths competence but with the ability to activate *specific reading or spelling traces or arithmetic facts*.

Research on the relationship between automaticity and reading illustrates a key problem in obtaining a measure of the individual sensitivity to acquire fast responses to specific events with practice, as adjudicated by the "Instance theory of automaticity" of Logan (1988, 1992). This essentially makes predictions over relatively long periods of training. In this vein, it is difficult to find a single task that directly measures individual differences in automaticity. By definition, tasks at "just one point in time" are sensitive to the product of a process that, however, depends upon both the initial performance on the task, the rate of improvement and the degree of practice. Thus, to obtain a process measure of automaticity, it is necessary to examine the course of acquisition, not only the performance at one point in time. The model of Logan (1988, 1992) provides clear predictions of how to measure performance to the extent in which it specifically envisages a power function rate of learning for new tasks; this can be expressed at both group and individual basis in terms of the coefficient of the curve as well as its setting parameters.

Nicolson and Fawcett (2000) were aware of this complexity and carried out one of the few studies based on long-term learning in relationship to dyslexia. They investigated the effect of a long-term training on a keyboard spatial task and a choice reaction task and reported a greater difference between the initial and final performance in typically developing children than in children with dyslexia, though the rate of learning was not different in the two groups. In the perspective advanced here, it is difficult to directly extrapolate from this type of tasks (which were conceived in a distal perspective) the performance in learning tasks, such as reading, spelling and doing maths. At any rate, this study is one of the first attempts to examine rate of learning in children with learning disorders over a relatively large time-scale. Other more recent studies (Martens and de Jong, 2008; Pontillo et al., 2014; Suárez-Coalla et al., 2014; Kwok and Ellis, 2015) have focused on reading tasks and examined the ability to improve performance on individual orthographic items devoid of meaning (pseudo-words) upon repeated presentations. In general, these studies indicate that rate of learning is slower in children with dyslexia. Characteristically, with training typically developing children considerably reduce their sensitivity to pseudo-word length while children with dyslexia do not (or do so to a much lesser extent). These findings with originally unknown items (pseudo-words) are in keeping with the idea that children with dyslexia have a deficit in optimizing their performance to individual items with training. Thus, at least part of the reading deficit may be ascribed to a reduced tendency to build and automatize responses to individual items.

Role of Task Requirements (Performance Factors) in Co-morbidity

Other sources of association among behaviors (and henceforth of co-morbidity) may originate from similarities among task requirements across different behaviors (see performance labels in the yellow ovals and arrows in **Figure 2**). As stated above, reading in standard conditions is a task with an inherent speed component. Similarly, in order to achieve an effective skill in making the moderately complex calculations typical of high-school teaching, adolescents have to learn to quickly and strategically activate algorithms and arithmetic facts knowledge. A task like RAN, which is particularly sensitive to the "*integration of task sub-components*" may well capture the "fluency" variance associated with performance in these two behaviors (as sketched by the two yellow arrows from the box pointing toward both reading and maths behaviors), possibly contributing to their frequent association. Consistently, a recent meta-analysis of 38 studies on the relationship between RAN and maths found that the correlation between RAN and fluency in doing calculations (speed) was on average higher than that between RAN and maths accuracy (Koponen et al., 2017).

In this vein, note that, presumably due to the diluting effect produced by the requirement of sequentially manually articulating the script (i.e., a relatively slow procedure), spelling does not usually pose such stringent time constraints in the integration of task sub-components (and spelling speed is generally not taken as a critical measure of orthographic competence). Consistently, performance on RAN tasks did not predict spelling performance, a finding in keeping with previous research in the literature (Moll and Landerl, 2009; Furnes and Samuelsson, 2011). Conversely, depending on the type of performance (spontaneous, from dictation etc.) writing may more or less call into action *phonological short-term memory* processes (as sketched by the arrow pointing only to spelling behavior).

Recent evidence on the partial dissociability between reading and spelling deficits also points to the mediating role of the speed component in reading (Mehlhase et al., 2019). Thus, spelling deficits were associated to deficient storing of orthographic representations in long-term memory while isolated reading fluency deficits were associated to spared orthographic representations but slowed access to these representations.

A full account of the role of "performance" factors is difficult as, by definition, they are task-dependent and one can use a large variety of tasks to study reading, spelling or doing maths. However, we feel that this is not a sufficient justification to exclude performance factors from a model of co-morbidity. Indeed, as emphasized by Pennington (2006), co-morbidity occurs among "complex" behaviors and the contribution of performance factors is indispensable if such behaviors need to be accounted for. In this vein, note that cognitive models of reading, spelling and maths give little, if any, space to performance processes (for a discussion see also Bishop, 1997). For example, models, such as the DRC, the CDP + or the triangle model, do not take into consideration the time constraints typical of the reading tasks and limit their formulation to an abstract analysis of single word reading. It is well established that reading deficits occur already at the level of single word processing, and predicting single word reading may be instrumental to build a model of the reading competence. However, experiments also show that the requirement to read multiple stimuli, such as in functional reading, selectively aggravates the reading deficit (e.g., Zoccolotti et al., 2013), a finding that has no clear space in current reading models. Thus, simulations based on models such as DRC or CDP + account for some effects shown in the literature (such as frequency, lexicality, regularity by frequency and so on) but provide a limited prediction of reading performance in everyday conditions. This limitation does not only affect our understanding of the target behavior (e.g., reading) but it also dampens our understanding of the sources of the co-morbidity among complex behaviors as they may not depend only upon the pervasive role of automatization deficits but also on complex interactions between competence and performance factors.

By contrast, some limited consideration of the actual need to implement an actual behavior is present in models of spelling (e.g., Hillis and Rapp, 2004). Thus, dual route models envisage that graphemes have to be converted into letter shapes for actual, motor performance. Yet, this terminal process is entirely encapsulated and supposedly does not interact with the central spelling processes. Interestingly, empirical evidence seems to go in the opposite direction of this independence. For example, it was reported that after training in handwriting, children showed significant improvements in compositional fluency (Graham et al., 2000). In a similar vein, Jones and Christensen (1999) reported that orthographic-motor integration accounted for a large proportion of variance in written expression over and above the effect of reading. These findings are in keeping with the idea that performance factors interact in complex ways with competence to determine actual behavior.

CONCLUSION, LIMITS AND PERSPECTIVES

The general aim of the present study was to develop a proximal model of the factors accounting for individual performances in learning skills, which could as well provide a base for understanding the co-morbidities among learning disorders. Our focus on proximal predictors, i.e. featuring explicit relationships between predictors and behavior, is in recognition of the great difficulty to pinpoint distal relationships. Present results indicated considerable overlap between the predictors of reading, spelling and maths. This overlap cannot be simply interpreted in terms of general cognitive abilities, as measured by well-established cognitive tests, because these latter predicted only a limited amount of variance. Notably, proximal predictors of reading accounted for performance in calculation tasks considerably better than did control factors measuring general cognitive abilities and much the same occurred when other crossed analyses were carried out, such as predicting reading with maths predictors and so on.

To interpret these results, we propose that it is necessary to separately consider factors in terms of competence, performance as well as acquisition/automatization. This multi-level distinction seems particularly suitable to account for the association of learning skills and, in perspective, for the widespread presence of co-morbidity among learning disorders. We have tentatively proposed that the three skills (reading, spelling and calculation) are made possible by the development through extended practice of three different abstract competences; this separation may account for the presence of partial dissociations among learning disorders. By contrast, crossed predictors point to associations (or co-morbidities). In particular, these can be seen as due to the domain general influence of the ability to automatize responses to specific items. Furthermore, also overlap between task characteristics (such as time pressure or the use of contextual information in different domains) may contribute as performance factors in producing associations between learning behaviors.

Three main conclusions of the present study come to the foreground.

Firstly, a proximal approach such as that presented in **Figure 2** may have the potential to interpret co-morbidities; in particular, it provides the ground to predict both associations and dissociations among disorders. This is an important advancement over previous models of learning focusing on a single behavior (or deficit) which, by definition, left associations with other learning disorders aside (for a discussion see Pennington, 2006). A proximal approach is potentially able to focus on a limited set of possible dimensions underlying each behavior (as it was done in Zoccolotti et al., 2020) and forces to interpret also unexpected relationships (as in cross-over analyses in the present study) in terms of explicit links between predictors and behavior. Indeed, the present results indicate that seeing learning disorders in their multi-level complexity may actually help in better interpreting every single disturbance to the extent in which it provides a framework to interpret cross-modal predictors. For example, the presence of deficits in developing automatic responses to individual targets (such as reading a word or retrieving arithmetical facts) may be more easily interpreted within a general learning framework than when examining a single disorder.

A second general conclusion is that a cognitive multi-level approach that distinguishes between competence, performance and acquisition factors, may be particularly effective in framing learning disturbances (Berent et al., 2013, 2016). In fact, reading models, whether in the cognitive or connessionist tradition only focus on the description of a competence and largely ignore performance factors (Bishop, 1997). However, both competence and performance influence the actual measures taken for reading, spelling and doing maths and failing to distinguish between the two hinders the actual possibility to test such models.

It is less obvious the need to assume that acquisition should be considered as a separate level of analysis. After all, practice affects all levels of processing. Thus, in the particular case of reading, spelling and maths, prolonged practice is necessary for creating a competence, possibly by tuning the response selectivity of moderately flexible cortical areas (as envisaged in the cultural re-cycling hypothesis; Dehaene and Cohen, 2007). Similarly, practice affects performance factors, such as the ability to process multiple targets in reading (e.g., de Jong, 2011; Protopapas et al., 2013) or using contextual information in maths and reading (present data). However, in our model we propose that "the ability to consolidate instances" should be seen as a separate level of analysis.

On general grounds, it has been emphasized that the learning system has to balance the need of "*detecting regularities in the world through generalization versus encoding and remembering particular events and their details through mnemonic specificity*" (Keresztes et al., 2018). Recent evidence indicates that the developmental lag between these two general functions (the former emerging ontogenetically much earlier than the latter) is at least partially mediated by differences in the timing of hippocampal maturation (Keresztes et al., 2018). Thus, we may extend this view to learning abilities such as reading, spelling and calculation, with "competence" as a form of learning by generalization and "ability to consolidate instances" as a form of learning specific events (whether words or arithmetic facts).

Third, we think that the present proposal has the potential to drive new research. Following the seminal work of Pennington and colleagues (Willcutt et al., 2005, 2010; Pennington, 2006), there has been an increasing interest in the search for the cognitive factors accounting for the co-morbidity between disorders such as dyslexia and dyscalculia (see also Pennington and Bishop, 2009). Still, the search for the common factors accounting for the overlap among learning disorders has proven largely unconclusive (Willburger et al., 2008; Landerl et al., 2009; Slot et al., 2016; Wilson et al., 2015; Cheng et al., 2018). In the view proposed here, learning disorders emerge when the combined effect of abilities/deficits in competence, performance and acquisition levels passes a threshold of overall inefficiency in reading, spelling or doing maths, generating a deficit with an identifiable effect on the child's life.

The present cognitive multi-level approach allows interpreting causal relationships at different levels of processing which may be instrumental in understanding previous results as well as making new predictions to be tested in future research. For example, recent research in maths difficulties contrasts a proposal of a deficit in a number module (Landerl et al., 2004; Butterworth, 2005; Wilson and Dehaene, 2007) with the alternative hypothesis of a close link between dyscalculia and a deficiency in visuo-spatial short term memory (Szucs et al., 2013). We propose here that both factors may actually be important, although acting at different levels of processing, the former in terms of numerical "competence", the second in terms of "processing" (or "performance") factors required by a typical calculation task. Furthermore, it is possible to make predictions about the possible combined role of competence, performance and acquisition including the presence of partial co-morbidities, i.e., deficits across learning disorders which may be specific of only some sub-components (and indeed may not reach the conventional standards for diagnostic purposes).

The limits of the present study should also be clearly spelled out. We examined the performance of an unselected group of children attending fifth grade on standardized tests of reading, spelling and maths. As we used a relatively large number of tests it was difficult to examine a very large sample; future research should consider the importance to confirm the present findings on a larger sample and also to extend them to other grades so as to support the generality of the conclusions.

As it is well known, performances on reading, spelling and maths tasks are described by continuous distributions and so-called "pathological" performances merely indicate performances lying at the very low ends of such continuous distributions (Protopapas and Parrila, 2018). These considerations suggest the importance of studying an unselected group of children; in particular, one may expect that associations and partial dissociations among key behaviors can be demonstrated both in the "normal" as well as in the "extreme" ranges of performance. Note that this approach is somewhat atypical. For example, models of reading, such as the DRC (Coltheart et al., 2001) or the CDP + (Perry et al., 2007) have been especially developed to account for selective deficits in reading in both acquired and developmental disorders (and similar considerations apply to models of spelling and maths). Still we consider this a good starting point and in future research we will test the multi-level model on children with established mixed deficits in reading, spelling and maths.

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 Comitato Etico – Fondazione Santa Lucia, Rome, Italy. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

PZ, MD, CM, and DS contributed conception and design of the study. MD organized the database and managed software and hardware. CM performed the statistical analysis. MD and CM designed the methodology. PZ 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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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2020.573998/full#supplementary-material

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Prevalence and Cognitive Profiles of Children With Comorbid Literacy and Motor Disorders

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There is a high prevalence of comorbidity between neurodevelopmental disorders. Contemporary research of these comorbidities has led to the development of multifactorial theories of causation, including the multiple deficit model (MDM). While several combinations of disorders have been investigated, the nature of association between literacy and motor disorders remains poorly understood. Comorbid literacy and motor disorders were the focus of the two present studies. In Study 1, we examined the prevalence of comorbid literacy and motor difficulties relative to isolated literacy and motor difficulties in a community sample ($N = 605$). The prevalence of comorbidity was five times greater than expected by chance alone, implying some relationship between difficulties. In Study 2, we examined the cognitive profiles of children with literacy and motor disorders amongst a subsample of children from Study 1 ($N = 153$). Children with literacy disorder had deficits in phonological processing, selective attention, and memory whilst children with motor disorder had deficits in visuospatial processing and memory, suggesting the disorders should be considered to have both independent and shared (memory) cognitive risk factors. Children with comorbid literacy and motor disorder demonstrated an additive combination of these deficits. Together, these findings are consistent with predictions from the MDM.

Keywords: comorbidity, dyslexia, developmental coordination disorder (DCD), prevalence, cognitive profiles, multiple deficit model

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INTRODUCTION

Disorders of literacy such as dyslexia, and of motor skills such as developmental coordination disorder (DCD), are complex, behaviorally defined, and neurodevelopmental in origin. Dyslexia is a disorder affecting accurate and fluent word reading and spelling (Rose, 2009), and DCD is a disorder affecting the acquisition and execution of coordinated motor skills (Blank et al., 2019). Despite being disorders of separate domains, it is reported that they are frequently comorbid with one another (Kaplan et al., 1998), and a notable overlap of cognitive impairments between these conditions is often reported. However, supporting evidence is scant. In this paper, we test whether the multifactorial view of neurodevelopmental disorders (e.g., Pennington, 2006) adequately explains comorbidity between literacy and motor disorders by (a) establishing whether the prevalence of comorbid literacy and motor difficulties is greater than expected and (b) investigating the nature of cognitive deficits in literacy, motor, and comorbid literacy and motor disorders.

The current view is that the etiology of neurodevelopmental disorders is multifactorial in nature (Thapar and Rutter, 2015). Accordingly, Pennington (2006) proposed the multiple deficit model (MDM) which conceptualizes disorders over four levels. At the etiological level, complex interactions between environmental and genetic risk and protective factors influence the development of multiple neural systems, either at the same time, or successively during later development. Neural systems affect the development and action of multiple cognitive processes which interact with one another. The impairments at the cognitive level lead to behavioral impairments at the disorder(s) symptom level.

An advantage of this model over alternative single-deficit models is that it offers a holistic and parsimonious explanation of the highly comorbid nature of neurodevelopmental disorders. Several different hypotheses about comorbidity assume that each disorder arises from a single underlying cause. These single-deficit explanations include the *severity hypothesis* (the deficits are associated with disorder *a* and a comorbid disorder *b*, but are separable to the deficits of disorder *b*), *synergy hypothesis* (separate deficits are associated with disorders *a* and *b*, but comorbidity between *a* and *c* leads to disorder *b*, although disorder *b* can also develop from other deficits), *cross-assortment hypothesis* (separate deficits for disorders *a* and *b*, but those with either disorder are more likely to have offspring with an individual with the other disorder), *pleiotropy hypothesis* (a single etiology manifests in two separate cognitive deficits which lead to separate disorders but can co-occur in comorbid cases), and *genetic heterogeneity hypothesis* (separate etiologies manifest in one cognitive deficit leading to comorbid cases). Pennington (2006) argues that none of these hypotheses adequately explains the independent and shared aetiological nature of the comorbidity between dyslexia and speech sound disorder. Rather, only a multiple deficit explanation may adequately explain comorbidity. Indeed, evidence for this multifactorial account of comorbid disorders has also been found in investigations of heterotypic comorbidities, namely in explaining the comorbidity between dyslexia and ADHD (McGrath et al., 2019). Investigations have reported shared genetic risk (e.g., Willcutt et al., 2002) and cognitive deficits (e.g., Gooch et al., 2011) amongst children with dyslexia, ADHD, and comorbid dyslexia and ADHD in both clinic- and community-based samples (Germanò et al., 2010).

We present two related studies, which seek to test whether the MDM adequately explains comorbidity between a disorder of word-level literacy (consistent with dyslexia) and motor skills (consistent with DCD). In the first study, we tested a key prediction of the multiple deficit model (MDM; Pennington, 2006) that the incidence of comorbid literacy and motor disorders is greater than expected based on the rates of isolated disorders. In the second study, we examined the cognitive profiles of children with literacy, motor, and comorbid literacy and motor difficulties, using subsamples from Study 1. In this latter study, we sought to identify shared and independent risk factors of literacy and motor disorders. In addition, we investigated the profiles of children with comorbid literacy and motor disorders to better understand the nature of their comorbidity. We tested three competing behavioral-genetic hypotheses which have been used to test the nature of comorbidity between dyslexia and ADHD (de Jong et al., 2006), but could be readily applied to test the comorbidity between literacy and motor disorders. These hypotheses are phenocopy (the etiology associated with one disorder manifesting as a second disorder), cognitive subtype (the etiology of comorbid disorders is distinct to that of the isolated disorders), or shared etiology hypothesis (there is some common etiology between the disorders). The phenocopy and cognitive subtype hypotheses attempt to account for comorbidity following a single deficit explanation whereas the shared etiology hypothesis follows a multiple deficit account.

STUDY 1

A crucial step in examining the relationship between disorders is to determine whether the frequency of comorbid disorders is greater than that predicted from the base rates of isolated disorders. If the frequency of children with comorbid disorders is greater than the frequency predicted from the combined frequency of isolated disorders, it can be concluded that comorbidity is not the result of statistical chance. Rather, it is likely that the two disorders are related. However, analyzing the frequency of comorbid disorders in clinic-based samples leads to artificially inflated prevalence estimates (see Caron and Rutter, 1991). To assess whether a true comorbidity exists (i.e., not confounded by sampling) it is important to estimate the prevalence of both isolated disorders and of comorbid cases from a large representative sample (Caron and Rutter, 1991). No large-scale study has investigated the prevalence of literacy, motor, and comorbid literacy and motor difficulties among a community-based sample. Although, as reviewed below, some small-scale studies of clinic- and community-based samples have been carried out.

Much of the work investigating the prevalence and profiles of comorbid dyslexia and DCD has used clinic-based samples (e.g., Kaplan et al., 2001; Dewey et al., 2002). One such early investigation by Kaplan et al. (1998) assessed motor, reading, and attention skills in 224 children referred for having learning or attention difficulties, along with 155 controls who had no reported difficulties. Despite no child being referred specifically for motor difficulties, the authors found 50% of the sample to meet their criteria for DCD. Using broad criteria for assessing reading ability (including both comprehension and word reading accuracy), 43.8% of the sample were identified as having dyslexia.

Of those who met the criteria for either DCD or dyslexia, 33% met the criteria for both disorders, suggesting one third of children presenting with either disorder had comorbid reading and motor difficulties. This high rate of comorbidity is somewhat surprising as no child was referred to the study for having motor problems. However, the rates reported in this study are likely inflated due to the recruitment of a clinic sample, and, due to the use of broad criteria for identifying disorders, particularly in reading disabilities (Caron and Rutter, 1991).

The prevalence of comorbid dyslexia and DCD has also been investigated in small community samples using parent/teacher questionnaires (e.g., Martin et al., 2010) or hybrid combinations of questionnaires followed up with behavioral assessments (Cruddace and Riddell, 2006). Cruddace and Riddell (2006) screened 129 children between 9 and 10 years of age using teacher reports of each child's reading and spelling, motor, and attention skills. Based on teacher identification, 68 children completed a behavioral battery and were categorized as having a reading and/or a motor difficulty. To establish prevalence estimates in their sample, the authors compared the number of children categorized as having dyslexia and/or DCD with the total number of children originally screened using teacher reports. Of the total sample, 21% of children met the criteria for reading difficulty, 23% for motor difficulty, and 13% for reading and motor difficulty. The frequency of reading and motor difficulties was below that reported by Kaplan et al. (1998) but more than double that would be expected based on the rates of the isolated disorders. Like Kaplan et al. (1998) and Cruddace and Riddell's (2006) data suggest an increased risk of comorbid literacy and motor difficulties.

Cruddace and Riddell (2006) report the prevalence estimates of comorbid reading and motor difficulties based on their sample probabilities and not population probabilities. However, the high incidence of isolated reading (11.6%) and motor (12.4%) difficulties in their sample was inflated in comparison to commonly reported population prevalence rates (e.g., Blank et al., 2012; Snowling, 2013). These very high rates of isolated difficulties may reflect the small sample size for a study of this nature and/or the use of teacher report questionnaires, which are not optimal for identifying reading and motor difficulties (Shaywitz et al., 1990; Blank et al., 2012; Barnett et al., 2015). The high base rates observed in the sample also raise questions about their validity. To conclude that there is an increased risk of comorbidity between dyslexia and DCD it is necessary to examine the frequency of comorbid difficulties in a sample where the rates of isolated dyslexia and DCD are similar to population prevalence estimates (Caron and Rutter, 1991). To date, no such study has been reported, although, Schoemaker et al. (2013) observed an increased risk of reading difficulties in a representative sample of children with motor difficulties who were part of a large community sample (the ALSPAC cohort; Lingam et al., 2009). Unfortunately, these authors did not examine the number of children with reading (and not motor) difficulties in the same sample, but nevertheless, these findings, along with those from Kaplan et al. (1998) and from Cruddace and Riddell (2006) suggest an above-chance risk of comorbidity between literacy and motor difficulties.

Building on the foregoing research, the aim of the first study reported here was to estimate the prevalence of isolated and comorbid literacy and motor difficulties in a representative community sample using a screening approach. Based on previous, smaller-scale studies, we expected to find the frequency of comorbid literacy and motor difficulties to be greater than expected based on the frequencies of children with isolated difficulties.

We used a community rather than a clinic sample, primarily to control for the aforementioned bias in clinic samples. This means that we did not recruit children who had a clinical diagnosis of dyslexia or DCD. Rather, we utilized types of measures that are often used to identify markers of these disorders (e.g., Blank et al., 2019). In the case of identifying DCD/motor difficulties we opted to measure handwriting and fine motor difficulties owing to the ease with which these skills can be estimated in large group settings, and because weaknesses in these skills are often the primary reason for referral for possible DCD (Miller et al., 2001).

It is also important to recognize that whilst screening tests, in the main, are useful for identifying those with likely difficulties in large samples, an individually administered assessment battery remains the most accurate assessment. To make the distinctions clear between (a) using a community rather than clinic sample and (b) screening vs. a more comprehensive assessment, we do not refer to our groups with the diagnostic terms *dyslexia* and *DCD*. Instead, we use the terms literacy difficulties and fine-motor difficulties for children who were categorized as having difficulties using the screening battery of Study 1. We use the terms literacy and motor disorders for children who we later identified in Study 2 to have significant markers of difficulties in the literacy and motor domains, on the basis of results from an individually administered diagnostic battery.

Methods

Participants

To establish the prevalence of comorbid literacy and fine motor difficulties in a community-based (unselected) sample, 605 children took part in classroom screening. Children from six primary schools across North-West Wales participated in Years 3 ($n = 204$, Mage = 8.2 years, $SD = 0.52$, 50% female), 4 ($n = 200$, Mage = 9.1 years, $SD = 0.54$, 50% female), and 5 ($n = 201$, Mage = 10.1 years, $SD = 0.55$, 48% female). We selected children in this age band, rather than younger children, to reduce the heterogeneity that is often seen in the profiles of younger children (aged < 7 years). This is in line with previous large-scale studies conducted in the U.K. examining children's literacy and motor skills (e.g., Lewis et al., 1994; Lingam et al., 2009). Prior to the start of data collection, 12% of children were identified by their schools as potentially having literacy difficulties, and, 3% of children were identified by their school as having diagnosed motor difficulties. All schools delivered instruction through the medium of English and the average proportion of pupils eligible for free school meals (a proxy of socioeconomic disadvantage) was 17%, in line with the national average for Wales (18%).

Procedure and Measures

Whole classes of children completed all tests in specially prepared booklets in a normal class setting. Any tests designed for individual administration were adapted for class administration; the adaptations are noted where relevant. Classes completed the booklets over two 60-min sessions to reduce fatigue effects. All groups received explanations and brief training prior to the beginning of each testing session to ensure they understood and complied with the instructions. The first author and two or three research assistants oversaw children's progress, along with the

TABLE 1 | Descriptive statistics for measures of literacy and motor skills used in the screening battery as a function of school year group.

	Year 3		Year 4		Year 5		Reliability
	M (*SD*)	Range	*M* (*SD*)	Range	*M* (*SD*)	Range	
Literacy							
Word spelling							0.90[a]
Raw	24.73 (5.06)	6–41	27.77 (5.89)	12–48	30.24 (5.58)	17–44	
Standardized	105.68 (17.65)	56–144	105.65 (17.45)	56–145	105.09 (15.15)	67–145	
Sentence spelling	35.11 (11.51)	2–55	40.82 (11.27)	2–59	45.29 (9.71)	17–60	0.94[a]
Cloze reading	16.27 (5.02)	2–33	20.06 (5.73)	5–36	22.27 (6.96)	2–41	0.91[b]
Fine motor							
VMI							0.73[a]
Raw	19.16 (2.59)	12–27	20.70 (3.07)	12–29	21.78 (3.50)	11–29	
Standardized	92.60 (9.98)	63–126	92.86 (12.16)	47–126	91.8 (13.87)	45–122	
Coding							0.85[c]
Raw	32.65 (8.05)	3–51	35.83 (8.25)	6–57	38.96 (8.30)	17–59	
Standardized	8.45 (3.05)	1–16	9.11 (2.70)	1–16	8.59 (2.54)	3–15	
Overall legibility	11.55 (2.12)	6.5–17.5	12.54 (2.5)	5.1–19.7	13.21 (2.73)	5.1–19.6	0.83[d]

Standardized scores M = 100, SD = 15. VMI, Visual Motor Integration. [a]Internal consistency (Cronbach's alpha) derived from the current, class administered, data. [b]Test-retest correlation reported in Caravolas et al. (2005). [c]Average internal consistency reported in the WISC-IV manual (Wechsler, 2003). [d]Inter-rater (two-way random effects intra-class correlation).

class teacher, to ensure good adherence to the test procedures. In the main, both sessions were completed on the same day with sessions separated with a break of at least an hour or within 1 week of each other. All performance scores for the measures comprising this screening, and their reliabilities are reported in **Table 1**.

Literacy Assessments

Word-level literacy measures were selected on the basis of ease of administration to classes. This meant that we could not use read-aloud measures of word reading (accuracy and fluency) that are typically administered to individuals. Evidence shows word reading and spelling tap the same word-level literacy construct and so we opted to administer word spelling tests (e.g., Kim et al., 2018). In addition, we used a cloze reading measure which relies on word reading accuracy as well as on broader comprehension (e.g., Keenan et al., 2008). As such, literacy skills were assessed using the Word Spelling subtest from WRAT-IV (Wide Range Achievement Test-IV; Wilkinson and Robertson, 2006), Sentence Dictation task from Caravolas et al. (2005), and the Cloze Reading task from Caravolas and Volín (2001).

Word spelling. The WRAT-IV Spelling test was adapted for classroom administration. In accordance with the manual, all participants first wrote 13 alphabet letters, after which, they were asked to write the first 36 words of this graded test. Each word was administered first in isolation, then within a carrier sentence, and a final time in isolation. We selected the first 36 words as the cutoff because this corresponds to a standardized score of 145 for a child in Year 5, and it was expected that most children would not surpass this score. Published guidelines were followed for administration and scoring. Each correct response received one point and scoring was discontinued after 10 consecutive errors.

Sentence spelling. We assessed spelling using a dictation task of 10 sentences. Sentence length varied from four to eight words. The sentences, comprising 62 words in total, were graded in their phonological, morphological, lexical, and orthographic complexity, in line with the national curriculum for England (c.f. Caravolas et al., 2005). Each correctly spelled word was awarded one point. This test was designed for group and individual administration.

Cloze reading. Children read short passages with missing words. For each missing word, they selected the most appropriate from a possible set of five word(s) printed below each passage. The first 14 passages were missing one word and the remaining 16 passages were missing two words. Passages varied between 7 and 45 words and were graded in complexity (c.f. Caravolas and Volín, 2001; Caravolas et al., 2005). Children read for 8 min, after which they were asked to stop and immediately put their pencils down. Each word correctly selected was awarded one point. This test was designed for group and individual administration.

Fine Motor Assessments

The lack of standardized motor assessments for the screening of motor skills in groups limited our choice of measures for use in the classroom. We therefore opted to use tests of perceptual-motor (e.g., visual motor integration) and handwriting skills. Whilst perceptual-motor skills are utilized in all types of skilled motor action (Halsband and Lange, 2006), the tasks used in this study are arguably those most related to fine-motor skills and less so to other motor functions such as gross motor skills or balance. We used several measures of fine motor skills including the Beery Visual Motor Integration Test-VI (VMI-VI; Beery and Beery, 2010), the Coding subtest from the Wechsler Intelligence Scale-IV (WISC-IV; Wechsler, 2003), and

Handwriting Legibility scores from the Spelling and Handwriting Legibility Test (SaHLT; Caravolas et al., in preparation). We used handwriting skills as a marker for fine-motor difficulties because poor handwriting and fine motor problems, are predominant reasons for referal of children with DCD (Miller et al., 2001); morevoer, poor performance on handwriting measures has been found to descriminate well between children with and without DCD (Rosenblum and Livneh-Zirinski, 2008; Rosenblum et al., 2013). Therefore, the inclusion of fine-motor and handwriting skills in a screening battery was likely to result in reasonably good sensivity of a screening battery to detect broader motor problems.

Visual motor integration. This was assessed by the Beery VMI-VI (Beery and Beery, 2010). Children copied a series of 24 shapes of increasing complexity. They copied the shapes exactly as the saw them into a box directly below each item without using any additional aids (rulers, rubbers, etc.). Only one attempt was allowed per item. Scoring followed published guidelines and each correctly copied item was awarded one point. Scoring was discontinued after three consecutive items were awarded one point.

Coding. Coding tests place demands on visual-motor speed and accuracy (Sattler, 2001) and have been used as a proxy of graphomotor speed previously (Caravolas et al., 2001; c.f. Sattler, 2001) and we used the WISC IV Coding subtest (Wechsler, 2003) for the same purpose here. In an adaptation for group administration, children used a numbered key of symbols printed at the top of the page to reproduce the corresponding symbol into a numbered box located in the second half of the page as quickly as possible in 2 min. Scoring followed published guidelines and responses were scored as correct if they were identifiable as the relevant symbol.

Handwriting legibility. We assessed handwriting legibility using the protocol from the SaHLT (Caravolas et al., in preparation; see also Caravolas et al., 2020). Children's handwritten responses to the sentence dictation task were scored on four dimensions as follows: (a) Letter Formation, which measures the child's accuracy and consistency in producing letters; (b) Letter Spacing, which assesses the child's ability to appropriately and consistently space letters within words; (c) Word Spacing, which evaluates the child's ability to appropriately and consistently spaces words within a sentence; (d) Line Alignment, which gauges the degree to which the child can write along the line. Each of the four dimensions was scored using a 5-point Likert scale ranging from 1 *highly illegible* to 5 *highly legible*. The dimensions were applied to each sentence individually. The scores for each dimension were calculated by averaging the score across the number of sentences the child wrote. An Overall Legibility score was derived by summing the average dimension scores. This test was designed for group and individual administration.

Ethics

Both studies were approved by the School of Psychology's Research Ethics Committee at Bangor University (reference: 2015-15287) and an NHS Research Ethics Committee (reference: 16/WA/0141). They were conducted in accordance with the British Psychological Society Code of Ethics and Conduct.

Results

Descriptives

The means, standard deviations, ranges, and reliabilities for the measures administered in the screening battery are reported in **Table 1**. The descriptive statistics on the raw scores show large variations in ability across all measures without evidence of floor or ceiling effects. Increases in performance with increasing school years is apparent for all measures. Reliability estimates suggest good-to-excellent reliability for all measures. We also report norm-referenced standardized scores, where available, to assess whether the group-administration produced any aberrant patterns of performance relative to the performance patterns obtained from individual administration. Note, importantly, that we did not use the published standard scores reported in **Table 1** in our further statistical analyses. For the latter purpose, we computed internal standard scores (z-scores) from the raw scores obtained in the present study. The means, standard deviations, and ranges of Word Spelling standardized scores also show a large variation in ability, with averages in the normal range reflecting the unselected sampling method we used. Performance on the fine-motor tasks (VMI and Coding) was on average lower than Word Spelling, however, average performance was still within the normal range. It is also important to note that the reliability of the VMI was relatively lower than all the other tests. However, the reliability derived from the current sample is not too dissimilar from the published reliabilities for children in these year groups ($\alpha = 0.79$–0.81; Beery and Beery, 2010). To investigate potential subclinical motor difficulties in children with literacy difficulties we plotted the score distributions for each group on each measure (see **Supplementary Figure 1**). We found large variations in groups, but that the distribution of children with LD was fully overlapping with that of the typically developing group, suggesting the absence of subclinical motor difficulties in this group.

Prevalence Estimates

To assess the prevalence of literacy and fine-motor difficulties separately, and in co-occurrence in individual children, we used a marker approach (see Snowling and Hulme, 2015). Often studies examining literacy or motor disorders apply diagnostic cut-offs of between 1 and 1.5 *SD* below the age or year group average (e.g., Lewis et al., 1994; Blank et al., 2019). In deciding cut-offs for this study, we followed the recommendation of Rutter et al. (2004) to strike a balance between identifying children who have clear difficulties while ensuring a sufficient number of children to obtain representative and accurate base rates. Therefore, we decided 1.33 *SD* was an appropriate cut-off. To apply this, we generated z-scores ($M = 0$, $SD = 1$) as a function of year group on a selection of the literacy and motor tests administered. Thus, children who scored below the cut-off of < 1.33 *SD* of their year group average on two out of three of the selected literacy tests—Word Spelling, Sentence Spelling, or Cloze Reading—were identified as having potential literacy difficulties. Children who

TABLE 2 | Proportion of children in the sample identified as having literacy, fine motor, comorbid difficulties, or as being typically developing.

	n	%
Literacy difficulties	42	6.94
Fine-motor difficulties	34	5.62
Comorbid literacy and motor difficulties	16	2.64
Typically developing	513	84.79

scored below the cut-off on two out of the three selected fine-motor measures—Visual Motor Integration, Coding, and Total Handwriting Legibility—were identified as having potential fine-motor difficulties. Children who met the criteria for both literacy and fine-motor difficulties were identified as having potential comorbid literacy and fine motor difficulties. Children who did not meet any criteria were labeled as typically developing (TD).

The prevalence estimates of literacy, fine-motor, and comorbid literacy and fine-motor difficulties are reported in **Table 2**. These isolated disorder prevalence rates are broadly in line with previous epidemiological studies of dyslexia and DCD, respectively (Lingam et al., 2009; Snowling and Hulme, 2015). To determine whether the frequency of comorbid literacy and motor difficulties exceeded that expected by chance, the derived base rates of isolated literacy and motor difficulties were multiplied to obtain the percentage of expected cases of comorbid difficulties. Following these procedures described by Caron and Rutter (1991) and Landerl and Moll (2010), the expected rate ($n = 3$, 0.54%) was then compared to the number of observed cases ($n = 16$, 2.64%) meeting our criteria for comorbidity. The observed frequency of children with comorbid literacy and fine-motor difficulties was significantly higher than that expected by chance (OR = 5.78, $p < 0.001$), suggesting that comorbid literacy and motor difficulties cannot be attributed to chance alone.

In sum, we found the measures in the screening battery to be reliable in assessing literacy and fine-motor skills. Furthermore, the rates of isolated literacy and fine-motor difficulties derived from this battery were in line with previous studies examining the prevalence of these difficulties in British children (Lingam et al., 2009; Snowling and Hulme, 2015). Such plausible base rates are critical for determining whether the rate of comorbidity between literacy and (fine-)motor difficulties exceeds chance significantly. Indeed, the rate of comorbid literacy and fine-motor difficulties was five times greater than expected by chance. In what follows, we extended the current findings in a second study by (a) assessing the sensitivity and specificity on the screening measures, and (b) examining the cognitive profiles of children with literacy, motor, and comorbid literacy and motor disorders.

STUDY 2

The greater-than-chance incidence of comorbid literacy and motor difficulties reported in Study 1 presents tentative support for the claim that these disorders are to some extent related. Pennington's (2006) multiple deficit model (MDM) explains this relationship in the context of shared etiological and cognitive risk factors, where each disorder results from numerous biological and cognitive risk factors that act in a probabilistic manner to increase the likelihood of an individual meeting a diagnostic threshold. Some of these risk factors are specific to a disorder, that is, they are independent, whilst others are shared between disorders. The presence of shared risk factors increases the likelihood of comorbidity between the disorders. This hypothesis has led to a proliferation of studies investigating independent and shared risk factors of dyslexia (e.g., Gooch et al., 2011; Moll et al., 2016). To date, however, it remains unclear what are the independent and shared risk factors of literacy and motor disorders.

Studies investigating each of these disorders separately suggest that some cognitive deficits are observed in both. In Study 2, we investigated the reported co-incidence of deficits in phonological processing, visuospatial processing, memory, and selective attention. Below, we briefly evaluate the literature reporting the potential overlap of deficits in the cognitive domains of literacy and motor disorders.

Variations in phonological skills are a critical determinant in learning to read and spell (Caravolas et al., 2012; Melby-Lervåg et al., 2012). Children with dyslexia typically experience phonological processing deficits (e.g., Snowling, 2008), which precede and predict their later literacy (dis)abilities (Pennington and Lefly, 2001; Hulme et al., 2015). Moreover, effective training in phonological skills improves the phonological and literacy skills of children at risk of or experiencing dyslexia (e.g., Hulme et al., 2012). Thus, phonological deficits are common in dyslexia and are causally related to the disorder.

Notably, however, some children who have phonological deficits go on to develop typical reading and spelling skills, while others with poor literacy do not appear to have phonological deficits (Ramus et al., 2003). Therefore, phonological deficits by themselves may not be sufficient to cause dyslexia/literacy difficulties. Rather, phonological deficits act probabilistically (rather than deterministically) with other cognitive deficits to increase the risk for a child to meet diagnostic criteria for dyslexia (Pennington et al., 2012; Moll et al., 2016).

Difficulties on measures, which require phonological skills, have also been reported amongst some children with motor disorders. Case-control studies report that children with DCD perform less well than children without DCD on measures such as non-word reading and repetition, as well as on word reading and spelling (Alloway, 2007; Archibald and Alloway, 2008; Schoemaker et al., 2013). However, the reported prevalence of weaknesses in phonological and literacy skills among children with DCD is highly variable.

There are several potential explanations as to why children with motor difficulties may struggle on phonological, reading, and spelling tasks. One possibility is that phonological and literacy difficulties are a distal consequence of motor deficits. For example, oral-motor or graphomotor deficits may interfere with learning to read and write. Another potential, but unexplored, explanation for phonological deficits amongst children with motor difficulties could be the presence of children with comorbid literacy difficulties in the samples studied. For example, despite the variability observed in their sample, Dewey et al. (2002) did not discriminate between children with phonological deficits who had literacy impairments (i.e., those with comorbid dyslexia) and those who did not. Finally, visuospatial skills have been reported to also be involved in reading acquisition, in addition to phonological skills (Franceschini et al., 2012), and, children with motor difficulties often have visuospatial deficits (see below). In line with this view, some studies have found that children with motor difficulties struggle on reading tasks due to visuospatial deficits (Bellocchi et al., 2017).

Visuospatial skills are functional in localizing visual information and providing feedback for correction of goal directed movements (e.g., Wolpert and Ghahramani, 2000), hence they are important for acquiring and making skilled motor actions (Halsband and Lange, 2006; Jeannerod, 2006). It is not surprising, then, that children with motor difficulties tend to perform poorly on visuospatial tasks regardless of whether they require a motoric response. They are also reported to be impaired on tasks of visual perception without a motor component (Hulme et al., 1982; Tsai et al., 2008) and on visual-motor integration (Schoemaker et al., 2001; Bonifacci, 2004). Meta-analyses have confirmed large differences between children with and without DCD on tasks involving visuospatial processing (Wilson and McKenzie, 1998; Wilson et al., 2013).

Despite moderate-to-large group effects on these tasks, the relationship between visuospatial processing and motor disorders is unclear. Whilst some have found significant correlations between visuospatial processing and functional motor skills in children with DCD (Lord and Hulme, 1987; Tsai and Wu, 2008) others have reported no associations (Prunty et al., 2016). Such mixed findings and lack of longitudinal and training investigations examining the relationships between these abilities preclude strong claims about the causal role of visuospatial processing deficits in motor disorders. Nevertheless, the strong association between visuospatial skills and typical motor development as well as the clear difficulties of children with DCD on tasks involving visuospatial processing suggest that poor performance on visuospatial tasks is a probable cognitive risk factor of motor disorders.

Impairments in visuospatial and motor skills have been reported amongst children with literacy disorders (Ramus et al., 2003; Bellocchi et al., 2017). Yet, few studies have fully controlled for a comorbid motor disorder. In one study that did control for comorbidity, children with dyslexia scored within the average range on measures of visual perception and visual-motor integration, and better than children with isolated and comorbid DCD (Bellocchi et al., 2017). Thus, children with a comorbid motor disorder may have accounted for the visuospatial processing impairments reported in this study, however, the lack of a typical control group made it difficult to rule out the presence of a sub-clinical visuospatial deficit in dyslexia.

Children with a literacy disorder are known to perform less well than typically developing children on various memory measures—verbal memory being the most strongly affected (Kudo et al., 2015)–, albeit their verbal memory impairments tend to be smaller than their phonological deficits (Melby-Lervåg et al., 2012). In children with motor difficulties, memory impairments appear to be more diffuse with greater severity in the visual memory domain (Blank et al., 2012). More recently, a study by Maziero et al. (2020) directly compared performance on memory measures between children with dyslexia and DCD. The authors reported dyslexia was most strongly associated with verbal memory deficits whereas DCD was most strongly associated with visual memory deficits. However, measures of visual memory tap heavily on visuospatial processing, which is itself a skill often impaired in motor disorders. This potential confound is yet to be disambiguated.

Like memory, attention is not a unitary construct. According to one view, attention is divided into three sub-processes, namely sustained, selective, and control (Shapiro et al., 1998; Manly et al., 2001). In the present article, we focus on selective attention, that is, the enhanced capacity of processing specific stimuli. Impairments on measures of selective attention have been reported in children with literacy disorders (Menghini et al., 2010; Varvara et al., 2014) and motor disorders (Wilson et al., 1997). Cruddace and Riddell (2006) reported that groups with dyslexia, DCD, and comorbid dyslexia and DCD all attained relatively low scores on selective attention measures, as did the control group, and no statistical differences were observed between groups. Thus, either the measure under study was not sufficiently sensitive to detect selective attention deficits in the disorder groups, or, such deficits do not characterize these groups.

In establishing whether deficits in memory and selective attention are present in literacy and/or motor disorders, it is necessary to rule out potential confounds such as uncontrolled comorbidity and measurement issues. It is also important to note that memory and attention deficits are unlikely to be direct causes of literacy or motor disorders. Rather, deficits in these domain-general skills are more likely to interact with disorder-specific deficits to compound impairments and increase the likelihood of a child meeting a diagnostic threshold (Gathercole et al., 2016).

The above studies investigating phonological, visuospatial, memory, and selective attention deficits in dyslexia and DCD have predominantly examined their presence in one or the other disorder, but not both. Despite the seemingly high degree of overlap in cognitive deficits across studies, it is unclear in the vast majority of cases whether researchers have controlled for the potential comorbidity between the disorders. It is therefore timely to examine the incidence of deficits in these four cognitive domains among groups with isolated or comorbid literacy and motor difficulties. In doing so, we will delineate their cognitive profiles and allow the identification of independent and shared deficits between the disorders.

Beyond identifying shared and independent risk factors for literacy and motor disorders, it is also important to examine how children with comorbidity in these domains perform relative to children with isolated disorders. Such comparisons allow us to test competing explanations of comorbidity. Three main competing explanations of the etiology of comorbid developmental disorders have been postulated (de Jong et al., 2006). The phenocopy hypothesis suggests that a single etiology underlies the cognitive deficits consistent with an isolated disorder, but these deficits lead to behavioral manifestations of a second disorder (Pennington et al., 1993). In this view, children with comorbid literacy and motor disorders would have cognitive deficits that were only consistent with one or the other disorder. Alternatively, the cognitive subtype hypothesis suggests the comorbid disorder is a third disorder with a separate etiology to either of the isolated disorders (Rucklidge and Tannock, 2002). According to this hypothesis, children with comorbid literacy and motor disorders would have a different profile and/or greater severity of deficits to either isolated literacy or motor disorder. Finally, the shared etiology hypothesis suggests that comorbid disorders share at least some common etiology. Accordingly, children with comorbid literacy and motor disorders would have a similar profile of deficits—not differing in severity—to isolated literacy or motor disorders.

The phenocopy and cognitive subtype hypotheses follow a single deficit account while the shared etiology hypothesis is consistent with the MDM, which posits that comorbidity results from shared etiological and cognitive risk factors (Pennington, 2006). Recent studies examining the comorbidities between dyslexia and ADHD (Gooch et al., 2011) and reading and math disorder (Moll et al., 2016) find support for the latter view. However, to date, no study has comprehensively examined whether this account holds true for comorbid literacy and motor disorders. A study by Biotteau et al. (2017a) that examined general cognitive and attention abilities in children with dyslexia, DCD, and comorbid dyslexia and DCD found no differences between the comorbid and isolated disorder groups. These findings are most consistent with the shared etiology hypothesis. In line with this evidence, we predict that the profiles of comorbidity between children with literacy and motor disorder will follow that of the shared etiology account.

To investigate potential shared and independent risk factors for literacy and motor disorders and to delineate the nature of comorbid literacy and motor disorders, we invited children who we identified as having difficulties or being typically developing in Study 1 to complete a comprehensive battery of individually administered tests. Each child underwent a battery of 16 tests to assess functioning in the domains of literacy, fine and gross motor abilities, phonological processing, visuospatial processing, memory, and selective attention. This comprehensive assessment with a subsample of children from the previous study allowed us to validate the sensitivity and specificity of the screening battery (Study 2a), and to increase the accuracy of each child's group classification. Furthermore, children's scores on the tests of the broader battery were analyzed to elucidate the cognitive profiles of each disorder group (Study 2b).

STUDY 2A: VALIDITY OF THE SCREENING TEST BATTERY

Prior to examining profiles of cognitive deficits in literacy and motor disorders, we first examined the validity of the screening assessments used in Study 1 in identifying children with literacy and/or motor difficulties. In particular, we assessed the screening battery's ability to correctly categorize children with a significant difficulty (sensitivity) and those without significant difficulty (specificity). To this end, we carried out a discriminant function analysis where all children in Study 2a were assigned to a group of literacy disorder, motor disorder, co-occurring literacy and motor disorders, or typical development, independently of their group classification in Study 1, but rather on the basis of their performance on new individual assessments of literacy and motor skills (see details below). The discriminant function analysis was used to determine the sensitivity and specificity of classification to a disorder group by the screening battery relative to the group membership as determined by the results of more extensive battery of Study 2a.

Methods

Participants

A total of 153 children from Study 1 and their parents consented to take part in this second study. Children were now in Years 4 ($n = 47$, 51% female; Mage = 105.93 months, SD = 3.76), 5 ($n = 53$, 40% female; Mage = 117.62 months, SD = 4.42), and 6 ($n = 53$, 43% female; Mage = 130.36 months, SD = 4.84). No child was reported to have received a new diagnosis of literacy and/or motor disorder between Study 1 and Study 2.

Procedure and Measures

Approximately 4 months after Study 1, children completed a large battery of the diagnostic measures described in Study 2a and 2b. The battery, administered over 5 individual sessions, included multiple measures of literacy and motor skills, phonological, visuospatial processing, memory, and attention skills. Within each testing session, the administration order of the individual tests was fixed and manipulated to minimize the likelihood of transfer, or priming, from one test to the other. Each testing session lasted no longer than 1 h, and children were given an opportunity to take a short break after each test. Published administration and scoring instructions, including any discontinuation criteria, were followed.

Literacy Skills

This was assessed by three reading tests: WRAT-IV Single Word Reading subtest, 1 Min Word Reading Test and 1 Min Pseudoword Reading tests from the Multilanguage Assessment Battery of Early Literacy (MABEL; Caravolas et al., 2019).

Word reading accuracy. The Single Word Reading subtest was used to assess reading accuracy. The child was asked to read aloud from a 55-item graded word list. Words increased in difficulty and administration of basal and ceiling levels was carried out according to published guidelines. Each correctly read item was awarded one point. Internal reliability was $\alpha = 0.94$.

One-minute word reading. The child was asked to read aloud as many words as s/he could from a list of 144 high frequency words in 60 s. The words increased in length (one to eight letters) and in syllable number (one to three syllables). Each correctly read word

TABLE 3 | Group demographics and performance on classification measures.

	LD		MD		LD+MD		TD		Group comparison	
	M	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***F***	η_ρ^2
n	27		24		17		85		–	–
% Female	33		29		59		49		–	–
Age (months)	118.26	10.54	118.5	10.36	118.35	13.24	118.38	10.92	0.00	<0.01
Block design (NVIQ)[a]	9.88	3.70	8.73	2.76	6.53**	2.56	9.91	3.29	5.11**	0.10
Literacy[†]										
Single word reading[c]	82.26***	8.51	101.00	11.50	80.82***	6.95	101.82	9.93	44.38***	0.47
One minute word read[b]	66.42***	14.14	87.76	13.40	70.47***	20.19	96.48	13.90	34.20***	0.43
One minute pseudoword read[b]	25.22***	12.46	43.71	12.23	21.71***	12.14	48.59	13.80	34.81***	0.41
Motor[‡]										
Motor coordination[c]	91.11	7.18	75.54***	9.08	76.88***	8.22	91.78	9.44	30.53***	0.38
Threading[a]	8.81	2.37	6.64***	3.20	5.33***	2.23	9.64	2.78	14.78***	0.24
One board balance[a]	9.92	2.37	8.78**	3.37	7.59***	2.62	10.78	2.37	9.23***	0.16

*LD, literacy disorder; MD, motor disorder; LD+MD, comorbid literacy and motor disorder; TD, typical developing. [†]Measures used to classify literacy disorder. [‡]Measures used to classify motor disorder. Subscript asterisks of group mean represent significant differences from Bonferroni corrected post-hoc comparisons with typically developing children. [a]Scaled scores; [b]Raw scores, [c]Standardized scores. **p < 0.01, ***p < 0.001.*

in the time limit was awarded one-point. Reported test-retest reliability was $r = 0.91$ (Caravolas, 2017).

One-minute pseudoword reading. Following the same procedure as the 1 Min Word Reading, the child read aloud from a list of 144 pseudowords as fast as they could in 1 min. Each pseudoword read plausibly in the time limit was awarded one-point. Reported test-retest reliability was $r = 0.87$ (Caravolas, 2017).

Motor Skills

Motor ability was measured using the Beery VMI-VI Motor Coordination subtest (Beery and Beery, 2010), Lace Threading and One Board Balance from the Motor Assessment Battery for Children 2 (MABC-2; Henderson et al., 2007).

Motor coordination. The child traced as accurately as possible inside 24 shapes of increasing complexity. Only one attempt was allowed per form and children were asked to stop after 5-min, although most children completed the task in this time. Scoring followed detailed guidelines reported in the manual. Each correct response was awarded one point. Scoring was discontinued when a child made three consecutive errors. Internal reliability was $\alpha = 0.70$.

Lace threading. The child threaded a piece of string back and forth through eight holes in a small plastic board. The task was timed from when the child's hands—positioned on the table either side of the board—left the mat, until they had pulled the string tight through the final hole. The threading time was the fastest time of two consecutive attempts. The intraclass correlation (ICC) was 0.61.

Balance board. Static balance was measured by the One Board Balance test where the child balanced with one foot on a plastic board with a thin keel. Once the child had achieved a balanced position, the administrator began timing and continued for up to 30 s or when balance was lost. Two attempts of balancing for up to 30 s were allowed per foot. The ICC was 0.64 for the right foot and 0.62 for the left foot.

Results

The descriptive statistics of the measures across all participants are reported in **Supplementary Table 1**. As expected, there was wide variation in ability but there was no indication of floor or ceiling effects in any of the measures. All measures' reliability ranged from acceptable-to-excellent.

Group Classification

Performance on the literacy and motor assessment battery was used to identify whether each participant had literacy, motor, or comorbid literacy and motor disorders, or was typically developing. We used a similar approach to Study 1 and a child was identified as having a *literacy disorder* if they scored 1.33 *SD* below their age average on two out of the three literacy tests. They were identified as having a *motor disorder* if they performed 1.33 *SD* below their age average on two out of the three motor tests. If they met the criteria for both literacy and motor disorder, children were identified as having *comorbid literacy and motor disorder*. Those who did not meet any criteria were classified as being *typically developing*.

The characteristics of each of the four groups, along with the statistical comparisons of the groups on classification measures, are reported in **Table 3**. Groups did not differ in age but children with comorbid disorders had significantly lower non-verbal ability. Children with literacy disorder only had significantly lower scores on all literacy measures, as expected, but did not differ from typically developing children on motor measures. Children with motor disorder had significantly lower scores on all motor measures, as expected, but did not differ from typically

TABLE 4 | Discriminant function analysis of Study 1 measures in classifying literacy and motor disorders showing canonical correlations (top section), loadings (mid-section), and group means (bottom section) of each function.

	Function one	Function two
Canonical correlations		
	0.72***	0.51***
Canonical loadings		
Sentence spelling	0.92	0.23
Word spelling	0.70	0.14
Cloze reading	0.62	−0.07
Visual motor integration	0.10	0.68
Coding	0.18	0.77
Overall legibility	0.07	0.85
Group means on canonical variables		
Literacy difficulties	−1.92	0.13
Motor difficulties	0.30	−1.15
Typically developing	0.62	0.35

***$p < 0.001$.

developing children on literacy measures. Children classified as having comorbid literacy and motor disorder achieved significantly lower scores than typically developing children on all literacy and motor tests.

Validity of the Screening Battery

Predictive discriminant function analysis (DFA) was run to assess whether tests of literacy and motor-related skills administered in Study 1 predicted group membership in Study 2a. Accordingly, performance on the tests in Study 1 were entered as predictors for the classification of literacy or motor disorder, and typically developing children in Study 2a. Predictive DFA requires groups classified to be mutually exclusive and so we did not attempt to classify comorbid literacy and motor disorders here. Given the unequal sample sizes, we also set group-size-proportional prior probabilities. The top section of **Table 4** shows the canonical correlations for function 1, $\chi^2 = 0.36$, $F_{(12, 222)} = 12.39$, $p < 0.001$, and function 2, $\chi^2 = 0.74$, $F_{(5, 112)} = 7.78$, $p < 0.001$. Both functions are statistically significant indicating they are both needed to describe differences between the classifications.

The canonical structure (mid-section of **Table 4**) reveals high loadings for literacy measures on function one and high loadings for motor-related measures on function two. Furthermore, children later classified as having a literacy disorder had the lowest group mean on function one whereas children with motor disorder had the lowest group mean on function two (bottom section of **Table 4**). The battery achieved sensitivity and specificity rates of 86 and 95%, respectively, for identifying literacy difficulties which exceeded the recommended limits of 80 and 90% for sensitivity and specificity rate, respectively, for screening tools of this nature (Glascoe and Byrne, 1993). The battery also achieved sensitivity and specificity rates of 79 and 84% respectively for identifying motor disorder. These rates are recognized as being "good" for motor assessments (see Blank et al., 2019). Therefore, the literacy and fine-motor screening assessments used in Study 1 had relatively good sensitivity and specificity in detecting literacy and motor disorders, assessed using a broader individually administered battery.

STUDY 2B: COGNITIVE PROFILES

Having established that comorbidity between literacy and motor difficulties is greater than chance (Study 1) and having validated the aforementioned screening battery (Study 2a), we sought to examine group profiles across the four cognitive domains of phonological processing, visuospatial processing, memory, and attention. By examining profiles across children with literacy, motor, and comorbid literacy and motor disorders, we sought to elucidate independent and shared risk factors for these disorders, as well as to identify whether comorbid literacy and motor disorder is most consistent with the phenocopy, cognitive subtype, or shared etiology hypothesis.

Method

Procedure and Measures

Tests of visuospatial processing, phonological processing, memory, and attention were administered as part of the same battery of tests measuring literacy and motor skills reported in Study 2a.

Visuospatial Processing

Both motor and non-motor visuospatial processing were measured using scores from the Beery VMI (described in Study 1; Beery and Beery, 2010) and Visual Perception subtest (Beery and Beery, 2010). We also derived a third measure of visuospatial processing from the Wide Range Intelligence Test (WRIT; Glutting et al., 2000).

Visual perception. The child was asked to look carefully at a shape (target) printed at the top of the page and select and mark the shape that matched the target from several distractor shapes as accurately as possible. The complexity of the shapes increased as did the number of distractor shapes from two to seven. Each shape correctly identified in 3 min was awarded one-point until the child met the discontinue rule of three consecutive errors. The reported reliability of this measure was acceptable ($\alpha = 0.71$).

Matrix visual perception. Matrix reasoning tests tap, in part, visuospatial processing (Sattler, 2001; Stephenson and Halpern, 2013). As such, the first author along with a research assistant each selected items from the WRIT Matrix Reasoning subtest (Glutting et al., 2000), which fulfill the criteria of visuospatial processing as outlined in the Test of Visual Perceptual Skills-4 (TVPS-4; Gardner, 2017). Inter-rater reliability was excellent between the first author and the research assistant (Kappa = 0.84) and internal reliability of the selected items was acceptable ($\alpha = 0.73$).

Phonological Processing

Phonological processing was measured using the Phoneme Deletion, Phoneme Blending, and Rapid Automatized Naming (RAN) tasks from the MABEL (Caravolas et al., 2019).

Phoneme deletion. The child was asked to repeat a pseudoword after removing either the initial (10 items, onsets) or final (10 items, codas) phoneme. Performance was measured in term of accuracy, which was expected to be high in these age groups, and in terms of speed. As such, speed was used as the measure of performance. The intraclass correlation (ICC) for the speed measure was 0.86 for onsets and 0.76 for codas.

Phoneme blending. The child was asked to synthesize speech sounds (phonemes) presented at 1 s intervals into real words. The test comprised 24 target words of increasing length and phonological complexity. Internal reliability was $\alpha = 0.78$.

Rapid automatized naming (RAN). Two variants of the RAN task—*digits and letters*—were administered. In each case, the child named the stimuli presented on two A4 display cards, with 8 items repeated pseudo-randomly in two arrays of eight by five from left to right. During the RAN Digits subtest the child was asked to name the digits: 2, 3, 6, 7, and 9. In the RAN Letters subtest, the child was asked to name the lowercase letters: a, d, p, o, and s. Accuracy is usually at ceiling in RAN tasks and so we used speed as the measure of performance. The ICC for the speed measure was 0.95 for RAN Digits and 0.92 for RAN Letters. Furthermore, we produced a composite of RAN by averaging the scores of both variants.

Memory

Verbal memory was measured using the Digit Span task from the WISC-IV (Wechsler, 2003) and visual memory using the Block Recall task of the Working Memory Test Battery for Children (WMTB-C; Gathercole and Pickering, 2001).

Verbal memory. Both forward and backward digit span was measured. In the forward subtest, the child was asked to recall sequences of single digit numbers the administrator read aloud. In the backward subtest, the child was asked to recall the single digit numbers in the reverse order. The sequence length increased from two to nine digits and the child recalled two trials per sequence length. Administration was discontinued when the child was unable to recall two trials of the same string length. The reported internal reliabilities for forward was $\alpha = 0.83$ and backward was $\alpha = 0.80$.

Visual memory. The child tapped the same sequence of blocks as was demonstrated by the administrator. The span of blocks in the sequence increased from one to nine. Each span had a total of six trials and one point was awarded per correct trial. The test was stopped when the child made three errors in one span. The reported reliability was $\alpha = 0.76$.

Selective Attention

Selective attention was measured using subtests from the Test of Everyday Attention for Children (TEA-Ch; Manly et al., 2001).

Sky search. The child was asked to circle pairs of spaceships comprising the same design (target) hidden amongst other pairs of spaceships composed of different designs (distractors) under speeded conditions. Two measures were derived from this task. *Time per target* was the time taken to complete task divided by the number of correctly circled target pairs. The *attention score* was the time per target minus the time per target of a motor control block (circle only visible targets). Reported test-retest reliability was $r = 0.90$.

Sky search DT. The child was asked to complete Sky Search again (using stimuli presented in a different order) whilst s/he counted sounds played via tape. Here, we used time per target (time taken to complete task divided by the number of correctly circled target pairs) as the measure of attention. Reported test-retest reliability was $r = 0.81$.

Results

We sought to (a) identify shared and independent cognitive risk factors of literacy and motor disorders and (b) to examine the profiles of children with isolated disorders relative to children with comorbid disorders to elucidate the nature of literacy and motor disorders comorbidity. Thus, we compared groups of measures of visuospatial processing, phonological processing, memory, and selective attention (see **Supplementary Table 2** for descriptive statistics of individual measures). As multiple measures of the same constructs were administered and there was a large variation in age, we used a Multiple Indicators Multiple Cause (MIMIC) model, regressing age, to confirm the validity of the battery and to derive factor scores for group comparisons.

Correlations

Pearson correlations between all measures (raw scores) aggregated across the whole sample (reported in **Table 5**) were conducted to examine the relationships between measures of the same and different constructs. There were significant correlations between age and all other variables, with the exception of the memory measures, indicating that attainment increased as children got older. On the whole, though, measures of the same construct had the highest intercorrelations, indicating convergent validity.

Factor Analyses

Analyses were run using full information maximum likelihood estimation in Mplus 7.2 (Muthén and Muthén, 2014) due to the small amount of missing data (< 2% across all measures). A four-factor (visuospatial processing, phonological processing, selective attention, and memory) baseline confirmatory factor analysis (CFA) was run where all indicators loaded onto their respective factors. Phoneme Blending and Forward Digit Span were correlated as were Sky Search and Sky Search DT to account for the variance shared by similar task demands. The final baseline model produced an acceptable fit, $\chi^2(46) = 57.20$, $p = 0.125$, RMSEA =

TABLE 5 | Pearson correlations among measures of visuospatial processing, phonological processing, memory, and selective attention skills.

	1	2	3	4	5	6	7	8	9	10	11	12
1. Age (months)												
Visuospatial processing												
2. Visual perception	0.21**											
3. Matrix visual perception	0.19*	0.24**										
4. Visual motor integration	0.11	0.43***	0.21**									
Phonological processing												
5. Phoneme deletion	−0.25**	−0.21**	−0.23**	−0.26***								
6. RAN	−0.25**	−0.16	−0.16*	−0.11	0.60***							
7. Phoneme blending	0.22**	0.24**	0.20*	0.19*	−0.21**	−0.32***						
Memory												
8. Forward verbal span	0.12	0.33***	0.14	0.31***	−0.20*	−0.19*	0.29***					
9. Backward verbal span	0.13	0.19*	0.02	0.23**	−0.32***	−0.32***	0.19*	0.35***				
10. Visual span	0.08	0.33***	0.10	0.36***	−0.31***	−0.28***	0.23**	0.25**	0.40***			
Selective attention												
11. Sky search	−0.26***	−0.21*	−0.20*	−0.19*	0.44***	0.46***	−0.20*	−0.14	−0.31***	−0.25**		
12. Sky search TPT	−0.35***	−0.22**	−0.22**	−0.25**	0.46***	0.48***	0.21**	−0.14	−0.31***	−0.28***	0.90***	
13. Sky search DT TPT	−0.26***	−0.21*	−0.23**	−0.35***	0.35***	0.33***	−0.13	−0.18*	−0.31***	−0.26***	0.52***	0.65***

*TPT, time per target. ***p < 0.001, **p < 0.01, *p < 0.05.*

0.040 [90% CI = 0.000, 0.070], SRMR = 0.061, CFI = 0.98, and TLI = 0.98.

To account for the effects of age on the latent variables, all four latent variables were regressed onto the age covariate. The MIMIC model produced an acceptable fit, $\chi^2(54) = 63.57$, $p = 0.175$, RMSEA = 0.034 [90% CI = 0.000, 0.063], SRMR = 0.059, CFI = 0.99, and TLI = 0.98, with significant loadings of all indicators onto their respective constructs (see **Figure 1**). The inclusion of age into the model did not alter the factor structure or introduce new areas of strain (modification indices) into the model. The small-to-moderate regression paths between age and the latent variables were all significant. Large significant correlations were present between the latent variables of memory and visuospatial processing, memory and phonological processing, and phonological processing and selective attention. All other factor correlations were moderate in size.

Group Comparisons

To compare groups, we extracted refined factor scores from the MIMIC model using the regression approach. That is, we used the factor scores of visuospatial processing, phonological processing, memory, and selective attention as DVs. Group comparisons were subjected to 2 (literacy disorder: present vs. absent) × 2 (motor disorder: present vs. absent) ANCOVAs, weighted to account for group size differences. ANCOVAs were initially run to account for group differences in NVIQ (see **Table 6**). Where NVIQ was not a significant covariate, we re-ran the analyses without NVIQ and report these. This design affords the opportunity to compare profiles between literacy and motor disorders. A significant main effect of either literacy or motor disorder suggests deficit performance in children with the disorder relative to children without the disorder indicating an independent risk factor. Main effects for both literacy and motor disorder would be indicative of deficits in both disorders, and a shared risk factor. In addition, we compared children with isolated and comorbid disorders to elucidate the nature of literacy and motor comorbidity using *post-hoc* oneway AN(C)OVAs. The means and standard deviations for each group, along with the results from group comparisons on each of the factors are reported in **Table 6**. In addition, the key findings from analyses on each of the factors is described below.

Visuospatial Processing

After controlling for NVIQ, there was a moderate effect of motor disorder status, but no significant effect of literacy disorder status. *Post-hoc* comparisons confirmed that children with motor disorder (MD and LD+MD) had significantly lower visuospatial scores than TD children. There were no significant differences between either MD groups, or between children with LD (in the absence of a motor disorder) and TD controls.

Phonological Processing

Children with literacy disorder (LD and LD+MD) performed less well than children without literacy disorder. *Post-hoc* comparisons revealed children with LD and LD+MD performed less well than both TD children and children with MD. No significant differences arose between children with isolated and comorbid LD or between children with isolated MD and TD controls.

Memory

Children with LD had poorer memory skill than children without literacy disorder. Similarly, children with MD had poorer memory skills than children without motor disorder. *Post-hoc* comparisons confirmed that all three disorder groups had significantly lower memory skill scores than TD children. Memory skill scores did not differ between children with LD-only and MD-only. However, children with LD+MD had

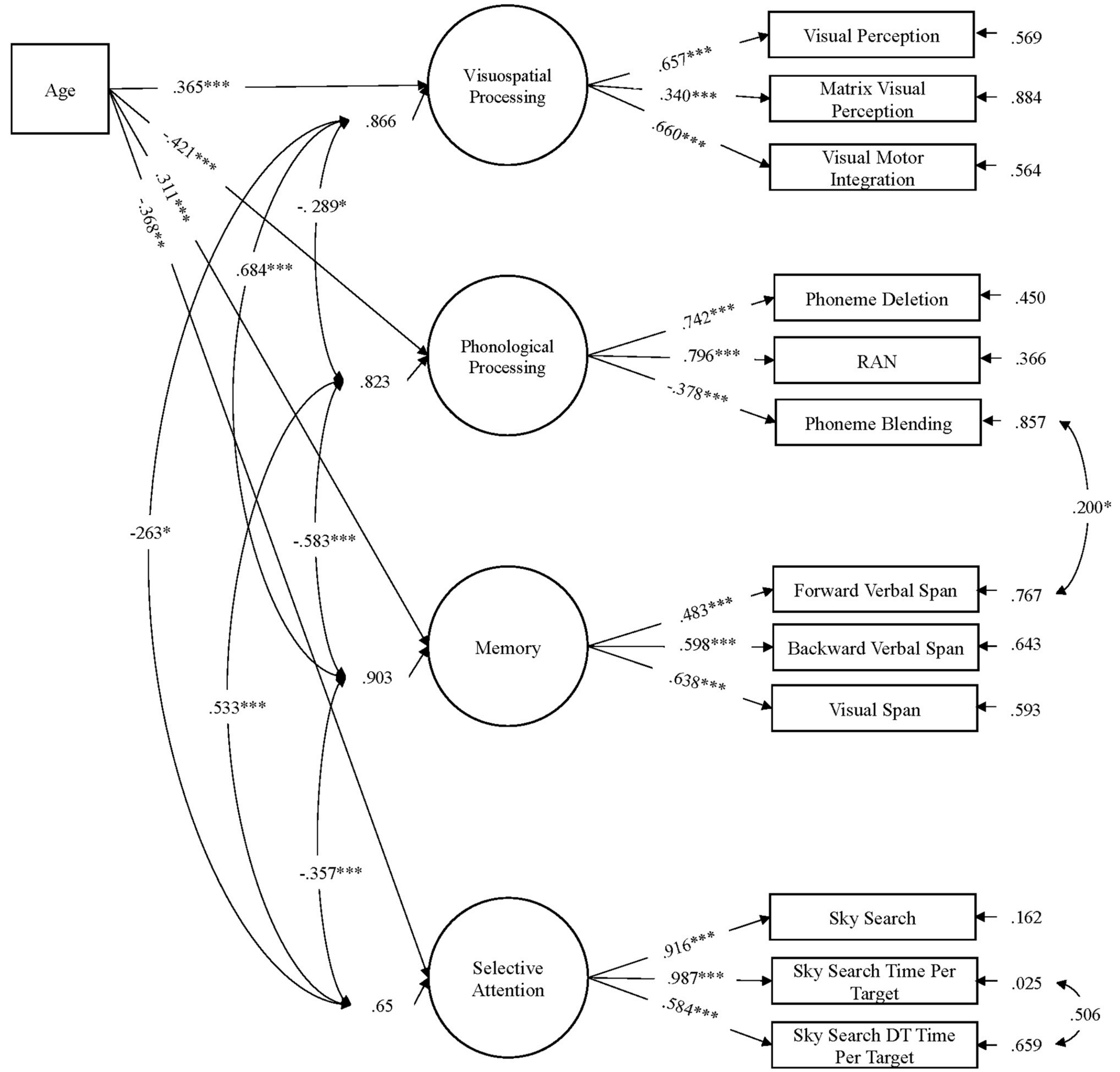

FIGURE 1 | MIMIC path model of age regressed onto the latent factors visuospatial processing, phonological processing, memory, and selective attention ($N = 153$). Standardized parameter estimates are reported. Performance on all latent variables significantly increased with age. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

poorer memory skills than either isolated disorder group. When interpreting this finding is it important to note that there is also a lack of significant interaction between literacy and motor disorder status, demonstrating statistical independence of the two disorders. Together, this suggests that the comorbid profile had a combination of deficits that were no different to children with isolated literacy and motor disorders.

Selective Attention

Children with LD had lower selective attention scores than children without literacy disorder. *Post-hoc* analyses showed that children with literacy disorder (LD and LD+MD) performed less well than TD children. No significant differences arose between children with LD and LD+MD or between children with MD and TD controls.

GENERAL DISCUSSION

We investigated the relationship between literacy and motor disorders within the context of Pennington's multiple deficit model (MDM). Specifically, in Study 1, we examined prevalence

TABLE 6 | Means, standard deviations, main effects, covariates, and interactions from the 2 × 2 weighted AN(C)OVAs of factor scores.

	LD^{a}		MD^{b}		LD+MD^{c}		TD^{d}		Main effect				Covariate			
									LD		MD		NVIQ		LD × MD	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*F*	η_ρ^2	*F*	η_ρ^2	*F*	η_ρ^2	*F*	η_ρ^2
Visuospatial	2.62	0.49	2.42^{d}	0.41	1.91^{ad}	0.43	2.82	0.49	3.34	0.02	7.32**	0.05	42.91	0.24	0.62	< 0.01
Phonological	−2.96^{bd}	0.70	−3.76	0.47	−2.60^{bd}	0.72	−3.68	0.47	27.20***	0.15	2.65	0.02	–	–	0.45	< 0.01
Memory	1.55^{d}	0.25	1.53^{d}	0.36	1.08^{abd}	0.39	1.78	0.34	8.33**	0.05	5.98*	0.04	7.22	0.05	0.48	< 0.01
Selective Attention	−3.46^{d}	1.05	−3.77	0.65	−2.83^{d}	1.11	−3.88	0.77	8.74**	0.06	1.75	0.01	–	–	0.72	< 0.01

*LD, literacy disorder; MD, motor disorder; LD+MD, comorbid literacy and motor disorder; TD, typically developing; NVIQ, non-verbal IQ. The covariate, NVIQ, is not reported for phonological speed and literacy analyses because NVIQ was a non-significant covariate and so was dropped from the model. Superscript letters refer to each group (see first row). Superscript letters by means represent significant (at p < 0.05) differences between groups after applying Bonferroni corrections. *p < 0.05, **p < 0.01, ***p < 0.001.*

rates of isolated and comorbid literacy and motor difficulties in a community sample to establish whether comorbid literacy and motor difficulties were greater than would be predicted by the base rates of isolated disorders. We found cases of comorbid literacy and motor difficulties to be five times more prevalent than would be expected from the product of isolated disorder base rate estimates, suggesting comorbidity is not the result of chance alone. In Study 2, we examined the relationship between literacy and motor disorders using a subsample of children from Study 1. We aimed to identify potential independent and shared cognitive risk factors of literacy and motor disorders and to compare the profiles of performance on these between children with isolated and comorbid disorders to elucidate the nature of comorbidity between the two disorders. We found phonological processing and selective attention to be independent risk factors for literacy disorders and visuospatial processing to be an independent risk factor for motor disorder. Memory, however, was a shared risk factor for literacy and motor disorders. Comparisons between isolated and comorbid groups revealed children with comorbid literacy and motor disorder to have deficits similar in nature and magnitude to children with isolated literacy and motor disorders.

Prevalence of Isolated and Comorbid Literacy and Motor Difficulties

The prevalence rates of isolated disorders observed in the present study are considerably lower than those reported in previous studies using clinic and smaller community-based samples to examine comorbid literacy and motor difficulties (Kaplan et al., 1998; Cruddace and Riddell, 2006). However, despite differences in how literacy and motor difficulties were operationalized, the prevalence rates of isolated disorders found here (7% for literacy difficulties and 6% for motor difficulties) corroborate estimates often reported in the literature (e.g., Blank et al., 2012; Snowling, 2013). Such good agreement suggests the current rates are accurate, which is in turn crucial for investigating comorbid disorders because they act as base rates in establishing whether the prevalence of comorbid disorders is greater than would be expected by chance (Caron and Rutter, 1991).

The current prevalence rates of children with comorbid literacy and motor difficulties were also considerably smaller than those reported in previous community (Cruddace and Riddell, 2006) and clinic (Kaplan et al., 1998) samples. Specifically, 3% of the entire sample studied here had comorbid literacy and motor difficulties whereas Cruddace and Riddell (2006)—who also assessed children in community primary schools—identified 13% of children with comorbid profiles. The authors reported relatively high prevalence rates of isolated reading and motor disorders suggesting their sample was not representative of the general population. Indeed, the class teachers in the study noted there was an unexpected number of children with developmental disorders in the classes that were tested. The abnormally high rates of developmental disorders in Cruddace and Riddell's (2006) sample may explain why their estimates of comorbid difficulties were larger than the ones we found in this investigation.

Despite there being little agreement in the exact prevalence rates of comorbid literacy and motor difficulties across studies, all investigations have reported a disproportionately high frequency of comorbid disorders (Kaplan et al., 1998; Cruddace and Riddell, 2006). This corroborates the current findings, where the frequency of children with comorbid literacy and motor difficulties was greater than would be expected by chance alone when using accurate base rates of isolated disorders. Furthermore, the current risk of comorbidity between literacy and motor difficulties is similar to other heterotypic comorbidities found between reading disorder and ADHD (OR = 2.63–5.57; Carroll et al., 2005) and math disorder (OR = 4.1; Landerl and Moll, 2010). Nevertheless, our findings of a relatively high prevalence of comorbidity between literacy and motor difficulties are in accordance with predictions from the MDM and offers some evidence that literacy and motor disorders are likely related.

Relationship Between Literacy and Motor Disorders

After identifying a high risk of comorbidity between literacy and motor difficulties, we considered the cognitive profiles of children with literacy, motor, and comorbid literacy and motor disorder. In doing so, we re-assessed children on a second, individually administered reclassification battery. As a more in-depth assessment of literacy and motor skills could be carried out, we defined literacy disorder as an impairment in word-level reading (and spelling) skills and motor disorder as an impairment in executing coordinated motor skills. These definitions are closer in classification to the diagnostic labels of dyslexia and DCD.

Group comparisons of factor scores allowed us to search for potential independent and shared cognitive risk factors for literacy and motor disorders. Much of the literature reporting an overlap between literacy and motor disorders had appeared to do so without controlling for comorbid cases in their samples (but see Bellocchi et al., 2017; Biotteau et al., 2017a). In identifying and considering comorbidity separately in the present study, we found independent and shared deficits between the two disorders.

It is often reported that children with motor disorders have deficits in visuospatial processing, with and without a motor component (e.g., Bonifacci, 2004; Tsai and Wu, 2008; Wilson et al., 2013). Such processing deficits have also been reported in children with literacy disorders, although to a much lesser extent (Iversen et al., 2005; Bellocchi et al., 2017). We found a moderate deficit in children with motor disorder, but not in children with literacy disorder, suggesting visuospatial processing is an independent risk factor of motor, but not literacy, disorder. Further analyses (available upon request from the first author) of group performance on the individual tasks visuospatial processing with and without motor components tasks revealed only children with MD to have deficits on these, with larger deficits on the task with a motor component than the task without, in line with Wilson and McKenzie (1998). The absence of evidence of visuospatial processing deficits in our sample of children with literacy disorder contradicts claims that visuospatial deficits may feature in literacy disorders, and instead suggest that such findings may reflect the addition of children with comorbid literacy and motor disorders.

We also examined potential overlap in phonological deficits between literacy and motor disorders. Phonological deficits are widely believed to be a cognitive risk factor of literacy disorder (Pennington and Lefly, 2001; Dandache et al., 2014; Moll et al., 2016), but there are also reports of children with motor disorder performing less well on phonological processing tasks (Dewey et al., 2002; Archibald and Alloway, 2008). As expected, we found large deficits in phonological processing in literacy but not motor disorder. Again, the differences between our findings and those of previous studies could be explained by their lack of control of comorbid cases (e.g., Dewey et al., 2002). Specifically, many previous studies have not controlled for potential comorbid cases and they often reported large variations in phonological skills amongst children with DCD. In the present study, we did not find any significant impairments in phonological skills amongst children with motor disorder, suggesting that findings of phonological deficits in earlier studies reflected the lack of control for comorbid LD cases.

Deficits in memory and attention have also been suggested in both literacy and motor disorders (Cruddace and Riddell, 2006; Alloway, 2007; Swanson et al., 2009). Interestingly, we found the presence of selective attention deficits only in children with word-level literacy disorder, suggesting this is an independent risk factor for dyslexia and not shared between dyslexia and motor disorders. Selective attention deficits in dyslexia have been reported in other studies (e.g., Varvara et al., 2014). In considering the relationship between word-level difficulties and selective attention deficits, it is likely that selective attention deficits on their own are not directly causally related to dyslexia, but rather are distally related to increasing the risk of a child meeting a diagnostic threshold (Hulme and Snowling, 2013; Gathercole et al., 2016).

The lack of selective attention deficits amongst children with motor disorder may appear contradictory at first glance, given the oft reported incidence of attentional difficulties amongst children with DCD (e.g., Dewey et al., 2002). However, the type of attention of interest in this study—selective attention—does not discriminate between children with and without attentional difficulties (see Manly et al., 2001). Therefore, our findings are important as they seem to rule out selective attentional difficulties as a risk factor for isolated and comorbid motor difficulties and LD+MD. However, the impact of attention on the expression of various developmental disorders is evidently complex, and further work should explore this issue.

Consistent with the literature, we found somewhat poorer memory skills in isolated and comorbid disorder groups, suggesting deficits may be shared between these disorders. Further analyses (available on request from the first author) of group performance on the verbal vs. visual memory tests revealed that impairments of verbal memory are a stronger marker for literacy disorder whereas impairments of visual memory are a stronger marker for motor disorder. These findings are in line with previous studies on the differential nature of memory impairments associated with dyslexia and DCD (Maziero et al., 2020). It is important to note, though, that the measure of visual memory used in this study includes a motor component, which limits the strength of the conclusion we can draw about visual memory as a specific marker for motor disorders. To mitigate this potential confound, we used a latent variable approach to reduce variance which may have been related to the motor skills. Nevertheless, we still found children with motor disorders to have poorer memory skills. Future studies should consider how best to disambiguate the influences of memory in different modalities on motor skills in children with DCD.

There is some debate in explaining poor performance on memory tasks in children with developmental disorders (see Gathercole et al., 2016). We take the view that deficits in memory are not directly causally related to the disorder, but rather reflect two, not mutually exclusive, possibilities. The first is that poor performance on memory measures is a downstream consequence of the proximal causal deficit. For example, in dyslexia, poor performance on measures of verbal memory have been attributed to deficits in phonological processing (e.g., McDougall et al., 1994). Similarly, in DCD, visual memory has been attributed to deficits in motor planning (Alloway and Warner, 2008). Another possibility is that memory impairments may be a correlate of literacy and motor disorders, and may not directly cause, but rather act synergistically with proximal causal deficits to increase the likelihood of children meeting a diagnostic threshold (Hulme and Snowling, 2013; Gathercole et al., 2016). The current data—demonstrating poorer performance of children with literacy and/or motor disorders on a measure comprising verbal and visual memory—suggests the latter possibility may be true but does not preclude the former also being true. Further work should examine the nature of memory deficits and their relations to proximal causes of comorbid literacy and motor disorders.

Nature of Comorbid Literacy and Motor Disorders

Another aim of this study was to examine the profiles of children with comorbid literacy and motor disorders in the light of the three competing hypotheses of the basis of comorbidity (phenocopy, cognitive subtype, and shared etiology). In this group, most children achieved lower non-verbal ability scores. We were careful, however, to ensure these children were not deemed at risk for, nor had received a diagnosis of ID. Furthermore, we controlled (covaried) for group differences in nonverbal ability during the analyses. Children with comorbid literacy and motor disorder performed similarly to children with isolated literacy and isolated motor disorders in all domains. Notably, on memory (a shared risk factor for literacy and motor disorders) children with comorbid literacy and motor disorder had larger deficits than the isolated groups. Moll et al. (2016) found a similar pattern of larger deficits amongst children with comorbid dyslexia and dyscalculia when compared to children with isolated disorders on measures of verbal memory. In both the current study and in Moll et al. (2016), the absence of a statistical interaction between the literacy and motor factor suggests that deficits in the comorbid group reflected deficits in both isolated groups. Taken together, the current findings are most consistent with a shared etiology hypothesis (de Jong et al., 2006) and add to the growing evidence in favor of this hypothesis between dyslexic heterotypic comorbidities (e.g., Gooch et al., 2011; Moll et al., 2016). A shared etiology account proposes that comorbid disorders result from shared genetic origins and is consistent with the MDM account.

It is clear then from the current findings and those from studies of other heterotypic comorbidities at the behavioral and cognitive levels that comorbidity between neurodevelopmental disorders reflects a shared etiology. However, further work on the neural profiles of children with comorbid disorders should be undertaken. Biotteau et al. (2017b) recently examined the behavioral and neural profiles of children with dyslexia, DCD, and comorbid dyslexia and DCD when completing a sequence learning task. The authors found no difference between the groups on task accuracy, consistent with predictions of the shared etiology hypothesis and the MDM. Yet, the fMRI data revealed neural correlates were similar in children with dyslexia and comorbid dyslexia and DCD but different in children with DCD. This suggests children with DCD could have a distinct neural profile to children with comorbid dyslexia and DCD, potentially contradicting predictions from the multiple deficit model. However, such a conclusion requires confirmation from a comparison with typically developing controls. Whilst the juxtaposition of results from behavioral/cognitive and neural profiles should be treated with caution, they raise the valid point that predictions of the MDM should also be tested at the neural level.

The current findings have implications for both researchers and educators. They highlight the potential confounding influence of comorbid cases in research and practice in neurodevelopmental disorders. Researchers and practitioners should be encouraged to screen for additional disorders beyond the disorder of focus. The additive nature of comorbid literacy and motor disorders means that existing tests rather than new comorbid-disorder-specific measures, can be applied in combination to assess comorbidity. Indeed, analysis of the screening battery we used in Study 1 suggests that a battery screening for fine-motor skills was appropriate for group screening class children for motor difficulties. This offers a potential economical and logistical method for identifying motor difficulties among children in large group settings. Further work should examine this possibility closely and consider whether the concomitant use of questionnaires (e.g., DCDQ′07; Wilson et al., 2000) may additionally improve the sensitivity and specificity.

This study investigated the relationship between literacy and motor disorders. It was concerned with exploring and disentangling the high degree of apparent overlap between literacy (e.g., dyslexia) and motor disorders (e.g., DCD), and understanding the nature of comorbidity between the disorders within the context of predictions made by the MDM. In accordance with these predictions, we found a higher rate of comorbidity between literacy and motor disorders, than would be expected by chance. After controlling for comorbidity, it was apparent that literacy and motor disorders were separable disorders with independent—phonological, visuospatial, and selective attention—and shared—memory—deficits. Children with comorbid literacy and motor disorders had deficits that were additive in nature suggesting a shared etiology. Taken together, literacy and motor disorders are two neurodevelopmental disorders that seem to result from independent and shared risk factors that lead to difficulties in literacy and/or motor skills acquisition.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because the data set is new, part of a larger data set, and still being exploited by the authors. The data will be made available in the future. Requests to access the datasets should be directed to Markéta Caravolas, m.caravolas@bangor.ac.uk.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Research Ethics Committees of the School of Psychology, Bangor University, and the National Health Service (NHS). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

This work was undertaken as part of CD's doctoral studies. CD and MC conceptualized the aims and design of the study. CD performed data collection, scoring, undertook the analysis, and drafted the manuscript. MC supervised the research undertaken, provided guidance on structure and content of the manuscript, and edited each draft version. All authors contributed to the article and approved the submitted version.

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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.2020.573580/full#supplementary-material

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Comorbidity Between Math and Reading Problems: Is Phonological Processing a Mutual Factor?

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There is a relationship between reading and math skills, as well as comorbidity between reading and math disorders. A mutual foundation for this comorbidity could be that the quality of phonological representations is important for both early reading and arithmetic. In this study, we examine this hypothesis in a sample traced longitudinally from preschool to first grade ($N = 259$). The results show that phonological awareness does not explain development in arithmetic, but that there is an indirect effect between phoneme awareness in preschool and arithmetic in first grade *via* phoneme awareness in first grade. This effect is, however, weak and restricted to verbal arithmetic and not arithmetic fluency. This finding is only partly in line with other studies, and a reason could be that this study more strongly controls for confounders and previous skills than other studies.

Keywords: reading, math, numeracy, comorbidity, phonological awareness

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INTRODUCTION

Mastering reading and math is vital for not only academic performance but also important life skills critical for employment and participation in society. Researchers have long known that there is a rather close relationship between reading and mathematics. The two skills correlate moderately to highly (Peng et al., 2020), and a large number of children with dyslexia also struggle with math difficulties. Reversely, many children with dyscalculia also have difficulties in reading (Joyner and Wagner, 2020). A question yet to be answered is what kind of foundational skills might be a common factor underlying reading and arithmetic. One hypothesis that has gained support is that phonological processing underlies not only early reading skills but also foundational mathematic skills. In this study, we investigate this hypothetical cause of the relationship between early reading and mathematics skills and thus focus on the relationship between math and early reading.

TO WHAT EXTENT ARE READING AND ARITHMETIC CORRELATED?

Although correlation does not imply causation, a correlation is often a starting point for disentangling causality. Studies have shown that reading and mathematics are correlated both at the genetic level and in brain activation patterns (Shaywitz et al., 1998; Temple et al., 2001; Ashkenazi et al., 2013; Pollack and Ashby, 2018). These correlations are also reflected at a behavioral level: on a broader level, a recent meta-analysis illustrated that the mean correlation between language and math across 392 independent samples was moderate (r = 0.42; Peng et al., 2020). This correlation, unsurprisingly, is also reflected in children at the lower end of the distribution with math and reading problems. A recent review showed that children with a math disorder were over two times more likely to also have a reading disorder than those without a math disorder (odds ratio = 2.12; Wagner et al., 2019). This result coincides with findings from other meta-analyses (see Swanson et al., 2009; Landerl and Moll, 2010).

PHONOLOGICAL PROCESSING AS A FOUNDATION FOR ARITHMETIC AS WELL AS WORD DECODING

Theoretically, the "triple code model," the most influential framework for understanding early number processing, assumes a pathway from language to numeracy (Dehaene, 1992). An important question then is which aspects of language might be causally related to mathematics. One candidate is skills related to phonology. The consensus concerning reading is that phonological processing of sounds in words (often measured with phoneme awareness tasks) is an important causal precursor of growth in word decoding and the primary cause of reading problems such as dyslexia (Melby-Lervåg et al., 2012; Caravolas et al., 2013; Snowling and Melby-Lervåg, 2016). In a meta-analytic comparison of the effectiveness of reading interventions, phoneme awareness programs were found to be among the most successful approaches to boosting children's reading skills over time (Suggate, 2016). To master such phonological awareness tasks, a child must be able to encode, maintain, and reproduce accurate representations of words from memory. Performance on phonological awareness tests is therefore considered to reflect the quality of phonological representations stored in memory. Thus, the more fine-grained and detailed the phonological processing and representations are, the better the performance on phonological awareness tests.

However, performance on such phonological processing tasks is highly correlated with not only decoding but also early mathematics skills. In particular, performance on such phonological processing tasks is strongly correlated with arithmetic, the part of mathematics that concerns numbers and basic operations on them—addition, subtraction, multiplication, and division. A review by Peng et al. (2020) showed an average moderate correlation between phonological awareness and arithmetic (r = 0.35).

The quality of phonological representations can be important for arithmetic problem-solving in several ways. First, to solve a computation problem, a child must first transform the numbers and operators in the problem into a speech-based code (Dehaene, 1992; Hecht et al., 2001). Studies have shown that this Arabic-to-verbal translation appears to be routinely used by children not only to solve simple arithmetic problems but also for more general math computation problems, such as long division and fractions. A second stage during which phonological representations might be important is after the Arabic-to-verbal translation. The child must then process the phonological information using a specific task-solving strategy. For a simple arithmetic problem (4 + 3 = ?), one must retrieve the answer directly from long-term memory, and so the ability to solve such a problem is dependent on the storage of phonological information. Another alternative can be to use a counting-based strategy to retrieve the answer. The phonological system is then employed when the child uses the phonological codes for the number names in counting. Thus, there are several ways in which phonological processing may also yield a causal influence on numeracy. Phonological processing tasks are likely important for both decoding and arithmetic since both tasks depend on mental processes that use sound-based representations.

As for previous studies, some observational investigations have offered support for this theory. One study followed children from second to fifth grade (N = 201; Hecht et al., 2001). The researchers found that phonological processing was uniquely associated with the development of early arithmetic skills. Importantly, phonological processing (as measured by digit span, rapid naming, and phonological awareness) almost entirely accounted for the relationship between reading and math. However, the authors found no unique influence of phonological processing on arithmetic fluency speed from fourth to fifth grade. There are several potential explanations for this result. For example, the children could have been too old for phonological processing to have an influence. Another explanation might be that phonological processing (or, more specifically, the quality of phonological representations) influences accuracy but not speed. A study by De Smedt et al. (2010) of fourth- and fifth-grade children (N = 37) yielded results in line with those of Hecht et al. (2001): they found that the quality of phonological representations was particularly important for the retrieval of existing arithmetic facts (e.g., 2 + 3 = 5). Such single digits problems are easier and faster to retrieve compared to larger problems requiring procedural strategies.

Recently, a larger 1-year longitudinal study of Finnish 7-year-olds (N = 200) followed up on Hecht et al. (2001) and examined predictors of the covariance between reading and arithmetic fluency (Koponen et al., 2019). The results showed that phonological awareness is a unique longitudinal predictor of this variation. Along the same lines, a 1-year study of students in kindergarten and first grade by Cirino et al. (2018) examined predictors for the mutual variance between reading and math (N = 193). This study found that phonological awareness, together with other linguistic naming tasks, accounted for nearly the same amount of overlap as all predictors together. This finding matches that of an earlier concurrent study (N = 233) from the same research environment, which showed a relationship between both timed and untimed arithmetic tasks (Child et al., 2019).

Furthermore, a recent concurrent study of 5-year-old kindergarteners (N = 188) also suggests that phonological awareness is related to early arithmetic (Vanbinst et al., 2020). The main finding was that phonological awareness was related not only to early reading but also to early arithmetic. The relationship notably remained after controlling for early reading- and arithmetic-specific cognitive correlates. Finally, Singer et al. (2019) also found, using concurrent data on children aged 9–11 years (N = 262), that phonological awareness was uniquely related to simple arithmetic fluency computations.

Still, other observational studies have found no unique relationship between phonological awareness and arithmetic, despite high correlations between the two. Purpura et al. (2011) found that letter knowledge—but not phonological processing—uniquely predicted development in arithmetic from 1 year to the next. Moll et al. (2015) reported that children with arithmetic difficulties only, and not comorbid reading problems, had difficulties restricted only to the arithmetic domain, while children with only reading difficulties also had problems with tasks related to arithmetic exercises that involved a verbal code. The comorbid math/language group exhibited difficulties with both. Thus, in this study, only the result of the comorbid group was in line with the hypothesis that children with arithmetic difficulties have phonological problems. In a previous study by Landerl et al. (2009), findings suggested that dyslexia and dyscalculia have separable cognitive profiles; when comparing groups of dyslexic, dyscalculic, and dyslexic/dyscalculic children, the researchers found a phonological deficit in both dyslexic groups, but not in the dyscalculia-only group. Contrastingly, they found difficulties in symbolic and non-symbolic number processing in both groups with dyscalculic children, but not in the dyslexia-only group.

Thus, taken together, findings on the role of phonological processes as a foundation of arithmetic as well as word decoding are inconclusive. Two possible reasons for discrepancies in the findings are differences in age of the children studied as well as differences in tasks used to measure such phonological processes. It is possible that detection of this relationship depends on the degree of automated fact retrieval and whether or not the task used to measure phonological skill is a phonological awareness task or a different measure aimed at capturing other related processes. Phonological skills have been measured by different tasks reflecting different components, such as rapid automatized naming (RAN) and verbal working memory (Wagner and Torgesen, 1987; Hecht et al., 2001). However, results concerning rapid naming and phonology tasks tapping verbal working/short term memory can be difficult to interpret since it is not entirely clear what these components measure. Because the construct phonological processing has evolved over time, and recent theory relating to arithmetic has focused on phonological awareness, this is also the aspect of phonological processing assessed in the present study. Beyond phonological processes, it is also possible that other domain-general abilities can account for the observed relationship, as previous studies vary in the extent to which they include broader abilities.

THE CORRELATION BETWEEN PHONOLOGICAL AWARENESS AND ARITHMETIC: IS IT SPURIOUS AND CAUSED BY UNDERLYING GENERAL COGNITIVE SKILLS?

The first potential explanation for the correlation between phonological awareness and arithmetic is that general cognitive ability is the third variable that underlies both. Possible cognitive candidates that have been suggested to underlie this correlation are nonverbal abilities (Bull and Scerif, 2001; Geary, 2004) and general language skills (Moll et al., 2015). If this is correct, controlling for cognitive abilities in the relationship between phonological awareness and arithmetic would weaken the correlation or make it disappear entirely. A recent review by Peng et al. (2020) demonstrates that general intelligence explains a large proportion of the variance in the relationship between mathematics and language.

However, previous studies of phonological awareness and arithmetic have varied with the extent to which they take such variables into account: Hecht et al. (2001) controlled for general language skills and found that the relationship between phonological processing and arithmetic held. They did not, however, control for nonverbal abilities. Koponen et al. (2019) controlled for various memory-related variables but not verbal and nonverbal abilities, while Cirino et al. (2018) controlled for processing speed, visuospatial working memory, and nonverbal abilities. As for the concurrent studies, Child et al. (2019) controlled for working memory and processing speed; Vanbinst et al. (2020) controlled for nonverbal abilities; and Singer et al. (2019) controlled for both verbal and nonverbal abilities. Regarding those studies that did not find a relationship between phonological awareness and arithmetic, Purpura et al. (2011) controlled for nonverbal intelligence, while Moll et al. (2015) controlled for both verbal and nonverbal abilities.

PHONOLOGICAL AWARENESS—MORE IMPORTANT FOR SOME ASPECTS OF ARITHMETIC THAN OTHERS?

As mentioned, the quality of the phonological representations can be important for arithmetic problem-solving in several ways. This also implies that the relationship can stronger for some types of computation than others. However, only one previous study has examined whether there are differential effects for different types of arithmetic types. This study found a relationship between phonological awareness and addition/subtraction fluency, but not with number knowledge or word problems (Singer et al., 2019). This distinction is potentially significant because it implies that the general language ability required for word problem-solving is separate from the phonological processes involved in efficient arithmetic fact retrieval.

The remaining studies have used a variety of tasks: Hecht et al. (2001) used a latent variable with a range of tasks such as untimed simple digit addition and subtraction, multi-digit addition, multiplication, division, fractions, and algebra as well as addition and subtraction fluency. Koponen et al. (2019) used a latent variable with addition and subtraction fluency and basic arithmetic, while Vanbinst et al. (2020) measured basic addition and subtraction accuracy. While such tasks are likely to trigger arithmetic fact retrieval due to small problem sizes and frequent administration with a time limit, they are rarely compared to other types of arithmetic tasks that may or may not also rely on phonological processes. Comparing additional types of arithmetic concerning their ties to phonological skill could provide clarity on which aspects of early number ability account for the observed relationships. In addition to procedural vs. fact-retrieval demands, task characteristics such as the degree of vocalization, working speed, and use of digits vs. number words might matter in terms of whether a relationship is detected.

THE CURRENT STUDY

Taken together, several studies have pointed to phonological awareness as a candidate for explaining why there is a relationship between early reading and arithmetic. However, previous results have been inconclusive. Moreover, the studies have varied in whether they have controlled for confounders in their outcome measures. Furthermore, some of these studies have included tasks in their phonology construct tasks that would now be considered rather unconventional, such as rapid naming and verbal short-term memory measures. In the present study, we deal with these issues and examine the relationship between phonological awareness (measured with widely used task formats) and arithmetic in a large sample, controlling for measurement error and verbal and nonverbal abilities. We examine the following research questions:

- Can phoneme awareness in preschool predict both reading and arithmetic skills in first grade when controlling for early reading and number skills, general language skills, and nonverbal abilities?
- Does phoneme awareness predict reading and arithmetic concurrently, and are there indirect effects of phoneme awareness in preschool on arithmetic and reading outcomes through phoneme awareness in first grade?
- Does phoneme awareness relate differently to verbal arithmetic and arithmetic fluency?

MATERIALS AND METHODS

Participants

We recruited a cohort of 259 Norwegian-speaking children (135 boys and 126 girls) with a mean age of 5.5 years (range 4.9–6.1 years, *SD* = 0.3) when the study began. The children were recruited from a district in southeastern Norway that compared to the national average on aspects relating to educational level and socioeconomic status (Statistics Norway, 2020a,b). Children diagnosed with severe learning or developmental disorders, such as autism, sensory impairments, or an intellectual disability, were excluded from the study during data collection.

We obtained informed consent for the children's participation in the study from their parents. Additionally, the children gave verbal consent at each time point of the data collection.

At the first time point, the children were in their final year of preschool. Norwegian children enter primary school and begin formal literacy and numeracy instruction the year they turn six. No formal instruction in reading or math is given in preschool before children enter first grade in primary school. At the time of the testing in grade one, the children in our sample had had about 6 months of formal instruction, with some children yet to master reading and calculations. However, due to the early assessment point, there might be lower-performing children in our sample who will receive diagnoses as they age.

Design and Procedure

The children were assessed individually on a range of measures of numeracy, literacy, and general cognition with a 12-month time interval in their respective kindergartens and later schools. The tests used in the data collection are mainly internationally established and widely used measures that have been adapted to Norwegian. See **Table 1** for the descriptive statistics and reliabilities for all measures.

The tests were administrated individually in a fixed order by trained research assistants. The research assistants visited the children's kindergartens and later schools three times in the weeks between early January and late March 2 years in a row. The tests were part of a larger test battery involving a range of cognitive abilities, and each of the three sessions lasted about 35–55 min, depending on the child's working speed and needs.

MEASURES

The following indicators were used.

Preschool, Age Five

General language skills were measured with two indicators: first, receptive grammar skills were assessed using the Norwegian version of the Test for Reception of Grammar (TROG; version 2; Bishop, 2009). The Norwegian version of the TROG has been standardized and normed with a Norwegian sample (Lyster and Horn, 2009). In this task, the child hears sentences of increasing complexity and selects a picture for each sentence. Example sentences include the following: "The girl is sitting on the table" and "The blue cup is on top of the small yellow book." The test contains 80 four-choice items and is discontinued when the child makes one or more errors in five consecutive blocks.

Second, receptive vocabulary skills were assessed with a translated version of the British Picture Vocabulary Scale (BPVS; Dunn and Dunn, 2009). The Norwegian version of the BPVS has also been standardized and normed with a Norwegian sample (Lyster et al., 2010). The test requires the child to match a spoken word with one of four presented pictures. This instrument has a total of 144 items of increasing difficulty, and test administration ends when the child makes eight or more errors in a block of 12 items.

TABLE 1 | Descriptive statistics and reliability for all observed variables.

Task	*N*	Min-max	*M*	*SD*	Reliability ω
Preschool, 5 years					
Vocabulary (BPVS)	252	0–99	62.24	13.99	0.95
Grammar (TROG)	254	1–75	44.80	17.94	0.97
Ravens CPM	245	7–35	17.75	4.48	0.75
Matrices WPPSI	250	1–22	11.62	5.32	0.92
Number naming	254	1–13	8.32	2.60	0.82
Verbal arithmetic, addition	254	0–11	5.59	3.81	0.92
Letter knowledge, vowels	254	0–9	4.87	2.67	0.82[1]
Letter knowledge, consonants	254	0–17	9.33	6.07	0.82[1]
Phoneme isolation	254	2–24	11.31	6.55	0.95
First grade, 6 years					
Number naming	244	6–22	14.97	4.68	0.91
Number identification	244	1–8	5.44	1.77	0.71
Phoneme deletion, words	243	0–12	6.40	3.29	0.84
Phoneme deletion, non-words	243	0–12	4.72	3.38	0.85
Arithmetic fluency, addition	244	1–23	9.95	3.66	0.88
Arithmetic fluency, subtraction	244	0–20	6.08	3.87	0.89
Verbal arithmetic, addition	244	0–22	15.47	4.19	0.86
Verbal arithmetic, subtraction	244	0–14	9.82	4.25	0.93
Word reading A	252	0–83	21.72	14.02	0.94[1]
Word reading B	252	0–91	18.88	14.49	0.94[1]

Note: [1]Correlation between the two alternate forms.

Nonverbal general abilities were also measured with two indicators: first, Raven's Coloured Progressive Matrices (CPM) is a test designed for children aged 5–11 (Raven, 2000). The instrument measures nonverbal intelligence and abstract reasoning abilities, and very limited verbal instruction is given by the test administrator. The child sees a set of illustrations with a piece missing and is then required to identify the construction pattern of increasingly complex geometrical figures by selecting the piece required to complete the set. There are 36 items organized in sets, and the test is administered without time constraints.

Second, the matrix reasoning task from the Wechsler Preschool and Primary Scale of Intelligence, 4th edition (WPPSI-IV) is also an index of nonverbal abilities (Wechsler, 2012). In this task, the child sees an incomplete matrix and is required to select the missing alternative that completes the matrix. Picture or figure analogies must be nonverbally identified for the child to select the correct response. An example of such a task is a matrix with a horse, a barn, and a fish, as well as an empty square. Among the alternatives for the missing piece is an empty fishbowl, which would be the correct choice. As the child progresses, items become gradually more abstract and complex.

Number word knowledge in preschool was measured with a number-naming task. The child was shown a series of printed numbers and asked to name them: "Which number is this?" The numbers increased in size and range from single- to four-digit numbers.

Verbal arithmetic skills in preschool were measured with a verbal addition task. The task consisted of linguistically simple addition problems presented orally and calculated mentally (e.g., "What is seven plus nine?"). The child responded verbally. For 5-year-old children, we only used addition as an indicator of arithmetic skills due to the large number of children who are unfamiliar with subtraction at this stage.

Letter knowledge in preschool was assessed by having the child give the name or sound of letters in the Norwegian alphabet shown on a sheet of paper, ordered alphabetically. In task one, the printed letters were vowels (e.g., A, E, I . . .) and in task two, the letters were consonants (B, D, F . . .).

Phoneme awareness at age five was measured with a phoneme isolation task. The child was asked to identify a phoneme in a word read aloud by the test administrator (e.g., "What is the first sound in boat?"). We used two blocks where the child was asked to identify the first sound of a given word in block one and the last sound of the word in block two.

The four first items in each block were accompanied by pictures for support. The items consisted of three or four-letter words [either consonant-vowel-consonant (CVC), CCVC, or CVCC].

First Grade, Age Six

Number word knowledge in first grade was measured by two tasks assessing the child's knowledge of the correspondence between digits and number words.

Number naming. The first number-knowledge task was the same as that used in the previous year but extended to include more difficult items (i.e., larger numbers with up to four digits). The child was shown a series of printed numbers and asked to name them ("Which number is this?").

Number identification. The children were also given a number identification task, similar to the task used by Göbel et al. (2014). Number identification entailed drawing a circle around one of five printed numbers for each number read aloud by the test administrator. For example, the test administrator might read "163", and the child would then mark one of five options presented on a sheet (136, 10,063, 13, 163, 16). The target numbers ranged from one to three digits.

Phoneme awareness was assessed as follows: two phoneme deletion tasks were administered, one with words and one with non-words. The tasks required the child to delete sounds in the beginning, middle, or end of the words. A translated example is "Say 'cat' without saying '/k/'."

Arithmetic fluency was measured with two tasks, one with addition problems and one with subtraction problems. The subtasks were taken from the Test of Basic Arithmetic and Numeracy Skills (TOBANS; Brigstocke et al., 2016). The child completed three practice items for each set to ensure that they understood the mathematical operation required and was then asked to solve as many problems as possible with pencil and paper within 60 s. The number of correct answers was recorded.

Verbal arithmetic skills were assessed in first grade with linguistically simple arithmetic problems presented orally and calculated mentally. The test had two parts; part one consisted of increasingly difficult addition problems, and part two contained subtraction problems. The child responded verbally and the number of correct responses was recorded.

Reading efficiency was assessed by requiring children to read aloud two lists of words from a Norwegian translation of the Test of Word Reading Efficacy (TOWRE; Torgesen et al., 1999). Children are given 45 s to read aloud as many words as they can from each list. The score is the number of items read and pronounced correctly.

RESULTS

Descriptive Statistics and Correlations

Table 1 shows the means, standard deviations, minimum and maximum scores, and reliabilities for all measures, and the correlations between all observed variables are available in online supplement (**Supplementary Table 1**). **Table 1** shows that all variables had decent reliability. All further analyses were done in Mplus version 8 (Muthén and Muthén, 1998-2017) using the full information maximum likelihood approach to handle missing values.

Confirmatory Factor Analyses

To test the relations between the latent constructs and their respective observed indicators (i.e., the measurement model) and between the latent constructs themselves, we estimated a confirmatory factor analysis (CFA) in which we included all variables. Six constructs were measured in preschool (nonverbal abilities, language, letter knowledge, phoneme awareness, number knowledge, and verbal arithmetic) and five constructs were measured in first grade (phoneme awareness, number knowledge, verbal arithmetic, arithmetic fluency, and word reading). See **Table 2** for the indicators of the constructs. This model had an excellent fit to the data, $\chi^2_{(99)} = 109.902$, $p = 213$; RMSEA = 0.021 (90% CI = 0.000, 0.040); TLI = 0.993; SRMR = 0.026. **Table 2** shows the factor loadings and factor correlations. As illustrated, the factor loadings were relatively strong for most observed indicators, except matrixes ($\lambda = 0.407$). Regarding the hypotheses, strong correlations were found between phoneme awareness and both reading and verbal arithmetic. The correlations between phoneme awareness and arithmetic fluency were somewhat lower.

Does Phoneme Awareness Predict Reading as Well as Verbal Arithmetic and Arithmetic Fluency?

To test this, we first estimated a structural equation model (SEM) in which we regressed reading, verbal arithmetic, and arithmetic fluency in first grade on phoneme awareness in preschool together with the control constructs letter knowledge, number-word knowledge, verbal arithmetic, language, and nonverbal abilities in preschool. Also, phoneme awareness, letter knowledge, number-word knowledge, and verbal arithmetic skills in preschool were regressed on language and nonverbal abilities in preschool.

As shown in **Figure 1**, phoneme awareness in preschool predicted reading but not verbal arithmetic and arithmetic fluency in first grade. Number-word knowledge in preschool predicted both reading and the two arithmetic constructs in first grade; verbal arithmetic in preschool predicted both verbal arithmetic and arithmetic fluency in first grade. Also, there was a negative suppression effect of letter knowledge in preschool on arithmetic fluency in first grade. Language in preschool directly predicted phoneme awareness, letter knowledge, number-word knowledge, and verbal arithmetic in preschool and indirectly predicted reading and the two arithmetic constructs in first grade. The same was true for nonverbal abilities in preschool, with the exception that this construct did not predict phoneme awareness in preschool beyond language. This model had an excellent fit to the data, $\chi^2_{(56)} = 59.392$, $p = 353$; RMSEA = 0.015 (90% CI = 0.000, 0.042); TLI = 0.997; SRMR = 0.023.

Next, we added phoneme awareness and number naming in first grade as additional predictors of reading, verbal arithmetic, and arithmetic fluency in first grade. This was done to see if phoneme awareness predicted reading, verbal arithmetic, and arithmetic fluency concurrently, and if there were indirect effects of phoneme awareness on these three outcomes through phoneme awareness in first grade. As shown in **Figure 2**, and partially in line with the phonological hypothesis, phoneme awareness in first grade did predict both reading and verbal arithmetic but not arithmetic fluency in first grade. In addition to phoneme awareness in first grade, both phoneme awareness and number-word knowledge in preschool predicted reading in first grade, and verbal arithmetic and number-word knowledge in preschool predicted verbal arithmetic in first grade. Only number-word knowledge in first grade predicted arithmetic fluency in first grade beyond all other potential predictors. The indirect effect of phoneme awareness in preschool on reading and verbal arithmetic was 0.086 (bootstrapped 95% CI = 0.001, 0.191) and 0.080 (bootstrapped 95% CI = 0.001, 0.173), respectively. However, it should also be noted that phoneme awareness in preschool had a direct effect on reading so that the total effect of PA in preschool on reading in first grade was $\beta = 0.279$ (95% CI = 0.098, 0.429). This model had the same excellent fit to the data as the full CFA explained above.

TABLE 2 | Standardized factor loadings for all latent constructs and their respective indicators plus factor correlations between the latent constructs.

Latent constructs and observed indicators	Factor loadings[1]	1	2	3	4	5	6	7	8	9	10	11
1_Nonverbal abilities PS		1	0.456	0.359	0.392	0.353	0.348	0.200[3]	0.426	0.306	0.289	0.183[3]
Raven CPM	0.953											
Matrices WPPSI	0.407											
2_Language_PS			1	0.387	0.390	0.266	0.511	0.360	0.535	0.366	0.336	0.334
Vocabulary (BPVS)	0.531											
Grammar (TROG)	0.871											
3_Letter knowledge PS				1	0.731	0.408	0.676	0.503	0.549	0.370	0.304	0.577
Consonants	0.908											
Vowels	0.904											
4_Number knowledge PS					1	0.708	0.490	0.457	0.538	0.495	0.558	0.586
Number naming PS	0.905[2]											
5_Number knowledge G1						1	0.318	0.446	0.524	0.686	0.672	0.469
Number naming	0.845											
Number identification	0.825											
6_Phoneme awareness PS							1	0.508	0.538	0.382	0.246	0.540
Phoneme isolation	0.964[2]											
7_Phoneme awareness G1								1	0.540	0.643	0.384	0.638
Phoneme deletion W	0.849											
Phoneme deletion NW	0.906											
8_Verbal arithmetic PS									1	0.593	0.490	0.428
Addition	0.928[2]											
9_Verbal arithmetic G1										1	0.702	0.443
Verbal addition	0.860											
Verbal subtraction	0.581											
10_Arithmetic fluency G1											1	0.432
Addition fluency	0.848											
Subtraction fluency	0.796											
11_Reading												1
Word reading A	0.992											
Word reading B	0.948											

Note: [1]All factor loading have p-values <0.001. [2]The residual of the observed indicator is fixed to reflect the reliability of the variable. [3]The p-value of the correlation is <0.05. Correlations without superscript have p-values <0.001.

In both these models shown in **Figures 1**, **2**, there was an unexpected negative path from preschool letter knowledge to either first-grade arithmetic fluency (**Figure 1**) or first-grade number-word knowledge (**Figure 2**). These paths seemed to be caused by the high correlation between preschool letter knowledge and preschool number-word knowledge ($r = 0.731$). Deleting number-word knowledge from the model resulted in these two paths becoming positive but nonsignificant ($\beta = 0.080$, $p = 0.462$ for first grade arithmetic fluency in **Figure 1** and $\beta = 0.178$, $p = 0.078$ for first grade number-word knowledge in **Figure 2**). It should however be mentioned that all of the eight latent predictor variables in **Figure 2** were within the tolerances for commonly suggested thresholds for potential collinearity problems (e.g., all tolerances were above 0.2) and that the main results concerning the hypothesized relationships between phoneme awareness and arithmetic and reading did not change as a function of deleting the preschool number-word knowledge variable.

DISCUSSION

This study has revealed several interesting findings that add to the literature about the relationship between phonological awareness and arithmetic. First, we did not find that phoneme awareness can predict the development of arithmetic from preschool to first grade when early reading, arithmetic, general language skills, and nonverbal abilities are controlled for. However, we did find that phoneme awareness is concurrently related to arithmetic in first grade and that there is an indirect effect of phoneme awareness in preschool on arithmetic in first grade *via* phoneme awareness in first grade. Moreover, the relationship between phoneme awareness and arithmetic is restricted to verbal arithmetic—simple arithmetic problems presented orally and calculated mentally—and not arithmetic fluency.

Phoneme Awareness in Preschool Does Not Predict the Development of Arithmetic Skills in First Grade

The finding that phoneme awareness in preschool does not predict the development of arithmetic skills in first grade when controlling for early reading and number skills, general language skills, and nonverbal abilities contrasts with the two other longitudinal studies in this area. Hecht et al. (2001) found a uniquely direct relationship between phonological awareness and the development of early arithmetic. However, that study did not control for nonverbal abilities, and the researchers employed a rather broad phonological processing construct that also integrated verbal short-term memory and rapid naming. Thus, these two factors can perhaps explain

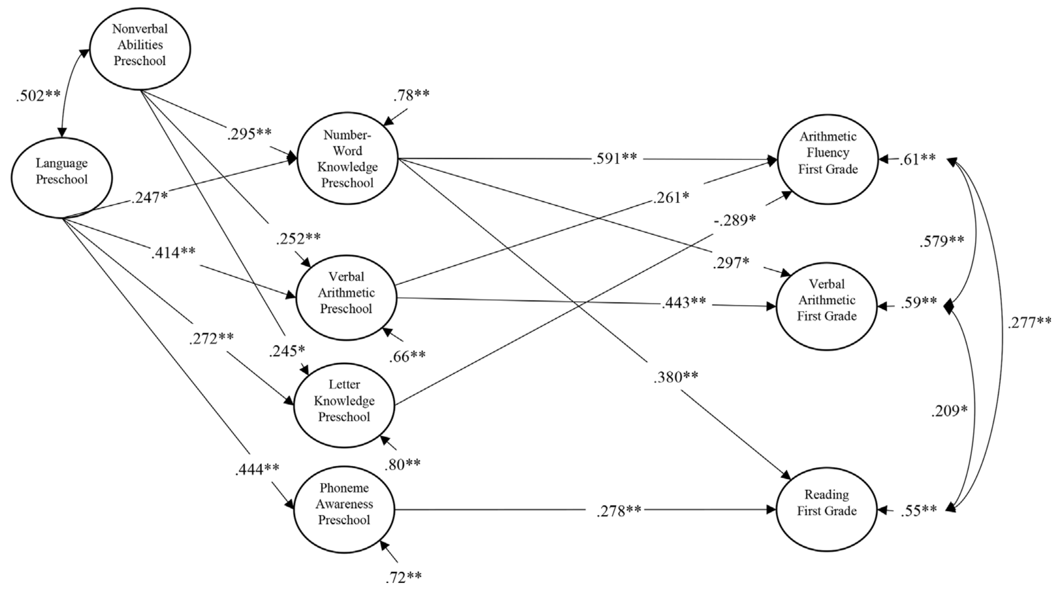

FIGURE 1 | Structural equation path model showing the longitudinal relations between Time 1 preschool preliteracy and numeracy skills, and Time 2 first grade reading and arithmetic. Single-headed arrows between the latent variables are standardized regression weights. Double-headed arrows indicate correlations (covariances). *$p < 0.05$, **$p < 0.01$.

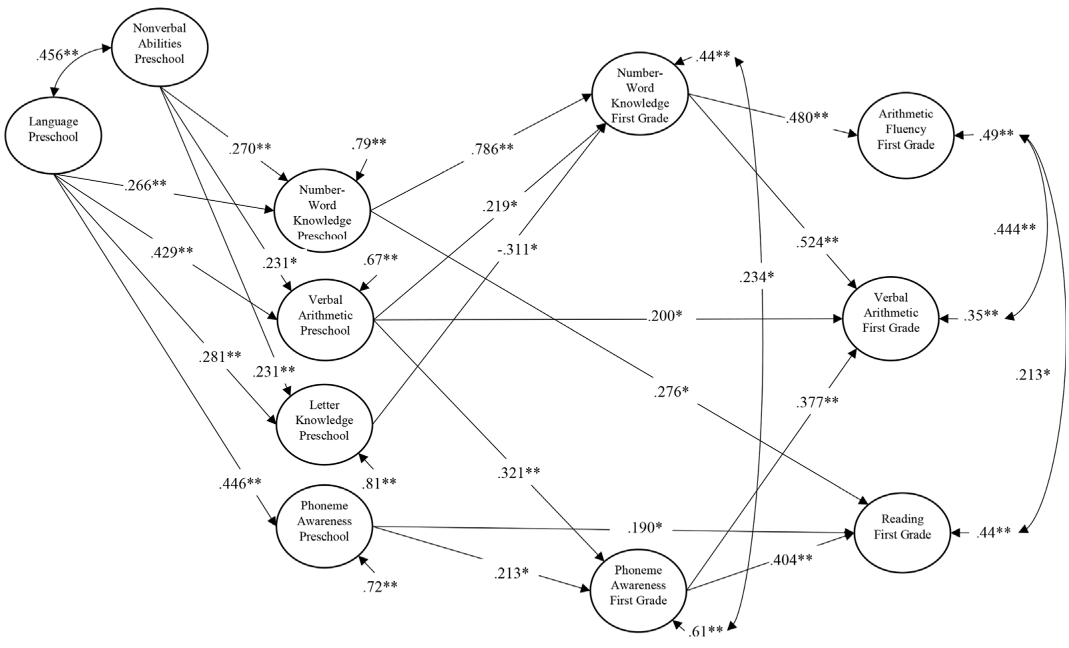

FIGURE 2 | Structural equation path model showing the longitudinal relations between Time 1 preschool preliteracy and numeracy skills, and Time 2 first grade phoneme awareness, number word knowledge, reading, and arithmetic. Single-headed arrows between the latent variables are standardized regression weights. Double-headed arrows indicate correlations (covariances). *$p < 0.05$, **$p < 0.01$.

why they found a different result. Koponen et al. (2019) also reported that phonological awareness is a unique longitudinal predictor of the covariance between reading and arithmetic fluency. Similarly, they did not control for verbal or nonverbal intelligence, and this might explain the differences in our findings. Thus, our study overall employed stricter controls, in particular for previous skills, but also confounders such as verbal and nonverbal abilities. We also controlled for measurement error using latent variables. These factors together could explain why we found that phoneme awareness did not predict development, while other studies have come to the opposite conclusion.

An Indirect Effect of Phoneme Awareness in Preschool on Arithmetic in First Grade

While we did not find a direct effect of phoneme awareness in preschool on arithmetic development, we did observe an indirect effect from phoneme awareness preschool *via* phoneme awareness in first grade. Notably, our study is the first to examine such indirect effects. As for the size of this effect, the indirect effect implies that being one standard deviation above the mean in phoneme awareness in preschool is associated with being 0.08 standard deviations above the mean in verbal arithmetic at age six. Thus, the effect is rather limited in size. Language-related interventions have been suggested as a tool for ameliorating math problems. For instance, for language comprehension, Fuchs et al. (2020) recently demonstrated the effects of a vocabulary and language intervention on word problem-solving. If we had found a large indirect effect, one could perhaps suggest something similar for phonology—that number-related phoneme awareness interventions in preschool could ameliorate arithmetic difficulties. However, since the effect size was rather limited, the prospects for training effects are also rather limited.

Phoneme Awareness Is Related to Verbal Arithmetic but Not Arithmetic Fluency

Our study found that phoneme awareness was related to verbal arithmetic when children were asked to solve a single-digit addition or subtraction task without time limits, but not to single-digit arithmetic fluency tasks that were timed and answered on paper with no verbal response needed. No other studies have examined differential effects on arithmetic accuracy vs. fluency; the two previous longitudinal studies had both types of tasks mixed in a latent variable. Among the concurrent studies, one had fluency tasks and found a relationship (Singer et al., 2019), and the other had accuracy tasks and found a relationship (Vanbinst et al., 2020).

While efficient fact retrieval should be expected to contribute to success in both these task variations, there are some interesting differences in terms of the additional skill needed in each format. First, fluency tasks are timed and require faster fact retrieval and symbolic number-knowledge. In this process, Arabic-to-verbal translation—thought to evoke phonological processes—is likely an integral aspect. Second, the verbally presented math problems are connected to language in a broader sense than is the case with arithmetic fluency. In addition to calling for an accurate representation of number-word knowledge rather than Arabic digit knowledge, they might also evoke a greater degree of procedural strategies due to the working memory load since there is no permanent visual information. Third, the verbal arithmetic tasks were somewhat more complex, implying less fact retrieval and more procedural strategies for the more challenging items.

Thus, one reason that we found a relationship between verbal arithmetic and phoneme awareness could be that this task was presented orally to the children and that the children then used the phonological codes for a counting-based strategy to retrieve the answer. In contrast, the arithmetic fluency tasks were presented visually to the children. These children had just started to receive numeracy instruction and were unlikely to be able to use stored phonological information to retrieve the answers directly from long-term memory. Thus, they more likely used, for instance, strategies such as finger-counting or writing down dots to find the answers, and since the tasks were presented visually, the visual presentation format did perhaps not induce a lot of language processing. While confirmatory factor analyses indicated that these two constructs are best treated separately, the obvious similarities between the tasks call for further investigations of how distinguishable the two processes are over time and whether they evoke different arithmetic strategies.

As mentioned, the degree to which fact retrieval is established could determine the degree of reliance on phonological codes necessary for efficiency in the fluency tasks. Therefore, it cannot be ruled out that the outcome would have been different had the second assessment been carried out a year later.

CONCLUSION AND PROSPECTS FOR FUTURE STUDIES

This study revealed that phonological awareness does not explain development in arithmetic, but that there is an indirect effect between phoneme awareness in preschool and arithmetic in first grade *via* phoneme awareness in first grade. This effect is, however, weak and restricted to verbal arithmetic accuracy and not fluency.

To rule out third variables that might have caused the detection of a relationship between phoneme awareness and arithmetic in other studies, we controlled for general language and nonverbal abilities. Future studies should aim to also include a working memory component as working memory has been established as an important aspect of both phonological processing and early arithmetic (Peng et al., 2016).

We examined a sample of typically developing children and focused on correlations between continuous variables, and not on co-occurrences of categorical diagnoses. As pointed out by Krueger and Markon (2006), the term "comorbidity" could legitimately refer to either phenomenon. In light of this, an interesting question is whether these findings would have been replicated in a sample with children with reading disorders, arithmetic disorders, or both. As mentioned, Moll et al. (2015) found that only their comorbid group and the reading-disabled group had phonological awareness difficulties; those with only a math disorder did not. In general, both reading disorders and math disorders are defined using rather arbitrary cut-offs on continuously distributed variables. This perhaps explains these results, and predictors of individual differences may not be any different at the lower end of the distribution.

Furthermore, there is little evidence of a qualitative difference between those who have a learning disorder and those who are above the threshold (Snowling and Melby-Lervåg, 2016). A recent study adopted a transdiagnostic approach to examine whether brain differences relate to cognitive difficulties in childhood (Siugzdaite et al., 2020). The results indicated patterns suggesting that cognitive strengths and weaknesses cut across disorders and difficulties. According to Siugzdaite et al. (2020), "This stands in contrast to theories that specify a particular cognitive impairment as being *the* route to a particular diagnosed learning problem but is consistent with earlier ideas that developmental difficulties reflect complex patterns of associations rather than highly selective deficits" (p. 7). Thus, based on the continuous nature of reading and arithmetic, their correlation, and the limited support for qualitative differences between them, a similar pattern for children at the lower end of the distribution is perhaps likely. Future studies seeking to examine comorbidity might benefit from approaches where testable models can be used to identify the functional nature of disabilities and the need for intervention, as opposed to forming categories of atypical and typical development based on cut-off criteria (Branum-Martin et al., 2013).

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Materials**, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Norwegian centre for data research https://nsd.no/nsd/english/index.html. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUITONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2020.577304/full#supplementary-material.

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Executive Functions in Neurodevelopmental Disorders: Comorbidity Overlaps Between Attention Deficit and Hyperactivity Disorder and Specific Learning Disorders

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The present study examines the comorbidity between specific learning disorders (SLD) and attention deficit and hyperactivity disorder (ADHD) by comparing the neuropsychological profiles of children with and without this comorbidity. Ninety-seven schoolchildren from 8 to 14 years old were tested: a clinical sample of 49 children with ADHD (n = 18), SLD (n = 18) or SLD in comorbidity with ADHD (n = 13), and 48 typically-developing (TD) children matched for age and intelligence. Participants were administered tasks and questionnaires to confirm their initial diagnosis, and a battery of executive function (EF) tasks testing inhibition, shifting, and verbal and visuospatial updating. Using one-way ANOVAs, our results showed that all children in the clinical samples exhibited impairments on EF measures (inhibition and shifting tasks) when compared with TD children. A more specific pattern only emerged for the updating tasks. Only children with SLD had significant impairment in verbal updating, whereas children with ADHD, and those with SLD in comorbidity with ADHD, had the worst performance in visuospatial updating. The clinical and educational implications of these findings are discussed.

Keywords: ADHD, SLD, comorbidity, neurodevelopmental disorders, executive functions

INTRODUCTION

Neurodevelopmental disorders are mainly explained by a multiple cognitive deficit hypothesis (Willcutt et al., 2010), which emphasizes how clinical profiles are the outcome of complex interactions between several cognitive deficits and shared risk factors (that Pennington called the liabilities hypothesis; Pennington, 2006). These disorders are often characterized by the concomitant presence of more than one clinical condition, leading to the phenomenon of *comorbidity*. The extant research has clearly shown that various developmental problems tend to co-occur (Fawcett and Nicolson, 1995; Dewey and Wall, 1997; Piek et al., 1999), and that their symptoms may lie along a continuum of severity

(Jensen et al., 2001; Kadesjö and Gillberg, 2001; Crawford et al., 2006). What is not clear, however, is whether children with these concomitant problems have two or more separate disorders or several symptoms associated with a single underlying condition. Comorbidity often means that developmental trajectories intersect for different disorders. Understanding these trajectories and how they intersect can shed light on their etiology and mutual interdependence (Pennington et al., 2005).

In particular, the comorbidity between attention deficit and hyperactivity disorder (ADHD) and specific learning disorders (SLD) has been widely studied, mainly because of their high prevalence (Lonergan et al., 2019; Astle and Fletcher-Watson, 2020), but also because they share several problems and symptoms. For example, when children have learning difficulties together with behavioral and attentional deficits, they exhibit symptoms that could indicate a learning disability and/or ADHD, raising issues in their diagnosis and treatment. The main challenge in this research field is to understand why these two disorders occur together, how they interact, and whether this comorbidity coincides with particular neuropsychological profiles.

ADHD and SLD

ADHD is characterized by persistent inattention and/or hyperactivity traits interfering with normal development (DSM-5, American Psychiatric Association, 2013). The clinical picture of ADHD varies considerably, making it difficult to establish whether, in addition to inattention and hyperactivity, other traits should be considered as a part of the syndrome (Wåhlstedt et al., 2009). ADHD is one of the most often diagnosed disorders in childhood (Döpfner et al., 2015), although the prevalence estimates range from 0.2% to 34.5%, depending on the clinical and methodological approach used (Thomas et al., 2015; Reale and Bonati, 2018). Generally speaking, its prevalence is estimated worldwide at 5% in children under 18 years old (Polanczyk et al., 2007). Many children diagnosed with ADHD also have at least one other associated disorder (Tarver et al., 2014). Gillberg et al. (2004) report that the proportion ranges between 60% and 100%, depending on the studies considered (Ianes et al., 2009).

Although the neuropsychological profile of ADHD is heterogeneous, numerous studies indicate that it involves impairments in various executive function (EF) domains (Barkley et al., 1992; Pennington and Ozonoff, 1996; Sergeant et al., 2002). Reported findings are hardly conclusive, however, since the mean effect sizes range from small to moderate for EF measures, and not all children with ADHD show EF deficits (Willcutt et al., 2005), which can also be seen in typically-developing (TD) children (Vaidya et al., 2020), suggesting that none of these EF deficits is a necessary or sufficient explanation for the ADHD profile (Willcutt et al., 2003).

Another complex set of neurodevelopmental disorders are described by the umbrella term *specific learning disorders/disabilities* (SLD). According to the DSM-5, SLD is characterized by problems in academic skills, such as reading, writing, or arithmetic, which provide the foundations for other, more advanced academic learning (DSM-5, American Psychiatric Association, 2013). SLD mainly involve reading-related (dyslexia) and math-related (dyscalculia) disorders. The academic indicators of dyslexia include difficulties in word recognition and reading fluency (decoding skills). Children with dyscalculia may show problems in basic number processing, arithmetic facts, and calculation skills. SLD may also include deficits in reading comprehension, grammar, written expression, math reasoning, and problem-solving skills (Somale et al., 2016).

Like ADHD, so too for SLD, the prevalence estimates vary, mainly depending on the assessment procedures employed. The overall prevalence of SLD is thought to range from 5% to 15%, with 4% to 9% for dyslexia, and 3% to 7% for dyscalculia (Devine et al., 2013; Görker et al., 2017). On the one hand, considering domain-specific processes, dyslexia and dyscalculia seem to exhibit distinct cognitive profiles, with a phonological deficit in dyslexia (Coltheart, 2015), and a deficit in numerosity processing in dyscalculia (Landerl et al., 2009; Moll et al., 2015). On the other hand, when we consider domain-general cognitive processes, the two disorders share cognitive deficits—in working memory (WM), for instance (Schuchardt et al., 2008; Wilson et al., 2015; Moll et al., 2016; Peng and Fuchs, 2016; Toffalini et al., 2017; Mammarella et al., 2018b). These WM impairments might help to explain the co-occurrence of math and reading disorders in 30–70% of individuals diagnosed with SLD (Willcutt et al., 2013).

Moreover, also the comorbidity rate for SLD and ADHD ranges from 31% to 45% (DuPaul et al., 2013), but the incidence varies when specific academic domains are considered. The rate of comorbidity between reading-related deficits and ADHD ranges between 25% and 48% (Sadek, 2018), while it is estimated at between 11% and 30% for math-related deficits and ADHD (Capano et al., 2008). As comorbidity between ADHD and SLD is so common, the two different neuropsychological profiles sometimes seem to overlap (de Jong et al., 2009), but in other cases, a unique new problem seems to emerge (Bental and Tirosh, 2007).

ADHD, SLD, and Executive Functions

In ADHD research, studies on the cognitive factors involved in SLD have generated mixed evidence, suggesting that although some deficits might be specifically related to SLD or ADHD, several factors might be shared (Pennington et al., 1984; Willcutt et al., 2010). Previous studies often showed that ADHD and SLD involve similar deficits in inhibition or planning (Marzocchi et al., 2002). Inhibition and planning are considered two of the most important EFs, which generally include several psychological processes, such as organizing, WM, attention, problem solving, verbal reasoning, cognitive flexibility, and monitoring (Diamond, 2013; Goldstein et al., 2014).

In the present study, we refer to Miyake's model (Miyake et al., 2000), which identifies three basic EFs: (a) inhibition, or the ability to deliberately inhibit dominant, automatic, or imperious responses when required; (b) shifting (also called cognitive flexibility or switching), which is the ability to switch between tasks, operations or mental sets to adjust to changed priorities; and (c) updating, or the ability to update and monitor information in the WM, replacing old and no longer relevant information with more recent and relevant input, and translating instructions into action plans.

A huge amount of studies revealed the presence of inhibitory processes impairments in children with ADHD (Sonuga-Barke et al., 2002; Willcutt et al., 2005; Toll et al., 2011; Shimoni et al., 2012; Crosbie et al., 2013; Rajendran et al., 2013; Schreiber et al., 2014). Martinussen and Tannock (2006) also indicated WM as having an essential role in ADHD deficits. According to Alderson et al. (2010), major deficits can be seen in the central executive system, followed by visuospatial WM, and then verbal WM. Anomalies in visuospatial WM are thought to be among the most important deficits in the neuropsychological profile of children with ADHD (Prins et al., 2011). Finally, a few studies focused on shifting abilities in children with ADHD, with mixed results. Some studies found no shifting deficit (Biederman et al., 2007); some reported impaired shifting functions in terms of both accuracy and response times (O'Brien et al., 2010); and some only identified a lower accuracy (Holmes et al., 2010) or slower response times (Oades and Christiansen, 2008). These conflicting findings are probably due to the tasks chosen, which usually involve other EFs (Irwin et al., 2019).

On the other hand, the relationship between EFs and poor academic achievement is well documented (Mulder and Cragg, 2014). Children with SLD show deficits in central executive functioning (Landerl et al., 2004; Pickering, 2006), and particularly in WM (Mammarella et al., 2013; Moll et al., 2016; Peng and Fuchs, 2016). Verbal and visuospatial WM both seem to be related to the early acquisition of reading and math abilities (Passolunghi et al., 2008; Peng et al., 2018b). Later on, verbal WM is more implicated in reading performance and comprehension (Peng et al., 2018a), while visuospatial WM seems to be linked to more complex math achievement (Giofrè et al., 2014; Caviola et al., 2020). Moreover, mixed results have been reported for inhibition deficits in children with both reading and math disabilities, probably depending on the type of paradigm used (De Weerdt et al., 2013). Finally, meta-analyses by Yeniad et al. (2013) showed a substantial and significant association between shifting and math, as well as reading performance.

Despite an apparent overlap between the two disorders, few studies have directly compared the different neuropsychological profiles of children with ADHD, SLD, and comorbid ADHD + SLD. Willcutt et al. (2010) found individuals with reading disabilities more impaired than those with ADHD on measures of WM and rapid automated naming. Korkman and Pesonen (1994) reported that children with ADHD showed impairment in inhibition processes, while children with SLD tended to exhibit deficits in verbal aspects (e.g., verbal WM). Other researchers (Marzocchi et al., 2008; Faedda et al., 2019) found that their SLD group scored significantly higher than children with ADHD in all EFs.

As for the comorbidity issue, some researchers emphasized comorbidity as a qualitatively distinct condition (Pennington et al., 1993), showing that impairments relating to the two single disorders co-occurred in some cases (Willcutt et al., 2005; Kibby and Cohen, 2008; de Jong et al., 2009), while new deficits with a distinct cognitive deficit profile (called interactive effect) emerged in others (Bental and Tirosh, 2007). Moreover, further studies underscored the additive effect (i.e., the sum of the single cognitive deficit profiles) of two comorbid disorders (Seidman et al., 1995, 2001; Willcutt et al., 2013; Horowitz-Kraus, 2015). For instance, participants with comorbidity involving ADHD and SLD revealed worse EF deficits than those with ADHD alone (Seidman et al., 2001; Mattison and Mayes, 2012). To the best of our knowledge, however, only a few studies have compared two single deficits with the same two deficits in comorbidity, and such studies mainly considered comorbidity for ADHD and dyslexia. Some authors (Van De Voorde et al., 2010) found no differences in inhibition and WM tasks between cases with single deficits and those with a comorbid condition. Others (Bental and Tirosh, 2007) found more severe impairments in WM in comorbid than in single-deficit groups. As regards the WM task presentation format (verbal or visuospatial), Martinussen and Tannock (2006) found verbal WM performance to be worse in their groups with dyslexia (with or without ADHD), than in their group with ADHD alone. Kibby and Cohen (2008) found that the comorbid group performed worse in both verbal and visuospatial WM tasks than ADHD or dyslexia alone. In short, a definite conclusion has yet to be reached on this matter.

Taking into account the extant literature, to the best of our knowledge, previous studies rarely compared EF profile in children with a clinical diagnosis of ADHD and SLD in comorbidity, with children who had either ADHD or SLD (with both reading and math impairments), despite some studies highlighted the importance of EF as potential shared risk factor between SLD and ADHD (Pennington et al., 2005; Pennington, 2006). This reveals a potential methodological bias in our understanding of the role of specific deficits in EF domains in these disorders. Astle and Fletcher-Watson (2020) suggested that this was because studies often used strict exclusion criteria that excluded children with co-occurring difficulties (Willcutt et al., 2001; Toplak et al., 2005). Since comorbidity is common in neurodevelopmental disorders, rather than an exception (Gillberg, 2010), we need to include a comorbid group (ADHD + SLD) in our efforts to understand the neuropsychological differences between the two disorders.

The Present Study

As previous studies showed that children with ADHD and SLD may both have specific EF deficits (Willcutt et al., 2010; Schreiber et al., 2014; Peng and Fuchs, 2016; Faedda et al., 2019), we analyzed EF profile to reveal potential differences in the profiles associated with ADHD and SLD considered separately, but also in comorbidity (ADHD + SLD). As mentioned earlier, no systematic studies in EF have directly compared children with a clinical diagnosis of ADHD, SLD, and ADHD + SLD.

We, therefore, assessed different EF components in four groups of children: children with ADHD; children with SLD; children with ADHD + SLD; and a control group of TD children. In our study measures of inhibition, shifting, and updating (verbal and visuospatial) were administered. Samples of children with a clinical diagnosis were matched with TD children for chronological age and intelligence level. Our main aims were to investigate specific impairments in EF domains in the clinical groups and to test the potential additive effect of the comorbidity between ADHD + SLD.

Based on previous studies, we expected all children in the clinical groups (ADHD, SLD, and ADHD + SLD) to show EF impairments (Hari and Renvall, 2001; Sergeant et al., 2002; Martel et al., 2007; Bull et al., 2008; Barkley, 2011) compared to TD children. We expected children with ADHD to have significant impairments in all EF measures compared with TD children, except for updating tasks, where we expected the ADHD group's performance to differ depending on the presentation format (verbal vs. visuospatial): the ADHD group was expected to perform less well than the TD group in the visuospatial task, but not in verbal one (Prins et al., 2011). Based on previous studies, the SLD group was expected to perform less well than the TD group in terms of inhibition (De Weerdt et al., 2013), shifting (Yeniad et al., 2013), and both verbal and visuospatial updating (Peng et al., 2018a; Caviola et al., 2020).

We expected that children with ADHD and SLD had difficulties in both inhibition and shifting, with specific WM differences, according to the presentation format (Willcutt et al., 2001; de Jong et al., 2009). Children with ADHD were expected to perform worse than children with SLD in visuospatial updating (de Jong et al., 2009). In contrast, children with SLD were expected to show more impairments in verbal updating (Kibby and Cohen, 2008).

Considering the few, inconsistent studies in the literature, we might expect several cognitive profiles in children with comorbid ADHD and SLD compared with those with either ADHD or SLD. Children with comorbid ADHD + SLD could have a more significantly impaired neuropsychological profile than those with a single disorder (Seidman et al., 2001; Mattison and Mayes, 2012), in line with an additive effect of the two disorders together (Willcutt et al., 2013). We might also expect children with comorbid ADHD + SLD to have a worse EF performance than those with a single neurodevelopmental disorder (either ADHD or SLD; Fernández-Andrés et al., 2019), pointing to the co-occurrence of the symptoms of the two clinical conditions rather than a third, separate disorder with a qualitatively different cognitive subtype.

MATERIALS AND METHODS

Participants

The total sample consisted of 97 children, 66 males, and 31 females, aged between 8 and 14 years (M = 11, SD = 1.73). Children with a clinical diagnosis of ADHD, SLD, or ADHD + SLD were recruited at the child and adolescent neuropsychiatry services. TD children were enrolled at primary and secondary schools. The children in the clinical groups had already been independently diagnosed according to the DSM-5 (American Psychiatric Association, 2013), based on comprehensive assessments reported in their medical records. All children in the SLD group had been clinically diagnosed as cases of SLD, with major impairments in both math and reading abilities. **Table 1** summarizes the general characteristics of the four groups.

All participants were native Italian speakers, and none had any diagnosed neurological conditions. Exclusion criteria for all participants were: a history or concurrent diagnosis of other neurodevelopmental disorders; a history of neurological problems; current use of medication; medical illness requiring immediate treatment; psychological treatments in progress; or a certified intelligence quotient (IQ) below 80 (**Table 1**). The clinical groups consisted of: 18 children with ADHD (M = 123.11 months, SD = 20.48); 18 with SLD (M = 136.83 months, SD = 17.67); and 13 with ADHD + SLD (M = 134.15 months, SD = 24.7). They were matched with 48 TD children (M = 133.08 months, SD = 20.15) for chronological age ($F_{(3,93)}$ = 1.56, p = 0.20, $AdjustedR^2$ = 0.02), gender ($\chi^2_{(df=3)}$ = 5.16, p = 0.16, *Cramer-V* = 0.231), and FSIQ[1] ($F_{(3,93)}$ = 0.39, p = 0.76, $AdjustedR^2$ = 0.02).

For the study, all diagnoses were confirmed by assessing ADHD symptoms and learning difficulties as explained below in the "Group Selection Measures" section.

The Research Ethics Committee of the University of Padua approved the study.

Materials

Group Selection Measures

Conners Rating Scale-Revised

CPRS R:S (Conners, 1997). This parent-report was used in the clinical evaluation of ADHD to identify and measure the intensity of inattention, hyperactivity, and impulsivity traits. It covers the criteria listed in the Diagnostic and Statistical Manual of Mental Disorders [4th Edition text revision (DSM-IV-TR); American Psychiatric Association, 2000] and oppositional traits that are often seen in children with ADHD. It took under 10 min to complete. The parent's form, consisting of 27 items, was used in this study to confirm the presence of ADHD symptoms. A parent-rated how much the symptoms described had been typical of their child's behavior during the previous month using a 4-point Likert scale from 0 (not true at all) to 3 (very true). Cronbach's alpha ranged from 0.86 to 0.94 (Maruish, 2004).

Reading Tasks

DDE-2 (Sartori et al., 2007). Children's reading skills were measured with two different tasks that involved reading lists of words and pseudo-words. The first consisted of four lists of 28 words each, including high-frequency words (i.e., man, morning) and low-frequency words (i.e., prowess, globule) of two to four syllables. In the pseudo-words task, there were three lists of 16 made-up words each. Participants were asked to read each word out loud as quickly and accurately as possible. The experimenter recorded the time spent on each list, and scored the reading errors (letter substitutions,

[1]All children in the clinical sample had already been diagnosed after a comprehensive clinical assessment that included the whole WISC IV battery (Wechsler, 2003), but only their full-scale IQ was made available to us by the clinical centers involved.

TABLE 1 | Characteristics of the groups: means (M) and standard deviations (SD) for group selection measures.

		ADHD (n = 18) *M* (SD)	SLD (n = 18) *M* (SD)	ADHD + SLD (n = 13) *M* (SD)	TD (n = 48) *M* (SD)	ANOVAs $F_{(3,93)}$	*p*	Adjusted R^2	*Post-hoc*
Age (in months)		123.11 (20.48)	136.83 (17.67)	134.15 (24.70)	133.08 (20.15)	1.56	0.20	0.02	
IQ		108.50 (8.95)	109.39 (8.86)	107.92 (13.27)	110.56 (8.66)	0.39	0.76	0.02	
CPRS-R:S (*T*-score)	Oppositive	66.00 (14.75)	52.17 (11.09)	58.62 (12.72)	50.40 (10.26)	8.56	<0.001	0.19	ADHD, ADHD + SLD > TD; ADHD > SLD
	Inattention	75.06 (12.99)	57.39 (8.3)	64.46 (10.03)	48.27 (8.74)	35.97	<0.001	0.52	ADHD > ADHD + SLD > SLD > TD
	Hyperactivity	62.78 (13.86)	45.17 (3.37)	59.92 (13.91)	46.69 (7.08)	19.18	<0.001	0.36	ADHD, ADHD + SLD > SLD, TD
	ADHD index	76.11 (12.14)	56.94 (8.43)	66.23 (12.20)	48.48 (8.25)	39.69	<0.001	0.55	ADHD > ADHD + SLD > SLD > TD
DDE-2 (*z*-score)	Words, syll/s	−0.28 (0.95)	−1.79 (1.07)	−1.41 (1.35)	−0.10 (1.23)	11.69	<0.001	0.25	TD, ADHD > SLD, ADHD + SLD
	Words, errors	0.39 (1.32)	1.23 (1.23)	2.83 (3.76)	−0.11 (0.97)	11.12	<0.001	0.24	ADHD + SLD > SLD > TD; ADHD + SLD > ADHD
	Pseudo-words syll/s	−0.27 (0.69)	−1.39 (0.92)	−1.22 (1.17)	−0.18 (1.08)	8.72	<0.001	0.19	TD, ADHD > SLD, ADHD + SLD
	Pseudo-words, errors	−0.17 (0.72)	1.17 (1.54)	0.75 (1.53)	−0.44 (0.86)	11.47	<0.001	0.25	SLD, ADHD + SLD > TD, ADHD
DDE-2 (*z*-score)	Homophones not homographs	0.96 (1.20)	1.92 (1.27)	2.94 (1.56)	0.82 (0.95)	13.69	<0.001	0.28	ADHD + SLD > SLD > TD, ADHD
AC-MT (*z*-score)	Mental C–errors	0.14 (1.25)	0.41 (1.11)	0.73 (1.59)	−0.53 (0.81)	6.77	<0.001	0.15	ADHD, SLD, ADHD + SLD > TD
	Mental C–time	0.25 (0.95)	1.13 (1.07)	0.47 (1.25)	−0.15 (1.00)	6.86	<0.001	0.15	ADHD + SLD, SLD > TD
	Written C–errors	−0.24 (0.53)	1.06 (1.10)	1.37 (1.28)	−0.14 (0.88)	15.15	<0.001	0.31	SLD, ADHD + SLD > TD, ADHD
	Written C–time	0.18 (1.12)	1.61 (1.31)	1.45 (2.14)	0.46 (1.30)	4.95	0.003	0.11	TD, ADHD > SLD, ADHD + SLD
	Transcoding	−0.05 (1.24)	1.52 (2.28)	1.38 (2.08)	−0.24 (0.78)	9.26	<0.001	0.21	SLD, ADHD + SLD > TD, ADHD
	Fact retrieval	0.19 (1.7)	1.52 (1.03)	0.64 (1.50)	−0.71 (0.84)	17.28	<0.001	0.34	SLD > ADHD + SLD, ADHD > TD
AC-FL (raw score)		25.56 (13.3)	22.64 (9.02)	20.15 (11.39)	34.71 (12.48)	7.98	<0.001	0.18	TD > ADHD, SLD, ADHD + SLD

Note: ADHD, attention deficit and hyperactivity disorder; SLD, specific learning disabilities; ADHD + SLD, ADHD and SLD in comorbidity; TD, typical development; IQ, intelligence quotient; CPRS-R:S, Conners' Parent Rating Scale; DDE-2, battery for assessing developmental dyslexia and dysorthographia–2; Mental C, mental calculation; Written C, written calculation.

omissions, position changes, or additions), scoring no more than one error point for any given word. Self-corrections were not counted as errors. Reading performance was measured in terms of: (1) reading speed, i.e., the number of syllables read per second, expressed as the total reading time for each list; and (2) reading errors, i.e., the total number of words misread. Reliability varies from $r = 0.74$ to $r = 0.96$ (Di Brina et al., 2018).

Writing Task

DDE-2 (Sartori et al., 2007). Children's spelling competence was tested with a "homophones-not-homographs test." They were asked to write a list of sentences read aloud by the experimenter that contained some words with the same pronunciation but different spelling. The appropriate spelling depended on the word's meaning drawn from the overall context (i.e., "flower" and "flour"). Only errors relating to this type of word were considered, scoring no more than one error point for any given word. Reliability varies from $r = 0.74$ to $r = 0.96$ (Di Brina et al., 2018).

Arithmetic Task

AC-MT 6-11; 11-14 (Cornoldi and Cazzola, 2003; Cornoldi et al., 2012). Math competencies were assessed with the AC-MT battery, with the age-appropriate subtests. For the present study, children were administered the individual part of the AC-MT battery, consisting of mental and written calculation, transcoding, and fact retrieval tasks. Mental and written calculations involved additions, subtractions, multiplications, and divisions appropriate for the participant's age and school level. The transcoding and fact retrieval tasks assessed their basic numerical knowledge. For both mental and written calculations, problems were administered verbally only once, and primary-school children were allowed up to 30 s (mental calculation) or 60 s (written calculation) to answer them, while middle-school children were allowed 60 s for both types of calculation. The number of errors and the time taken to respond were recorded. In the transcoding task, the experimenter read one number at a time aloud, and only once. The fact retrieval task involved children directly retrieving simple solutions to arithmetical problems within 5 s. For both these tasks, only the number of errors was considered. Test-retest coefficients range from $r = 0.70$ to $r = 0.79$ for primary-school children, and from $r = 0.72$ to $r = 0.83$ for secondary-school children (Hill et al., 2016).

Math Fluency Task

AC-FL (Caviola et al., 2016). In this task, the children were asked to solve three sets of calculations (additions, subtractions, and multiplications). They had 2 min to complete each set of problems as quickly and accurately as possible. Each set contained 24 complex problems involving two- or three-digit numbers. The task implicitly assessed children's calculation strategies. The total number of correct solutions was recorded. Cronbach's α was 0.89, 0.90, and 0.82 for additions, subtractions, and multiplications, respectively (Caviola et al., 2016).

Executive Function Tasks

Inhibition and Shifting

NEPSY II (Korkman et al., 2007). This task assesses the ability to inhibit automatic responses in favor of novel answers, and the ability to switch automatic responses. The children were shown a series of black and white shapes or arrows pointing in different directions. The task involved two conditions: (a) an inhibition condition, in which participants had to name the opposite shapes (i.e., if they saw a square the children should say "circle" and vice versa) or arrow directions (i.e., if the arrow was pointing upwards they should say downwards, and vice versa) as rapidly and accurately as possible; and (b) a shifting condition, in which they had to name shapes (or directions of arrows) differently depending on their color (i.e., if the shape or arrow was black, they had to say what they were seeing; if it was white, they had to name the opposite shape or direction). Response times and errors were recorded. According to the manual, response times were first converted into standard scores, and errors were converted into percentiles. Then the two scores obtained were converted into a single standardized "combined score" that took both parameters into account. Test-retest reliability ranges between $r = 0.79$ to $r = 0.82$ for the inhibition condition, and between 0.75 and 0.93 for the shifting condition (Brooks et al., 2009).

Verbal and Visuospatial Updating

Two updating tasks were devised with different types of stimuli, verbal in one and visuospatial in the other. Both tests, administered using E-prime (Schneider and Zuccoloto, 2007) and a laptop computer with a 15-inch LCD screen, were characterized by four levels of difficulty depending on the increased number of target categories. Each level consisted of two items in which the memory span required stayed the same. The children were asked to recall the last verbal stimulus or its last positions belonging to *target categories* (among 2–5) shown on the computer screen. A detailed description of both verbal and visuospatial updating is reported in the **Supplementary Materials**.

Accuracy in both verbal and visuospatial tasks was considered, based on the proportion of items correctly remembered out of the total words or positions to remember. Cronbach's α based on the current sample was 0.71 for verbal updating and 0.76 for visuospatial updating.

Procedure

After obtaining the written consent of children's parents to their participation in the study, the children were tested during two different sessions in a quiet room outside their classrooms (for TD children) or at the Child Neuropsychiatry Department of the hospital to which they referred for their diagnosis (for children in the clinical groups). At the same time, parents completed a rating scale to assess their children's ADHD symptoms.

Participants completed both the group selection measures and the cognitive tasks, administered in a counterbalanced order, during two individual sessions lasting approximately 1 h each. Instructions were given for each task, and participants practiced with each task before starting the experiment. All experimental tasks were preceded by two practice trials. For the computer-based tasks, the children sat in front of the computer screen and the experimenter sat on the child's right to present the tasks.

RESULTS

Data Analysis

Data analyses were conducted using R (RC Team, 2015). One-way ANOVAs were run for the group selection measures and the inhibition task, to examine the differences between groups.

The analyses were run in two stages. In the first, Group was included as an independent variable. In the second, to answer the question of whether or not the comorbid group has an additive profile, the same analyses as in the first stage were run, with the presence of ADHD (no/yes) and SLD (no/yes) as factors[2].

The Akaike information criterion (*AIC*, Akaike, 1974) was also taken into consideration for each of these models. It provided the best description of the relationships between the variables (Bentler, 1990; Schermelleh-Engel et al., 2003). Graphical effects were obtained using the "effects" package (Fox, 2003). The **Supplementary Results** contain detailed analyses of the updating tasks by span level.

The updating tasks (both verbal and visuospatial) allowed us to collect accurate data for each item from each participant. Generalized mixed-effects models were used (Baayen et al., 2008; Jaeger, 2008) and a "binomial" function family, using the "lme4" package (Bates et al., 2015). Participants were included as random effects. This latter analysis is extensively described in the **Supplementary Results** section.

Group Selection

In the first phase, the Conners' Parent Rating Scale-Revised, Short-Form (CPRS-R:S, Conners, 1997) was used to confirm their children's inattention and/or hyperactivity symptoms, and T-scores of 65 or more were required for inclusion in the ADHD group. To be assigned to the SLD group, children were required to show an impaired performance (>−2 SD) in at least one domain of academic achievement: reading (DDE-2; Sartori et al., 2007); spelling (DDE-2; Sartori et al., 2007); or math (AC-MT 6-11, Cornoldi et al., 2012; AC-MT 11–14, Cornoldi and Cazzola, 2003; AC-FL, Caviola et al., 2016). Confirmation of ADHD in comorbidity with SLD (ADHD + SLD group) required an impaired performance (>−2 SD) in at least one domain of academic achievement and a T-score of 65 or higher in the CPRS-R:S indexes for Inattention or ADHD.

As shown in **Table 1**, the group profiles were confirmed. Children with ADHD (with or without SLD) had significantly higher scores in CPRS-R indexes than those with TD and SLD, showing at least two clinically significant indices. Children with SLD (with or without ADHD) were more impaired in reading and writing than TD and ADHD. As for math abilities, all clinical groups performed significantly worse than children with TD. The ADHD group had a significantly better performance than SLD and ADHD + SLD in both transcoding and written calculation.

Executive Functions

Inhibition

Table 2 sums up the descriptive statistics by group (ADHD, SLD, ADHD + SLD, and TD) in the inhibition and shifting conditions. In the first stage, a main effect of Group emerged in both inhibition ($F_{(3,93)} = 6.80$, $p < 0.001$, $AdjustedR^2 = 0.15$), and shifting ($F_{(3,93)} = 3.27$, $p = 0.025$, $AdjustedR^2 = 0.07$). For both conditions, children with a clinical diagnosis performed significantly worse than TD children (inhibition: ADHD: $p < 0.001$, *Cohen's d* = 0.96; SLD: $p = 0.01$, *Cohen's d* = 0.83; ADHD + SLD: $p = 0.002$, *Cohen's d* = 0.89; shifting: ADHD: $p = 0.01$, *Cohen's d* = 0.66; SLD: $p = 0.05$, *Cohen's d* = 0.57; ADHD + SLD: $p = 0.056$, *Cohen's d* = 0.73). No other differences emerged between the groups. In the second stage, the same analyses were run using the presence of ADHD and SLD as factors. In the inhibition task, a main effect of ADHD emerged ($F_{(1,95)} = 11.04$, $p = 0.001$, full model: $AIC = 451.96$, model without ADHD $AIC = 460.74$) and SLD ($F_{(1,95)} = 4.30$, $p = 0.04$, model without SLD $AIC = 454.30$). As shown in **Figure 1A**, the interaction was not significant ($F_{(1,93)} = 2.40$, $p = 0.12$, model with interaction $AIC = 451.49$).

In the shifting task, a main effect emerged for ADHD ($F_{(1,95)} = 4.60$, $p = 0.03$, full model: $AIC = 472.32$, model without ADHD $AIC = 474.96$), but not for SLD ($F_{(1,95)} = 1.94$, $p = 0.16$, model without SLD $AIC = 472.31$). As shown in **Figure 1B**, the interaction was not significant ($F_{(1,93)} = 2.12$, $p = 0.15$ model with interaction $AIC = 472.13$).

Verbal and Visuospatial Updating

Table 2 sums up the descriptive statistics by group (ADHD, SLD, ADHD + SLD, and TD) in the Verbal Updating and Visuospatial Updating. In the first stage, a main effect of Group emerged in Verbal updating ($F_{(3,93)} = 3.40$, $p = 0.02$, $AdjustedR^2 = 0.07$), as children with a clinical diagnosis of SLD performed significantly worse than children with TD or ADHD (respectively: $p = 0.003$, *Cohen's d* = 0.83; and $p = 0.01$, *Cohen's d* = 0.83). There was also a main effect of Group in Visuospatial updating ($F_{(3,93)} = 3.59$, $p = 0.02$, $AdjustedR^2 = 0.07$), as children with ADHD and ADHD + SLD performed significantly worse than the TD or SLD groups (for TD: $p = 0.01$, *Cohen's d* = 0.65 and $p = 0.04$, *Cohen's d* = 0.63, respectively; for SLD: $p = 0.02$, *Cohen's d* = 0.94 and $p = 0.05$, *Cohen's d* = 0.96). No other differences emerged between the groups.

In the second stage, using ADHD and SLD as factors, a main effect on the Verbal updating task emerged for SLD ($F_{(1,95)} = 7.90$, $p = 0.006$, full model: $AIC = 133.77$, model without SLD $AIC = 139.94$), but not for ADHD ($F_{(1,95)} = 1.04$, $p = 0.31$, model without ADHD $AIC = 140.69$). As shown in **Figure 2A**,

[2] Additional analyses were run, controlling for the role of attentional difficulties derived from the CPRS: R-S. The results revealed no group differences for inhibition, switching, or visuospatial updating tasks after controlling for attentional difficulties. A slight difference emerged in the verbal updating task, with the SLD group performing worse than the other clinical groups (with ADHD or ADHD + SLD).

TABLE 2 | Measures of executive functions: means (M) and standard deviations (SD) by group.

		ADHD (*n* = 18) *M* (SD)	SLD (*n* = 18) *M* (SD)	ADHD + SLD (*n* = 13) *M* (SD)	TD (*n* = 48) *M* (SD)
Inhibition	Combined	7.33 (3.03)	8.00 (2.28)	7.31 (3.33)	9.73 (1.85)
Shifting	Combined	7.39 (3.11)	7.83 (2.85)	7.69 (1.65)	9.31 (2.65)
Verbal updating	Accuracy	0.65 (0.11)	0.56 (0.13)	0.63 (0.12)	0.66 (0.11)
Visuospatial updating	Accuracy	0.57 (0.19)	0.71 (0.09)	0.58 (0.17)	0.69 (0.18)

Note: ADHD, attention deficit and hyperactivity disorder; SLD, specific learning disabilities; ADHD + SLD, ADHD and SLD in comorbidity; TD, typical development.

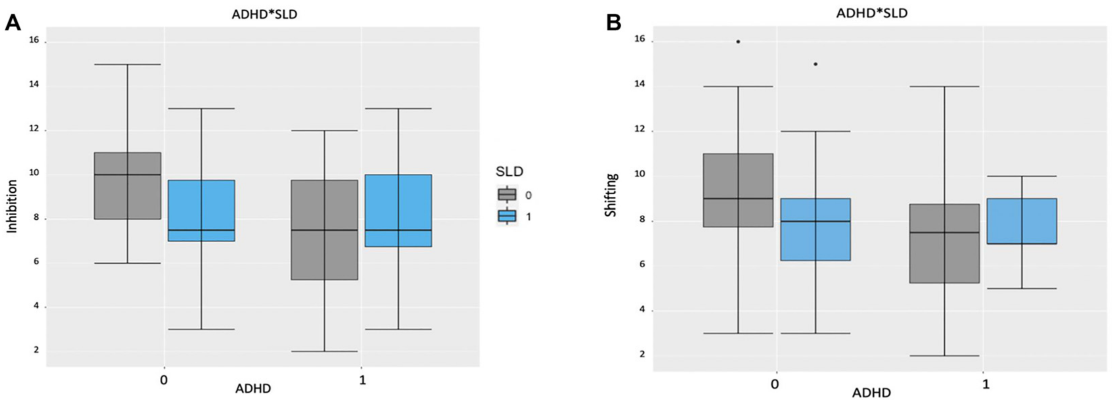

FIGURE 1 | **(A)** Boxplots representing the composite score by attention deficit and hyperactivity disorder (ADHD) and specific learning disorders (SLD) in the Inhibition task. The central mark is the median. The edges of the box are the 25th and 75th percentiles. The whiskers are the interquartile range. Note: 0 = absent; 1 = present. **(B)** Boxplots representing the composite score by ADHD and SLD in the Switching task. The central mark is the median. The edges of the box are the 25th and 75th percentiles. The whiskers are in the interquartile range and the symbols are outliers. Note: 0 = absent; 1 = present.

the interaction was not significant ($F_{(1,93)} = 1.85$, $p = 0.18$, model with interaction $AIC = 133.68$). In the Visuospatial updating task, there was a main effect of ADHD ($F_{(1,95)} = 10.87$, $p = 0.001$, full model: $AIC = 55.64$, model without ADHD $AIC = 64.26$), but not of SLD ($F_{(1,95)} = 0.15$, $p = 0.70$, model without SLD $AIC = 66.11$). Here again, the interaction was not significant ($F_{(1,93)} = 0.004$, $p = 0.95$, model with interaction $AIC = 62.27$), as shown in **Figure 2B**.

Finally, in the mixed-model analysis (extensively reported in the **Supplementary Results**) no main effect of the group emerged in the Verbal updating task. Instead, there was a significant main effect of Span ($\chi^2_{(3)} = 184.52$, $p < 0.001$, model without Span: $AIC = 1{,}993.9$). No significant interaction between Group and Span emerged. In the Visuospatial updating task, there was a main effect of Group ($\chi^2_{(3)} = 10.55$, $p = 0.01$, full model: $AIC = 2{,}013.5$, model without Group: $AIC = 2{,}018$) and Span ($\chi^2_{(3)} = 100.11$, $p < 0.001$, model without Span: $AIC = 2{,}107.6$). The interaction between Group and Span was also significant ($\chi^2_{(9)} = 33.63$, $p < 0.001$, model with Interaction: $AIC = 1{,}997.8$).

DISCUSSION

The main aim of our study was to examine the specific neuropsychological profiles of children with a clinical diagnosis of either ADHD or SLD—with major impairment in both reading and math, or both in comorbidity (ADHD + SLD), by comparison with TD children. We were particularly interested in understanding whether the EFs profiles of four groups differed and whether the comorbid group (ADHD + SLD) showed an additive (i.e., the sum of the deficits in the isolated groups) or rather an interactive effect (i.e., a distinct deficit profile). Children in the clinical groups had been previously diagnosed at centers specialized in neurodevelopmental disorders. In the first part of the assessment, all their diagnoses had been confirmed through specific questionnaires for parents and appropriate academic achievement tests.

To test potential differences in EFs profiles, children with a clinical diagnosis of ADHD, SLD, and comorbid ADHD + SLD were compared with TD children on measures of inhibition, shifting, and updating (verbal and visuospatial). In our analyses, we first compared our groups considering EF measures separately. Then, we ran the same analyses considering the presence of ADHD (no/yes) and/or SLD (no/yes) as factors to see whether the comorbid group reveals an additive profile. Finally, mixed-effects models were used to analyze in detail performances at different span levels for the updating tasks.

In the group comparisons, our findings showed that all clinical groups performed worse than the TD group, and no differences emerged between any of the clinical groups on measures of inhibition and shifting. A more specific pattern emerged when the groups were compared on updating measures. Children with SLD performed less well than the other groups in the verbal task, while the groups with ADHD or

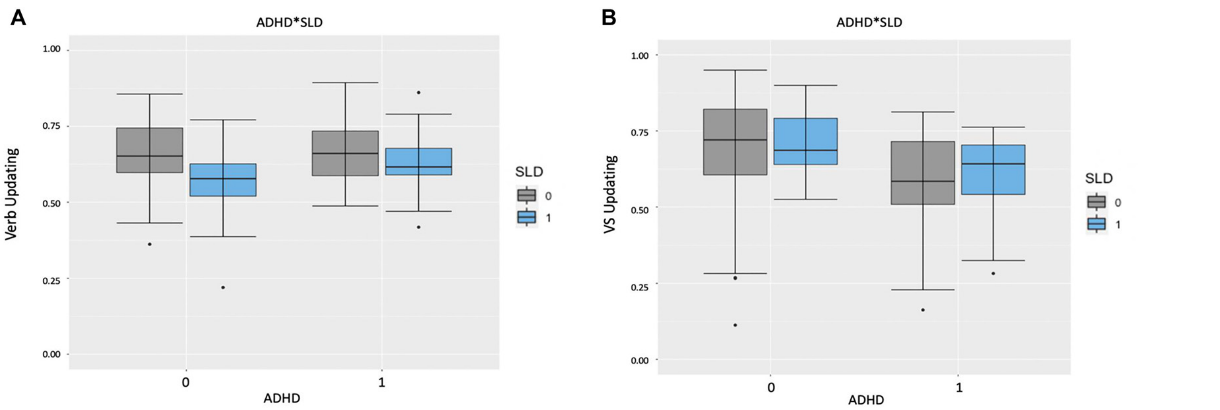

FIGURE 2 | (A) Boxplots representing the accuracy score by ADHD and SLD in the Verbal Updating Task. The central mark is the median. The edges of the box are the 25th and 75th percentiles. The whiskers are in the interquartile range and the symbols are outliers. Note: 0 = absent; 1 = present. **(B)** Boxplots representing the Accuracy Score by ADHD and SLD in the Visuospatial Updating Task. The central mark is the median. The edges of the box are the 25th and 75th percentiles. The whiskers are in the interquartile range and the symbols are outliers. Note: VS Updating = Visuospatial Updating; 0 = absent; 1 = present.

ADHD + SLD performed less well than either the SLD or the TD groups in the visuospatial task. This would contradict the idea of an additive effect of the two disorders combined (Seidman et al., 1995, 2001; Willcutt et al., 2013; Horowitz-Kraus, 2015). The pattern was slightly different when we considered the presence or absence of symptoms of SLD or ADHD: the effects of both SLD and ADHD could be seen in the inhibition task, but only those of ADHD in the shifting task. The effect of SLD was apparent for verbal updating and that of ADHD for visuospatial updating. Notably, from a qualitative perspective, children with ADHD + SLD were not more severely impaired than those with either ADHD or SLD alone. This would contradict the interactive hypothesis that children with several problems in comorbidity exhibit a qualitatively distinct condition (Pennington et al., 1993). Finally, by considering group performances at different span levels, a specific pattern emerged in the visuospatial updating task. Children with ADHD performed significantly worse on Span level 3 then showed a slight improvement on level 4, whereas the other groups had a more linear worsening performance with longer spans. Our results can be explained by altered motivational processes in ADHD (Sagvolden et al., 2005), or the children's inability to regulate their state of activation (Kuntsi and Klein, 2011).

The novelty of our investigation lies in that we compared these clinical groups with one another, as well as with a TD group, as previously reported. The results underlined that EFs are similarly compromised in all clinical groups, pointing to a comorbidity explanation based on a domain-general cognitive level. In particular, EF impairments, are not enough to differentiate between ADHD and SLD (Stern and Morris, 2013), shedding further light on the importance of comparisons across disorders and studies on comorbid conditions. Although ADHD is often associated with EF deficits (Barkley et al., 1992; Pennington and Ozonoff, 1996; Sergeant et al., 2003), this association did not seem sufficient to consider EF as core-deficits of the disorder (Willcutt et al., 2003), and impairments in inhibition (Booth et al., 2010; Mammarella et al., 2018a) and shifting (Van der Sluis et al., 2007; Andersson, 2008) have also been observed in children with SLD.

It is worth noting that SLD involves specific difficulties relating to achievement, particularly in reading (dyslexia) and math (dyscalculia). Dyslexia and dyscalculia seem to involve distinct cognitive profiles in terms of domain-specific processes (mainly phonological deficits for the former, and number processing deficits for the latter), but similar domain-general cognitive processes (particularly concerning WM). Domain-general cognitive processes like WM may therefore substantially overlap between dyslexia and dyscalculia (Peters and Ansari, 2019). In the present study, our SLD group consisted of children with major impairments in both math and reading abilities, unfortunately making it impossible to separately analyze the influence of reading or math. Our groups of children with either SLD or ADHD showed more specific patterns of results when looking at domain-general processes, linked to the presentation format of the WM tasks. In agreement with previous studies (Willcutt et al., 2001; de Jong et al., 2009), when verbal and visuospatial WM updating were compared, specific differences emerged between ADHD and SLD. Children with ADHD (with or without SLD) performed significantly worse than children with SLD in visuospatial updating (Kibby and Cohen, 2008; de Jong et al., 2009). In contrast, children with SLD were significantly more impaired than children with ADHD in verbal updating (Korkman and Pesonen, 1994; Willcutt et al., 2001; Kibby and Cohen, 2008). Our results thus suggest that the presentation format of an updating task (i.e., verbal or visuospatial), rather than the cognitive task *per se*, may be useful for distinguishing between ADHD and SLD.

As concerns comorbid ADHD + SLD, our data would support the claim that ADHD + SLD is not a third, separate disorder with a specific pattern of EF impairments since we could find no specific profile distinctive of children with both conditions. Thus, we could not rule out the possibility of ADHD and SLD shared the same biological and environmental risk factors, increasing the likelihood of their co-occurrence and supporting the correlated liabilities hypothesis (Pennington et al., 2005; Pennington, 2006).

Although our study produced some interesting findings, our results should be considered explorative because it has some limitations. First of all, the sample size was small and the children in the SLD group had significant impairments in both reading and math, which prevented us from analyzing their influence separately. Second, the SLD group also had some attention-related problems, though they were not clinically relevant, and some differences in achievement emerged between groups of ADHD and typical development and SLD and ADHD + SLD. It is worth emphasizing that the children in our clinical groups had previously received a clinical diagnosis, and the heterogeneity of our sample's difficulties was typical of neurodevelopmental disorders and the impairments were not fulfilling criteria for different diagnoses. Another limitation of our study lies in that we only administered a limited set of EF tasks, without differentiating between verbal and visuospatial tasks for inhibition and shifting. We chose these particular tasks because the procedure was already long and hard, particularly for children with ADHD, and because they reflected our theoretical background (Miyake et al., 2000). Finally, our group with comorbid ADHD and SLD was smaller than the other two. This was because, we paid more attention to confirming the comorbid condition (ADHD + SLD, without any other comorbidities). Further research might replicate our methodology but increasing the numerosity of the clinical samples and including other cognitive tests.

Even with the above-mentioned limitations, our study has some important clinical implications. Understanding the specific type of interaction, the similarities, and differences between ADHD and SLD, and the combination of the two is fundamental to our ability to assess and treat all three conditions. The DSM-5 (American Psychiatric Association, 2013) made an important effort to operationalize the concept of a dimensional approach to neurodevelopmental disorders, but some issues persist (Pham and Riviere, 2015). We agree with previous studies that a neuropsychological assessment is not enough to convey a diagnosis (for further details, see Pham and Riviere, 2015). As, we have reported, children with ADHD can have learning difficulties, and children with SLD can have attention deficits, and our group of children with both disorders did not have a specific domain-general cognitive profile. Neuropsychological impairments and learning difficulties are not as uniquely associated with these disorders as was earlier supposed (Nigg and Huang-Pollock, 2003; Happé et al., 2006). Clinicians should therefore bear in mind the kinds of challenges they may encounter in the assessment process and the differential diagnosis. It is good practice not to focus on seeking specific neuropsychological deficits associated with a potential disorder, but rather to assess a child's abilities as a whole, to identify particular strengths and weaknesses.

To conclude, it is important to emphasize that no important differences emerged from our study between the clinical conditions considered as regards the children's EF impairments. All three clinical groups were significantly impaired by comparison with TD children. However, a more specific pattern emerged for the WM updating, in which verbal and visuospatial presentation format seems to better differentiate the SLD and ADHD profiles. Nevertheless, further studies are needed to confirm our findings.

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 Psychology Research Ethics Committee of the University of Padua. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

SC and IM developed the study concept. Testing was performed by GC. RC and GC performed the data analysis. GC and SC drafted the manuscript and IM provided revisions. All authors contributed to the article and approved the submitted version.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2021.594234/full#supplementary-material.

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How Cognitive Strengths Compensate Weaknesses Related to Specific Learning Difficulties in Fourth-Grade Children

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The goal of the present study was to investigate whether children's cognitive strengths can compensate the accompanied weaknesses related to their specific learning difficulties. A Bayesian multigroup mediation SEM analysis in 281 fourth-grade children identified a cognitive compensatory mechanism in children with mathematical learning difficulties (n = 36): Children with weak number sense, but strong rapid naming performed slightly better on mathematics compared to peers with weak rapid naming. In contrast, a compensatory mechanism was not identified for children with a comorbid mathematical and reading difficulty (n = 16). One explanation for the latter finding could relate to the lack of ability to compensate, because of the difficulties these children experience in both academic domains. These findings lead to a new direction in research on learning difficulties in mathematics and/or reading by suggesting that children with a learning disability each have a unique profile of interrelated cognitive strengths and weaknesses. Children might compensate with these strengths for their weaknesses, which could lead to (small) learning gains in the affected domain.

Keywords: children, cognitive skills, comorbidity, compensation, learning difficulties, mathematics, reading, strengths and weaknesses

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INTRODUCTION

Primary school children's academic performance is characterized by great individual variation, and even within the group of children with a specific learning difficulty there is much heterogeneity (Moll et al., 2018). Children who experience learning difficulties, for example in mathematics or reading, each may have their own unique profile of cognitive weaknesses and strengths. Although previous research has to some extent recognized cognitive strengths in relation to learning difficulties (e.g., Toffalini et al., 2017), the main body of empirical research on learning difficulties solely investigated the weaknesses associated with them (for meta-analyses see Schwenk et al., 2017; Araújo and Faísca, 2019). Nonetheless, children may use cognitive strengths to compensate for their cognitive weaknesses, to prevent the development of more severe learning difficulties. The present study aimed to investigate children's cognitive strengths as potential compensatory mechanisms for cognitive weaknesses related to their performance on mathematics and reading.

Research so far has made a significant contribution in identifying cognitive skills related to mathematics. Mathematics is defined as problem solving in the domains of proportions and geometry, including—but not limited to—calculations with fractions and measurements

(Mullis et al., 2016). Variation in mathematics performance usually results from individual differences in number sense (Geary, 2011), working memory (Passolunghi and Siegel, 2004), and non-verbal reasoning (Kleemans et al., 2018). Number sense is defined as the capacity to recognize and understand symbolic numbers and non-symbolic numerosities (Dehaene et al., 1993, 2003), and has been found to play a key role in mathematics (Sasanguie et al., 2013). Working memory involves the temporal storage, processing and recollection (i.e., the executive function of updating) of verbal and visuospatial information (Passolunghi and Siegel, 2004; Alloway et al., 2009), and has been identified as a second cognitive factor in mathematics. However, reported effect sizes range from small (cf., geometry; Giofrè et al., 2014) to medium (cf., fractions; Hecht et al., 2003). Finally, non-verbal reasoning—or general intellectual ability—entails understanding of logical structure (Stock et al., 2009), and is strongly related to mathematics (with large effect sizes; Seethaler et al., 2011). Additionally, fact retrieval (i.e., automatizing and memorizing whole-number operations) is a prerequisite for advanced mathematics performance and acts as a mediator between effects of the cognitive skills on mathematics performance (Cirino et al., 2016).

Weaknesses in a cognitive skill related to mathematics often result in low mathematics performance. This idea corresponds with multiple-deficit models, wherein it is assumed that a specific learning difficulty develops as a result of a summation of its accompanying cognitive weaknesses (see e.g., Pennington, 2006; McGrath et al., 2011; Willcutt et al., 2013). Children with low math abilities thus would display weaknesses in number sense, working memory and/or non-verbal reasoning. However, some children experience (additional) weaknesses in phonological awareness and/or rapid naming, which originally are reading-related cognitive skills that also have become evident as predictors of mathematical difficulties (Vukovic and Lesaux, 2013). Other linguistic skills have been related to mathematics as well, such as grammatical ability (Kleemans et al., 2018), vocabulary (Purpura et al., 2017), decoding (De Smedt et al., 2010), and reading comprehension (Björn et al., 2016). These skills may either be directly associated with mathematics, or through their interaction with phonological awareness and rapid naming. When taking such cognitive variables into perspective, there now seem to be multiple alternative pathways to being (un)able to perform mathematics, which makes it difficult to predict mathematics performance from a unique set of (cognitive) skills (LeFevre et al., 2010). The averaged findings that result from such studies thus may not apply to all children within a group, as they all may have their own unique profile of cognitive weaknesses and strengths.

In a similar way, variation in reading performance (i.e., accurately decoding words and pseudo-words at an appropriate rate; Hasbrouck and Glaser, 2012) has consistently been linked to individual differences in phonological processing (i.e., phonological awareness and rapid naming; Landerl et al., 2009; Willcutt et al., 2013). Phonological awareness can be defined as the conscious process of recognizing and manipulating (i.e., deletion and segmentation of) sound segments, and is positively related to reading (Vellutino et al., 2004). Rapid naming refers to the capacity to quickly access and retrieve information from memory, and can be subdivided into alphanumeric (i.e., naming digits and letters) and non-alphanumeric (i.e., naming colors and pictures) skills (Willburger et al., 2008). Reaction times for (non-) alphanumeric rapid naming are negatively related to reading (Vellutino et al., 2004).

Children with comparable cognitive weaknesses can even vary in the severity of their learning difficulties (Huijsmans et al., under review). This clearly indicates that some children also have strengths in at least one other related cognitive skill, i.e., a *compensatory* mechanism to reduce the severity of their cognitive weaknesses. Compensation in the current study is defined as the ability to use an alternative (cognitive) skill to counteract a deficit in a closely related skill in order to maximize learning outcomes. This does not necessarily mean that a child with such compensatory strengths can fully overcome their learning problems, but we believe that the adverse effects of a cognitive deficit can be reduced by a cognitive strength.

Few empirical studies do explicitly report on cognitive strengths in children with learning difficulties, and those who did were limited to the assessment of reading disabilities only (e.g., Heim et al., 2008; Haft et al., 2016), or were restricted by only studying the intellectual profiles of various learning problems (Toffalini et al., 2017). Strengths in these studies, as well as in others (Ansari et al., 2003; Koriakin et al., 2017; Liu et al., 2017), have generally been defined as 'relative strengths,' meaning that these children display above average performance on a cognitive skill compared to other children with similar characteristics (e.g., a learning difficulty). Following this line of defining cognitive strengths, the same definition was used in the present study. Based on compelling evidence that phonological processing skills are related to mathematics (Berch and Mazzocco, 2007; Vukovic and Lesaux, 2013), it could be argued that strengths in phonological processing skills (i.e., phonological awareness and rapid naming) could act as a compensatory mechanism in mathematics performance. These cognitive skills might work on mathematics through related underlying cognitive deficits on for instance number sense and working memory. Children with such cognitive deficits may rely more on other cognitions when solving math problems. Their lack of understanding of number and numerosity (i.e., number sense) may to some extent be compensated by the ability to quickly retrieve procedural facts from long-term memory (i.e., rapid naming) to facilitate problem solving. Likewise, working memory and phonological awareness both enable children to manipulate (numerical) information (e.g., backwards recall or segmentation and blending, respectively), which can aid their math performance as well. The fact that children with specific mathematical difficulties mostly show weaknesses in number sense, working memory, and non-verbal reasoning (Slot et al., 2016), might indicate that a strength in phonological processing is a likely candidate for compensation of number sense or working memory weaknesses to prevent more severe math problems. In contrast, a strength in working memory could be a candidate for compensation of phonological deficits to reduce the severity of reading difficulties, because working memory has less consistently been related to reading than phonological awareness and rapid naming (Baddeley, 2003).

Given the fact that mathematics and reading show some overlap in terms of cognitive predictors (i.e., phonological awareness, rapid naming, and working memory; Wilson et al., 2015), it could be expected that a deficit in those cognitive skills might result in a comorbid mathematics and reading learning difficulty. Children with such a comorbid learning difficulty, on average, display the poorest academic outcomes in the domains of mathematics and reading compared to other children, despite intelligence being within the normal range (Landerl et al., 2009). For them, relying on compensatory cognitive skills when performing mathematics or reading tasks might not be possible, because cognitive strengths (relative to their peers) associated with mathematics and reading are less available to children with a comorbid learning difficulty (Jordan, 2007).

The Present Study

Although cognitive strengths of children with specific learning difficulties have occasionally been recognized in recent studies, research often neglects to discuss the important implications of these strengths. This seems to be a misrepresentation of reality, because children's cognitive strengths may in fact act as compensatory mechanisms against developing a comorbid learning deficit. Therefore, rather than just emphasizing children's cognitive weaknesses as a marker of the development of learning deficits, the present study aimed to investigate children's cognitive strengths as potential compensatory mechanisms for their cognitive weaknesses related to mathematics and/or reading proficiency.

It was hypothesized that children with either low mathematics performance, low reading performance, or a combination of both, show different compensatory mechanisms with respect to their learning difficulty. To examine this hypothesis, we assessed four different combinations of academic performance on mathematics and reading: Typical developing (TD) children, children with a specific learning difficulty in mathematics (MLD) or in reading (RLD) (i.e., below the 25th percentile on mathematics or reading respectively), and children with comorbid mathematical and reading learning difficulties (MRLD; i.e., below the 25th percentile on both mathematics and reading). Notice that we used a broad definition of learning difficulties, instead of just the inclusion of children with a diagnosis of dyscalculia or dyslexia. The reason for this approach is that it allowed us to investigate learning difficulties and associated cognitive strengths at the lower end of the continuum (Murphy et al., 2007). This interval includes the children wherein learning difficulties may be partly compensated, which may be a reason why they are not diagnosed with dyscalculia or dyslexia.

In each of these groups, we assessed which cognitive skills had the strongest effects on mathematics and reading. For TD-children it was expected that number sense, working memory, and non-verbal reasoning have the strongest effect on mathematics. Fact retrieval might mediate the effect between these cognitive skills and mathematics. We expected phonological awareness and rapid naming to have the strongest effects on reading. For children with a specific learning difficulty on mathematics and/or reading, it was expected that different cognitive skills would show a stronger effect on the academic performance of interest (e.g., mathematics in the MLD group) compared to TD-children, because there is little variability on the regular predictors. Therefore, we investigated whether other medium to strong cognitive effects could be identified as a cognitive strength to compensate for cognitive weaknesses in the learning difficulty groups. Phonological processing skills might act as a compensatory mechanism for mathematics in children with low math abilities, because some children might show relatively strong performance on those cognitive skills in spite of their learning difficulty. This will result in better performance on mathematics compared to their peers without such a compensatory cognitive strength. Compensatory effects of number sense, working memory, and non-verbal reasoning are unlikely, as children with math problems often experience difficulties with these cognitive skills, and thus will show little variation (i.e., smaller effects) for those variables. In contrast, working memory might have the strongest effect on reading as a compensatory mechanism for children with low reading abilities, because for some of them their working memory performance might be relatively strong compared to peers. Children with reading problems are likely to show the least variance (and thus smaller effects) on phonological awareness and rapid naming. As number sense and non-verbal reasoning play a minor role in reading, strength in working memory is the most likely candidate for compensation within reading. Finally, compensatory effects might be non-existent for children with comorbid learning difficulties, because they have low performance on all cognitive skills (i.e., little variance and thus smaller effects), and therefore cannot rely on cognitive strengths.

MATERIALS AND METHODS

Participants and Procedure

The present study reported on data collected during the first measurement of an ongoing longitudinal study on the predictors of numerical development. The final sample included 281 fourth-grade children (M_{age} = 9.3 years, SD = 0.5) from eleven Dutch primary schools. The study was approved by the institutional ethics review board, and parental active informed consent was obtained prior to data collection. Exclusion criteria included any physical, behavioral or learning disability other than MLD or RLD, as reported by the teacher. All participants spoke Dutch fluently. Missing data for 61 children were handled using multiple imputation (Rubin, 1987). Missing values were estimated ten times, and pooled into one aggregated score. Independent and dependent variables were imputed separately.

Four groups were created for further analyses, using the Dutch national standardized tests for mathematics (CITO Rekenen-Wiskunde, CITO-RW, *Mathematics test*; Janssen et al., 2010) and reading (Cito Drie Minuten Test, DMT, *Three Minutes Test*; Verhoeven, 1992). Children with a mathematical learning difficulty (MLD; n = 36) scored at or below the 25th percentile on the CITO-RW and above the 25th percentile on the CITO-DMT. Children with a reading learning difficulty (RLD; n = 42) scored at or below the 25th percentile on the CITO-DMT and above the 25th percentile on the CITO-RW. Children with a mathematics and reading learning difficulty (MRLD; $n = 16$) scored at or below the 25th percentile on both the CITO-RW and the CITO-DMT. Finally, typically developing children (TD; $n = 168$) scored above the 25th percentile on both tests. Parents of nineteen children (7%) did not permit the school to share their children's CITO-scores. Therefore, these children were excluded from further analysis.

Background characteristics for the children in the TD, MLD, RLD, and MRLD groups are shown in **Table 1**. There were no age differences between groups (BFs < 2.31; anecdotal support; Jeffreys, 1961). Gender was equally distributed across groups, with the exception that there were more girls than boys within the group of MLD-children (i.e., 72.2% girls). Most children in each group were Dutch, and the parents of one quarter to one third of the children per group were relatively highly educated (i.e., applied university or university). Ethnic background and SES did not differ across groups (χ^2s < 12.93, BFs < 1).

The test battery lasted 3.5 h per child (spread across several school days), consisting of classroom measures (mathematics, fact retrieval, phonological awareness, and non-verbal reasoning), computerized measures (number sense and working memory), and individual measures (decoding and rapid naming). All measures were administered by trained students who followed a standardized protocol. Classroom measures were administered in three test blocks of 45 min each (i.e., 2 h and 15 min in total), counterbalanced across schools. Block A and B consisted of Parts 1 and 2 of the mathematics task, respectively. In Block C, the tasks for fact retrieval, phonological awareness, and non-verbal reasoning were administered consecutively. Computerized measures were self-reliant: Tasks were administered in approximately 45 min (15 min for number sense, and 30 min for working memory) in a group-wise setting of approximately six children per subgroup. Individual measures were administered within 20 min per child in a quiet room, and included tests for decoding and rapid naming.

Measures

Academic Variables

Mathematics (for classification)

The CITO-RW (Janssen et al., 2010) was used for classification of children as MLD or MRLD. This task is a Dutch national standardized test for mathematics with different, grade-appropriate versions (50–54 items per version) that are administered twice a year by the classroom teacher. The scores obtained in the middle of fourth-grade were used in the present study. Internal consistency was good ($a > 0.91$; Evers et al., 2009–2012).

TABLE 1 | Background characteristics for the TD, MLD, RLD, and MRLD groups.

	TD (n = 168)	MLD (n = 36)	RLD (n = 42)	MRLD (n = 16)
Age (in months)	115.82 (5.25)	118.92 (6.52)	118.33 (5.63)	119.06 (4.94)
Gender (% girls)	45.2%	72.2%	50.0%	56.3%
Ethnicity (% Dutch)	93.6%	86.2%	91.9%	78.6%
SES (% higher-education)	33.3%	19.4%	35.8%	25.0%

A Bayesian one-way ANOVA for age and Bayesian Chi-square tests for ethnicity and SES revealed that there were no initial group differences (BFs < 3). However, there were more girls in the MLD-group, compared to the TD-, RLD-, and MRLD-groups.

Mathematics (for analyses)

An adapted version of the Schoolvaardigheidstoets Rekenen-Wiskunde (SVT-RW, *School Achievement Test for Mathematics*; De Vos and Milikowski, 2012) was used to assess advanced mathematics. Items from the original SVT-RW for grades 4, 5, and 6 were selected (i.e., to prevent ceiling effects) and were combined into one task (e.g., 3 km + 300 m = ___ m; calculate the surface of 'this' object). Additional items from an older, no longer used version of the Dutch national test for mathematics (CITO-RW; Janssen et al., 2005), and the *Fraction Competency Test* (FCT; Brown and Quinn, 2007) were added to obtain a comprehensive assessment of children's mathematical skills. An exemplary item for the CITO-RW was 'mom buys four tickets of 15 euros each, and pays with 100 euros. How much change does she receive?', and for the FCT 3 – 1/5 = __. The final mathematics paper-and-pencil task was administered in the classroom. The task consisted of two parts with 61 open-ended computational problems in total, and a time limit of 45 min per part. The computational problems contained little text to prevent that children should rely on their reading skills. We ran several analyses to assess the mathematics task at the item level. Combined findings regarding (1) internal validity using item response theory (two-parameter Birnbaum model) in the open-source R software (version 3.4.4), and (2) fit to the latent factor by means of factor analysis in SPSS (version 23.0), resulted in the removal of five items that either were too difficult, discriminated poorly, and/or did not fit to the latent factor. Each correct answer yielded one point, summing to a total maximum score of (61 – 5 =) 56 points. Internal consistency in the present study was good ($\alpha = 0.89$).

Reading (for classification)

The CITO-DMT (Verhoeven, 1992) was used for classification of children as RLD or MRLD. This task is a Dutch national standardized test for word reading with different, grade-appropriate versions (three reading cards per version) that are administered twice a year by the teacher. Each version consists of three reading cards with 150 words per card. Words increase in complexity across cards, shifting from monosyllabic words on the first card to polysyllabic words on the third card. The scores obtained in middle fourth-grade were used in the present study. Internal consistency was good ($a = 0.80$; Evers et al., 2009–2012).

Reading (for analyses)

Children's reading was assessed individually using two measures. Word decoding was measured with the Eén Minuut Test *(EMT, One Minute Test*; Brus and Voeten, 1999), and pseudoword decoding was measured with the Klepel (Van den Bos et al., 1994). In both tasks, children had to accurately read as many unrelated (pseudo-)words as they could within 1 min. To increase difficulty level, word length increased from one to four syllables. The number of correctly read (pseudo-)words for each task was the raw score, with a maximum of 116 words per task. Scores from both tasks were averaged into one score for decoding. Internal consistency was good, with α = 0.90 for the EMT and α = 0.92 for the Klepel (Evers et al., 2009–2012).

Fact retrieval

The Tempo Test Automatiseren (TTA, *Speeded Arithmetic Test*; De Vos, 2010) was used in the participants' classroom to assess children's fact retrieval. The four subtests addition, subtraction, multiplication and division each included 50 paper-and pencil problems of increasing complexity. Children were instructed to solve as many problems per subtest as possible within 2 min. Each correct answer yielded one point, summing to a maximum score of 200 points. Internal consistency for all subtests was at least sufficient (α's > 0.78; Evers et al., 2009–2012).

Cognitive Variables

Number sense

Number sense was assessed with the computerized *Dutch Assessment battery for Number Sense* (DANS; Friso-Van den Bos et al., 2015). There were two subtests: Symbolic comparison and non-symbolic comparison. Stimuli were presented at random using E-prime software (Version 2.0). The symbolic and non-symbolic comparison tasks required participants to rapidly indicate which of two numbers (symbolic) or sets of dots (non-symbolic) was the largest using key-press. Average size and range for symbolic number were M = 49.17, Range = 10; 96, and for non-symbolic numerosity M = 52.02, Range = 14; 97. The mean and range of the ratios were M = 0.75, Range = 0.63; 0.88, and M = 0.78, Range = 0.63; 1.00 for symbolic number and non-symbolic numerosity, respectively. Dot size, area, and density were manipulated in the non-symbolic condition using the approach of Dehaene et al. (2005), to ensure that the responses are being associated with quantity instead of dot patterns. After a training block, testing blocks with 33 and 43 items, respectively, of varying difficulty were administered in random order. Average reaction time in ms for the correct trials was used for further analysis, because accuracy scores produced ceiling effects in the symbolic condition (M = 32.43, SD = 2.52; non-symbolic condition, M = 27.92, SD = 3.50). Internal consistency of the comparison tasks is good (α's > 0.84; Kline, 1999).

Working memory

The online computerized tasks *Lion game* and *Monkey game* were used to assess visuospatial and verbal working memory, respectively. In the Lion game, children had to remember the locations of pictures of colored lions within a 4 × 4 matrix (Van de Weijer-Bergsma et al., 2015a). Children were presented with 20 items (five levels of four items) and for each item had to indicate the last location(s) of one or more lion(s) of a specific color (e.g., red, blue, yellow, green, or purple). In the monkey game, children had to remember and recall spoken familiar words in reversed order (Van de Weijer-Bergsma et al., 2016). Children were presented with 20 items (five levels of four items), and by mouse click on written words in a 3 × 3 matrix were able to indicate the correct backwards order of the spoken words. For both tasks, the average proportion of correctly recalled items was used as raw score. Internal consistency for both tasks was good (α's > 0.87; Van de Weijer-Bergsma et al., 2015b, 2016).

Phonological awareness

A phonological awareness task (Knoop-van Campen et al., 2018) was administered in the classroom. In the 18-item deletion subtask, children had 4 s to delete a letter (e.g., 's') from a spoken word (e.g., 'small'), and cross the corresponding picture (e.g., 'mall', with distracters 'ball' and 'wall'). In the 12-item spoonerism subtask, five pictures were shown and children had 5 s to switch the first letters of two verbally presented words (e.g., 'mouse' and 'heat' become 'house' and 'meat') by crossing the corresponding pictures. On each task, one point was given per correct answer [cf. a maximum score of (2 * 12 =) 24 points]. Internal consistency was sufficient (α = 0.70, Knoop-van Campen et al., 2018).

Rapid naming

The Continu Benoemen subtest of the Continu Benoemen en Woorden Lezen test *(CB&WL, Continuous Naming and Word Reading*; Van den Bos and Lutje Spelberg, 2007) was administered individually to measure rapid naming. It exists of four subtests with five high frequent items: Colors (black, yellow, red, green, blue), digits (2, 4, 5, 8, 9), pictures (tree, chair, duck, scissors, bike), and letters (d, o, a, s, p). Children were instructed to rapidly and accurately name these visually presented items. All items were at random presented 10 times (i.e., 50 items per subtest, 200 items in total). Averaged overall naming time in seconds was used as raw score. Split-half reliability and test–retest reliability were sufficient (α's > 0.75; Evers et al., 2009–2012).

Non-verbal reasoning

Raven's Standard Progressive Matrices were used to assess non-verbal reasoning (Raven, 1976). This task consists of 60 visual patterns (i.e., five sets of 12 items), with increasing difficulty. In the first set, one part was missing for each item. Children were asked to select the missing part to logically complete the design out of six alternatives. In the remaining sets, four to nine pattered figures were presented, from which the final figure was missing. Children selected the missing figure out of six to eight alternatives. The number of correct answers were counted, summing to a maximum score of 60 points. Internal consistency was good (α > 0.90; Raven et al., 1998).

Analysis Strategy

Preliminary Analyses

All variables were approximately normally distributed (standardized |skewness| and |kurtosis| < 3.0). This was computed by dividing the skewness and kurtosis statistics (obtained in SPSS, version 25) by their standard errors. Outliers that diverged more than three standard deviations from the mean (>|3.29|) were winsorized. Subvariables of all cognitive constructs were correlated in the total sample (BFs > 16.07; strong support; Jeffreys, 1961). This was the case for number sense (r = 0.34 for non-symbolic and symbolic comparison), working memory (r = 0.16 for verbal and visuospatial working memory), phonological awareness (r = 0.35 for deletion and spoonerism), and rapid naming (r = 0.64 for alphanumeric and non-alphanumeric rapid naming). It should be noted,

TABLE 2 | Correlations between the cognitive skills (*n* = 262).

	Number sense	Working memory	Phonological awareness	Rapid naming	Nonverbal reasoning
Number sense[a]					
Working memory	–0.06				
Phonological awareness	–0.11	0.37*			
Rapid naming[a]	0.13	–0.01	–0.14		
Nonverbal reasoning	0.08	0.39*	0.36*	0.05	

**BF* > 10 (strong support); see Jeffreys, 1961. [a]Reaction time measures.*

however, that the correlation between both working memory constructs was relatively weak, but both observed variables were still combined into one latent variable in further analyses in line with previous research (LeFevre et al., 2013; Giofrè et al., 2014; Gray et al., 2017). There was strong support (*BF*s > 7313174) for correlations between working memory, phonological awareness, and non-verbal reasoning, see **Table 2**. The other cognitive skills were not related to each other, thus covariances for those associations were set to zero in further analyses.

Statistical Analyses

Bayesian structural equation modeling (BSEM) was conducted to examine cognitive compensatory mechanisms in mathematics and decoding, using the blavaan-package (Merkle and Rosseel, 2018) in open-source R software (version 3.6.1). A Bayesian approach was chosen because this allowed us to estimate a complex multigroup mediation SEM model within a small sample: There are few children with a (specific) learning difficulty within a regular sample of primary school children (as explained in the introduction). Another advantage of the Bayesian technique is that we could specify informative priors. See Van de Schoot and Depaoli (2014) and Van de Schoot et al. (2014) for a further (introductory) discussion of the advantages of Bayesian analyses. Unique effects between the cognitive skills and mathematics, and between the cognitive skills and decoding have already been established in previous empirical research and including this information as priors in our comprehensive model lead to more reliable results. Beta's and precision scores (corrected for sample size) were obtained from the data reported in those studies, and were used to specify the limits to the normal distribution of the priors, see **Appendix**. Prior information was retrieved from mixed samples (e.g., TD and MLD) as much as possible, because the same values were used in all models as we employed a multigroup approach. BSEM does not require the same assumptions as frequentist SEM (e.g., asymptotic normality), because exact posterior distributions can be estimated (instead of assumed) for any functional of the parameters and latent variables (Levy, 2011).

First, a Bayesian confirmatory factor analysis (BCFA; measurement model) was conducted on the whole sample to depict indicators of the standardized latent exogenous cognitive skills (i.e., number sense, working memory, phonological awareness, and rapid naming), and the standardized latent endogenous behavioral skills (i.e., mathematics, decoding, and fact retrieval). Non-verbal reasoning had a single indicator and was therefore set to '1'. Number sense and rapid naming were reaction time measures, and were recoded prior to the analyses. Second, a Bayesian mediation path analysis (BSEM; structural model) was carried out to display the predictors of mathematics and decoding, once within the full sample (reference model), and once within TD, MLD, RLD, and MRLD children (multigroup model). Fact retrieval was included in the model as mediator between the cognitive skills and mathematics. Goodness of fit of the models was examined using the posterior predictive *p*-value (ppp $\geq$ 0.05 indicates good fit; Meng, 1994), and models were compared using several information criteria (dic, waic, and looic; smaller values indicate better fit of the model to the data compared to a model with larger values; Spiegelhalter et al., 2002). All Bayes Factors (i.e., the test statistic) were interpreted according to the guidelines by Jeffreys (1961), see **Table 3**.

To explore compensatory mechanisms, Bayesian independent samples t-tests were conducted in R using the BayesFactor-package (Morey et al., 2018). This exploratory analysis was carried out to examine whether children with a cognitive strength—as opposed to a weakness in that same cognitive skill—can compensate for a related cognitive weakness associated with their learning difficulty. In line with Ansari et al. (2003), Heim et al. (2008), Haft et al. (2016), Koriakin et al. (2017), Liu et al. (2017), and Toffalini et al. (2017), a strength was defined as +1 SD relative to the sample mean, and a weakness as –1 SD relative to the sample mean.

RESULTS

Descriptive Statistics

Descriptive statistics for all behavioral and cognitive measures are displayed in **Table 4**. Interesting to note is that mathematics performance in the MLD- and MRLD-group was significantly lower than the RLD-group, which in turn was weaker compared to TD-group. In contrast, performance on decoding of the RLD- and MRLD-group was significantly weaker than for the TD- and MLD-group. Fact retrieval of the MLD- and MRLD-group was significantly lower than for the TD-group. However, fact retrieval skills of the RLD-group were similar to those of the MLD- and MRLD-group.

TABLE 3 | Interpretation of the Bayes factor (Jeffreys, 1961).

Bayes factor			Interpretation
	>	100	Decisive evidence for H_1
30	–	100	Very strong evidence for H_1
10	–	30	Strong evidence for H_1
3	–	10	Substantial evidence for H_1
1	–	3	Anecdotal evidence for H_1
	1		No evidence
1/3	–	1	Anecdotal evidence for H_0
1/10	–	1/3	Substantial evidence for H_0
1/30	–	1/10	Strong evidence for H_0
1/100	–	1/30	Very strong evidence for H_0
	<	1/100	Decisive evidence for H_0

TABLE 4 | Means (standard deviations) for the TD, MLD, RLD, and MRLD groups.

	TD (*n* = 168)		MLD (*n* = 36)		RLD (*n* = 42)		MRLD (*n* = 16)	
	M (SD)	***Min; Max***	***M (SD)***	***Min; Max***	***M (SD)***	***Min; Max***	***M (SD)***	***Min; Max***
Mathematics	20.62 (7.36)[a]	6; 41	9.34 (5.08)[c]	2; 28	17.29 (7.49)[b]	5; 34	9.63 (5.02)[c]	3; 23
Decoding	53.04 (9.39)[a]	32.5; 82	51.79 (9.56)[a]	27.5; 72	36.69 (8.00)[b]	24.5; 60	35.09 (8.20)[b]	23; 59
Fact retrieval	126.34 (30.47)[a]	53; 196	91.38 (26.70)[b]	44; 174	106.51 (30.27)[b]	49; 176	84.63 (33.87)[b]	31; 156
Number sense (ms)								
Symbolic	1167.73 (259.64)[a]	600.00; 2000.00	1195.47 (224.02)[a]	851.24; 1774.18	1171.74 (192.13)[a]	829.32; 1624.64	1474.71 (255.02)[b]	847.03; 2000.00
Non-symbolic	1291.90 (300.28)[a]	505.30; 2000.00	1042.07 (308.28)[b]	500.00; 1683.57	1322.17 (283.27)[a]	668.05; 2000.00	1323.19 (317.37)[a]	888.98; 1728.29
Working memory (*p*)								
Verbal	0.58 (0.09)[a]	0.30; 0.85	0.48 (0.15)[b]	0.20; 0.80	0.51 (0.13)[b]	0.20; 0.74	0.48 (0.08)[b]	0.36; 0.62
Visuospatial	0.74 (0.12)[a]	0.31; 0.99	0.69 (0.14)[a]	0.30; 0.93	0.74 (0.12)[a]	0.44; 0.96	0.68 (0.15)[a]	0.35; 0.95
Phonological awareness								
Deletion	15.55 (2.51)[a]	7; 18	14.12 (3.05)[b]	7; 18	14.62 (2.30)[ab]	9; 18	13.38 (2.13)[b]	9; 17
Spoonerism	16.09 (4.21)[a]	3; 24	13.12 (3.95)[b]	3; 20	13.32 (4.55)[b]	6; 22	12.38 (4.47)[b]	6; 21
Rapid naming (sec)								
Alphanumeric	26.29 (4.45)[a]	18.15; 38.27	25.31 (3.81)[a]	15.79; 31.57	31.28 (6.14)[b]	21.36; 44.63	31.10 (7.06)[b]	20.45; 44.99
Non-alphanumeric	45.98 (6.62)[a]	32.27; 65.90	45.96 (6.58)[a]	34.10; 61.00	50.35 (7.67)[b]	34.54; 72.48	53.63 (9.57)[b]	40.20; 72.53
Nonverbal reasoning	41.11 (6.56)[a]	20; 54	33.41 (6.31)[b]	20; 44	39.85 (5.85)[a]	28; 51	33.53 (5.88)[b]	23; 42

Note that group means with different superscripts are different (BF > 3). Bayesian ANOVA was employed to assess group differences.

With respect to the mathematics predictors, for number sense the MRLD-group performed the worst (i.e., they had the slowest reaction times) on symbolic number sense. Contrary to our expectations, the MLD-group performed the best (i.e., quickest reaction times on correct trials) of all groups on non-symbolic number sense, which will be elucidated in the discussion section. Verbal working memory performance was significantly weaker in all learning-difficulty groups compared to TD-children, but visuospatial working memory did not differ across groups. Finally, non-verbal reasoning was significantly weaker in the MLD- and MRLD-group than in the TD- and RLD-group. Regarding the linguistic predictors, we found that phonological awareness was significantly weaker in the learning-difficulty groups compared to TD-children. Finally, rapid naming was significantly weaker in the RLD- and MRLD-groups compared in the TD- and MLD-groups. Variance across groups on all cognitive measures was quite similar.

Correlations

Correlations between the behavioral and cognitive skills of the overall sample are presented in **Tables 5A,B**. Mathematics had a significant positive correlation with working memory, phonological awareness, and non-verbal reasoning. Furthermore, mathematics was correlated to fact retrieval ($r = 0.52$, $BF = 7.34^{20}$; strong support; Jeffreys, 1961). Fact retrieval itself had a significant negative correlation with number sense and rapid naming (i.e., slower reaction times indicate lower fact retrieval scores), and a significant positive correlation with working memory, phonological awareness and non-verbal reasoning. Finally, decoding had a significant negative correlation with rapid naming (i.e., slower reaction times indicate lower decoding scores), and a significant positive correlation with phonological awareness.

Bayesian Multigroup Mediation Structural Equation Model

The combined sample of all children was used to create a measurement model (**Figure 1**) with subvariables of cognitive predictors (number sense, working memory, phonological awareness, rapid naming, and non-verbal reasoning), behavioral outcomes (mathematics and decoding), and behavioral mediator (fact retrieval). Model fit to the data was considered sufficient, ppp = 0.06.

TABLE 5A | Correlations between latent behavioral skills and latent cognitive skills (*n* = 262).

	Number sense[a]	**Working memory**	**Phonological awareness**	**Rapid naming[a]**	**Nonverbal reasoning**
Mathematics	–0.12	0.39***	0.38***	–0.13*	0.51***
Decoding	–0.12	0.07	0.33***	–0.56***	0.00
Fact retrieval	–0.19*	0.22**	0.31***	–0.29***	0.21**

**BF = 1–3 (anecdotal support); **BF = 3–10 (substantial support); ***BF > 10 (strong support); see Jeffreys, 1961.*
[a]*Reaction time measures.*

TABLE 5B | Correlations between observed behavioral skills and observed cognitive skills (n = 262).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
(1) Proportions																
(2) Geometry	0.273															
(3) Word decoding	0.097	0.148														
(4) Pseudoword decoding	0.063	0.101	0.850													
(5) Addition	0.201	0.395	0.403	0.448												
(6) Subtraction	0.181	0.496	0.366	0.374	0.839											
(7) Multiplication	0.130	0.311	0.411	0.394	0.678	0.703										
(8) Division	0.162	0.410	0.324	0.270	0.595	0.648	0.812									
(9) Symbolic comparison	−0.151	−0.276	−0.119	−0.103	−0.370	−0.392	−0.252	−0.259								
(10) Non-symbolic comparison	0.002	0.107	−0.040	−0.079	−0.004	0.043	0.047	0.058	0.348							
(11) Visuospatial WM	0.132	0.197	−0.002	−0.106	−0.015	−0.001	0.007	0.082	−0.055	0.000						
(12) Verbal WM	0.193	0.327	0.199	0.149	0.289	0.264	0.227	0.239	−0.280	0.125	0.200					
(13) Deletion	0.203	0.287	0.240	0.210	0.165	0.226	0.168	0.215	−0.197	0.022	0.190	0.322				
(14) Segmentation	0.125	0.277	0.290	0.291	0.212	0.244	0.222	0.227	−0.069	−0.081	0.207	0.312	0.361			
(15) Alphanumeric RAN	−0.040	−0.074	−0.605	−0.611	−0.426	−0.312	−0.321	−0.192	0.158	0.070	0.134	−0.050	−0.101	−0.084		
(16) Non-alphanumeric RAN	−0.066	−0.145	−0.451	−0.394	−0.344	−0.259	−0.259	−0.201	0.158	0.029	0.031	−0.133	−0.089	−0.150	0.655	
(17) Non-verbal reasoning	0.175	0.458	0.059	−0.025	0.145	0.213	0.131	0.222	−0.082	0.190	0.307	0.327	0.333	0.293	0.150	−0.019

Next, structural relations by means of informative priors were included in the measurement model to facilitate SEM. A Bayesian mediation SEM analyses was conducted on the combined sample of all children to create a reference model. A Bayesian multigroup mediation SEM analyses was conducted on the TD-, MLD-, RLD-, and MRLD-group, again using the measurement model that was retrieved from the combined sample of all children. The group factor was constructed such that the LD-groups were compared to the TD-group. Fit statistics and information criteria from the multigroup model were compared to the reference model, see **Table 6**, and revealed that the multigroup model was preferred because of better model fit and smaller values for the information criteria. In fact, the reference model showed poor fit to the data, and was therefore neither plotted nor interpreted in the present study.

For the TD-group (**Figure 2**), mathematics was mainly predicted by working memory and non-verbal reasoning. Fact retrieval did not mediate this effect, but number sense, working memory, phonological awareness, and rapid naming were predictors of fact retrieval. Decoding was mainly predicted by working memory, phonological awareness, and rapid naming. In total, the cognitive predictors explained 68% of the variance in mathematics, 64% of the variance in decoding, and 43% of the variance in fact retrieval.

For the children with low math abilities (**Figure 3**), mathematics was mainly predicted by rapid naming. Fact retrieval mediated this effect. Decoding too was mainly predicted by rapid naming. In total, the cognitive predictors explained 53% of the variance in mathematics, 55% of the variance in decoding, and 59% of the variance in fact retrieval.

For the children with low decoding abilities (**Figure 4**), mathematics was mainly predicted by number sense, rapid naming, and non-verbal reasoning. Fact retrieval mediated this effect for rapid naming and number sense. Decoding too was mainly predicted by rapid naming. In total, the cognitive predictors explained 82% of the variance in mathematics, 75% of the variance in decoding, and 89% of the variance in fact retrieval.

For the children with mathematics and reading learning difficulties (**Figure 5**), mathematics was mainly predicted by number sense and rapid naming. Fact retrieval did not mediate this effect, but was predicted by number sense. Decoding was not predicted by any of the cognitive variables included in this model. In total, the cognitive predictors explained 41% of the variance in mathematics, 3% of the variance in decoding, and 22% of the variance in fact retrieval.

Indirect and total effects for mediation by fact retrieval are presented in **Table 7**. Within TD-children, direct effects of the cognitive skills on mathematics (especially for working memory and non-verbal reasoning) were stronger than indirect effects via fact retrieval. For the MLD-group and RLD-group, the effects of rapid naming, and rapid naming and number sense, respectively, on mathematics were mediated by fact retrieval, but the direction of these effects was negative and should therefore be interpreted with care: Children with higher scores on fact retrieval appeared to perform weaker on mathematics.

Lastly, to ensure that the priors did not affect our data substantially, a sensitivity analysis with non-informative priors

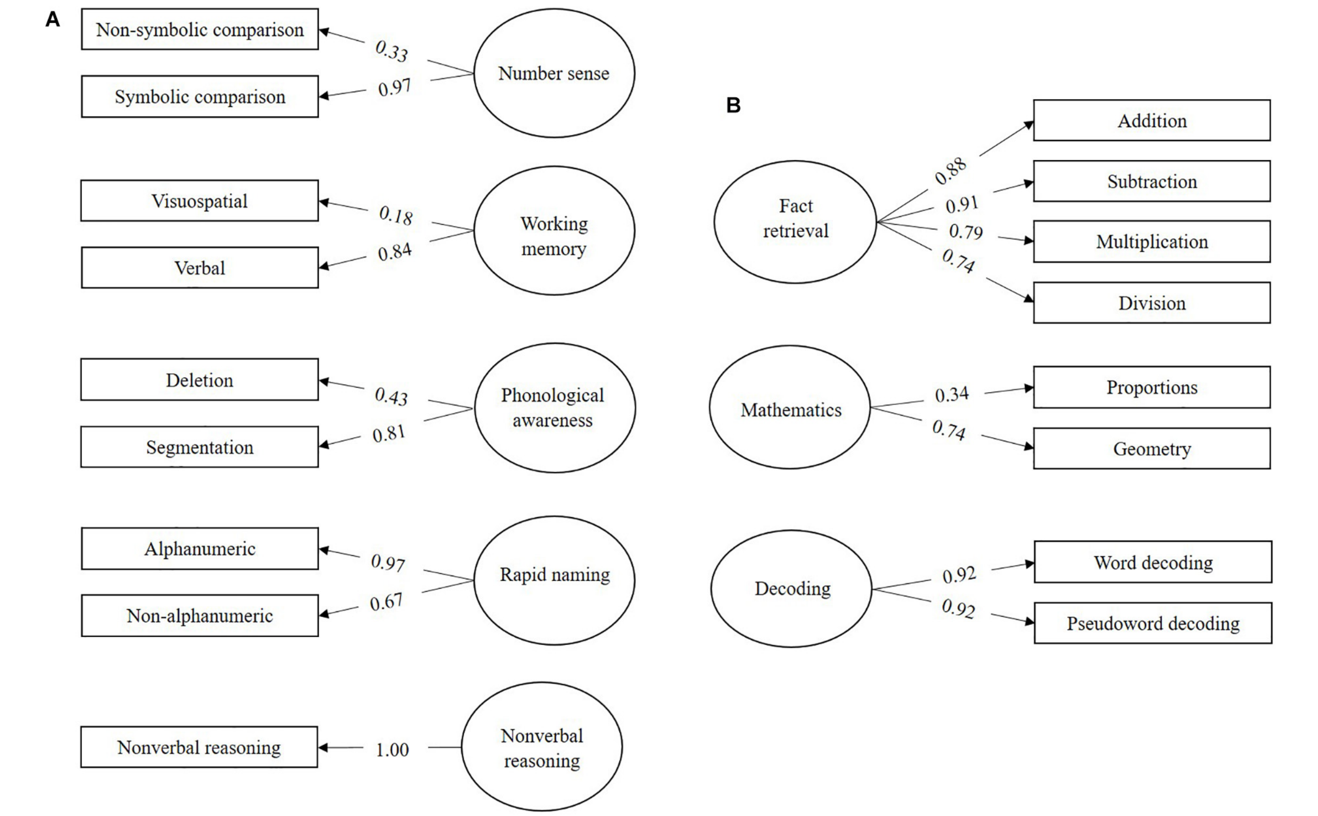

FIGURE 1 | Measurement model (CFA) for **(A)** the cognitive skills and **(B)** the behavioral outcomes in the combined sample of all children. Denoted values are beta weights.

was modeled. All other parameters were kept the same as in the main analysis. Fit statistics and information criteria are displayed in **Table 6**. Overall, results from the sensitivity analysis were quite similar to the main analysis. However, based on the sensitivity model it appears as if the priors have had some impact on the data. First, some effects were more extreme in the sensitivity analysis, whereas others were more tempered. To elaborate, the effects of working memory on mathematics and decoding were larger in the TD-group in the sensitivity model than in the main model, although they remained to be in the same direction. In contrast, the effects of number sense and rapid naming on mathematics were smaller in all four groups in the sensitivity model as opposed to the main model, but again the direction of the effects remained the same. Despite these shifts in the sizes of the effects, conclusions regarding those variables were the same for both the sensitivity analysis and the main analysis. In contrast, conclusions regarding the mediation effects were different based on how informative the priors were. Under the non-informative priors (i.e., sensitivity model), the effect of fact retrieval on mathematics became close to zero (but was still negative) in the MLD-group, and even switched directions in the RLD-group (i.e., became positive instead of negative) as opposed to the informative priors (i.e., main model). This finding will be further reflected on in the section "Discussion." Overall, except for the mediation effects, data were not substantially affected by the priors.

TABLE 6 | Information criteria for the comparison of the multigroup model to the reference model.

Model	ppp	DIC	WAIC	LOOIC
Multigroup	0.26	9963.78	10070.79	10079.98
Reference	0.00	10916.68	10933.02	10933.21
Sensitivity	0.48	9855.93	10018.36	10026.07

Smallest values for information criteria indicate preferred model.

Taken together, the Bayesian SEM model for the TD-children was matching findings from empirical research: Mathematics and fact retrieval were predicted by the mathematic cognitive skills, and also to some extent by the linguistic predictors. Decoding was predicted by these linguistic cognitive skills as well. For the children with MLD, rapid naming was the strongest predictor for mathematics, fact retrieval and decoding. Their rapid naming scores were at the same level as TD-children's performance, in spite of the specific numerical learning difficulty of these children with MLD. For the children with RLD, number sense was a strong predictor for mathematics. Rapid naming too was a strong predictor for mathematics, fact retrieval and decoding. Their number sense scores were at the same level as TD-children's performance. Rapid naming scores of children with RLD were

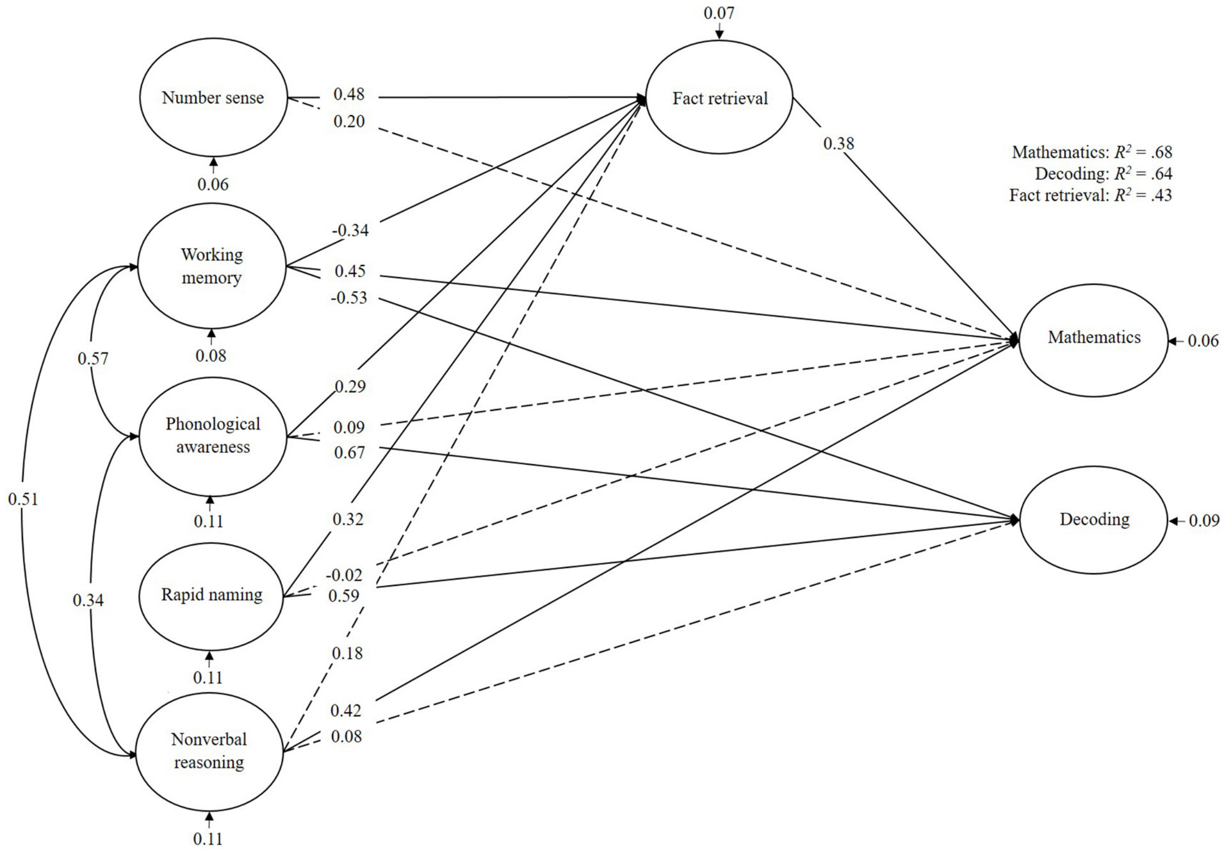

FIGURE 2 | Bayesian structural equation model for typical developing children. Denoted values are beta weights.

weaker compared to TD-children. Finally, for the children with MRLD, number sense was a strong predictor for mathematics. There were no strong effects for fact retrieval and decoding. Symbolic number sense was the weakest in the MRLD-group compared to the other groups. Fact retrieval mediated the effect of rapid naming on mathematics in children with MLD and RLD, as well as the effect of number sense on mathematics in children with RLD.

Follow-Up Analysis

To further examine whether rapid naming could be identified as compensatory mechanisms for mathematics, an exploratory Bayesian independent samples t-test was conducted in R using the BayesFactor-package (Morey et al., 2018). The previous analyses showed that number sense also predicted mathematics. Moreover, number sense has been indicated as an important marker of mathematics performance in the literature (Geary, 2011). Therefore, we first selected children whose number sense scores were $\leq$1 SD below the mean of the full sample. The full sample was used to avoid that selection of children with weak math scores might exclude those with strong compensatory mechanisms, who as a result do not fit with our selection criteria. Next, children were divided into two subgroups (-1 SD and $+1$ SD) based on their rapid naming scores: One group of children had weak number sense and weak rapid naming, and another group had weak number sense but strong rapid naming. Descriptive for both groups are displayed in **Table 8**.

The subgroups were compared on mathematics and on fact retrieval. Multivariate Bayesian analyses showed that the subgroups were different, $BF = 3.98$ (moderate support for H_1; Jeffreys, 1961). A Bayesian *t*-test revealed that the subgroups differed on mathematics, $BF = 4.77$ (moderate support for H_1; Jeffreys, 1961). Children with stronger rapid naming performed relatively better on mathematics ($M = 9.20$, $SD = 6.33$, $n = 54$) than children with weaker rapid naming ($M = 8.10$, $SD = 5.80$, $n = 61$). A Bayesian *t*-test for fact retrieval also suggested that the subgroups differed, $BF = 2.11$ (anecdotal support for H_1; Jeffreys, 1961). Children with stronger rapid naming performed relatively better on fact retrieval ($M = 116.13$, $SD = 30.73$, $n = 54$) compared to children with weaker rapid naming ($M = 106.31$, $SD = 33.51$, $n = 58$).

DISCUSSION

Cognitive strengths were investigated in the present study as potential compensatory mechanism for primary school children's cognitive weaknesses to partly overcome their learning difficulties in mathematics and/or reading. To elaborate, children with low

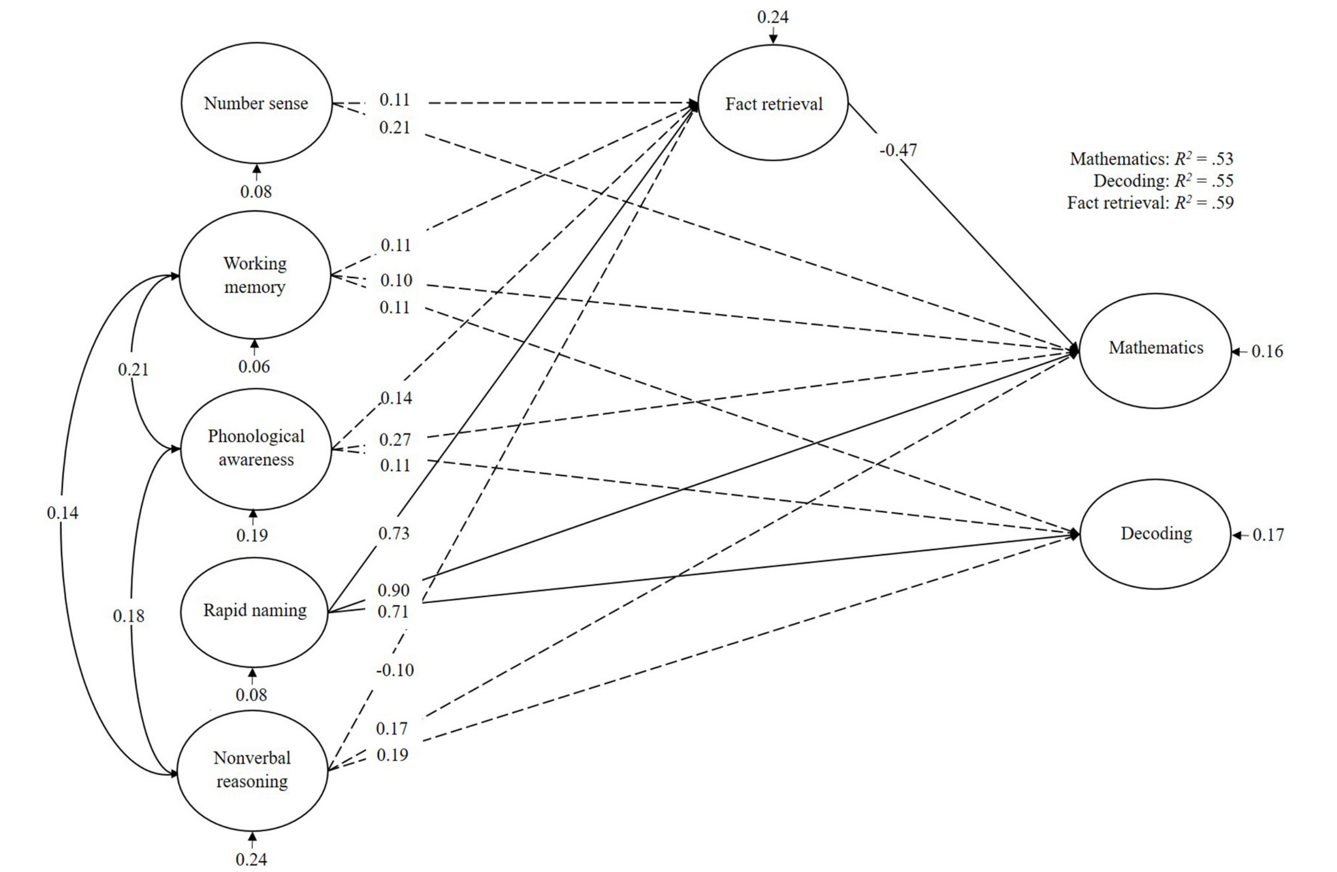

FIGURE 3 | Bayesian structural equation model for children with weak math abilities (MLD). Denoted values are beta weights.

mathematics performance seem to benefit from strong rapid naming skills to compensate for number sense and/or working memory weaknesses. A compensatory mechanism for a comorbid mathematics and reading learning difficulty was not identified in the present study.

Four groups were created using curriculum-based mathematics and reading scores in order to identify cognitive skills that could act as a compensatory mechanism for children with different ability levels. A Bayesian multigroup mediation SEM analyses showed that the model for typical developing (TD) children was consistent with the existing literature (see e.g., Friso-van den Bos et al., 2013; Araújo et al., 2015; Schneider et al., 2017 for meta-analyses). In short, mathematics was primarily predicted by number sense, working memory, non-verbal reasoning, and fact retrieval. Reading was primarily predicted by phonological awareness, rapid naming, and working memory. These findings are in line with our hypothesis. High achievers in any (combination) of those predictors, displayed higher performance on mathematics or reading as well.

It should be noted, however, that the direction of the effect of working memory on fact retrieval and reading was negative. In other words, weaker working memory skills were related to better fact retrieval and better decoding in TD-children. This somewhat unexpected result may be explained by means of a confounding variable. Working memory (or updating) can be viewed as an executive function (Miyake et al., 2000). The other executive functions of inhibition and shifting could be involved in fact retrieval and reading as well. Fact retrieval and reading both are timed measures, and a child will likely perform weaker on those tasks when he is, for example, distracted by task-irrelevant stimuli. When a child has to use much of his working memory resources on relatively simple tasks such as fact retrieval and reading, the efficacy of other executive functions might decrease, which may make him more prone to errors in those tasks.

Further it was expected that phonological processing (i.e., phonological awareness and/or rapid naming) could be identified as a cognitive compensation mechanism within children with mathematical difficulties. The results indeed showed that, within the MLD group, mathematics scores were better for children with relatively stronger rapid naming skills compared to peers with relatively weaker rapid naming skills. Note that the children with strength in rapid naming still performed worse on a mathematical task than children without any mathematical difficulties despite the compensatory effect from rapid naming.

Next, we investigated if our interpretation of the Bayesian SEM analyses holds: Does rapid naming also take on the role of a cognitive compensation in a regular primary school population? Performance on mathematics and reading was

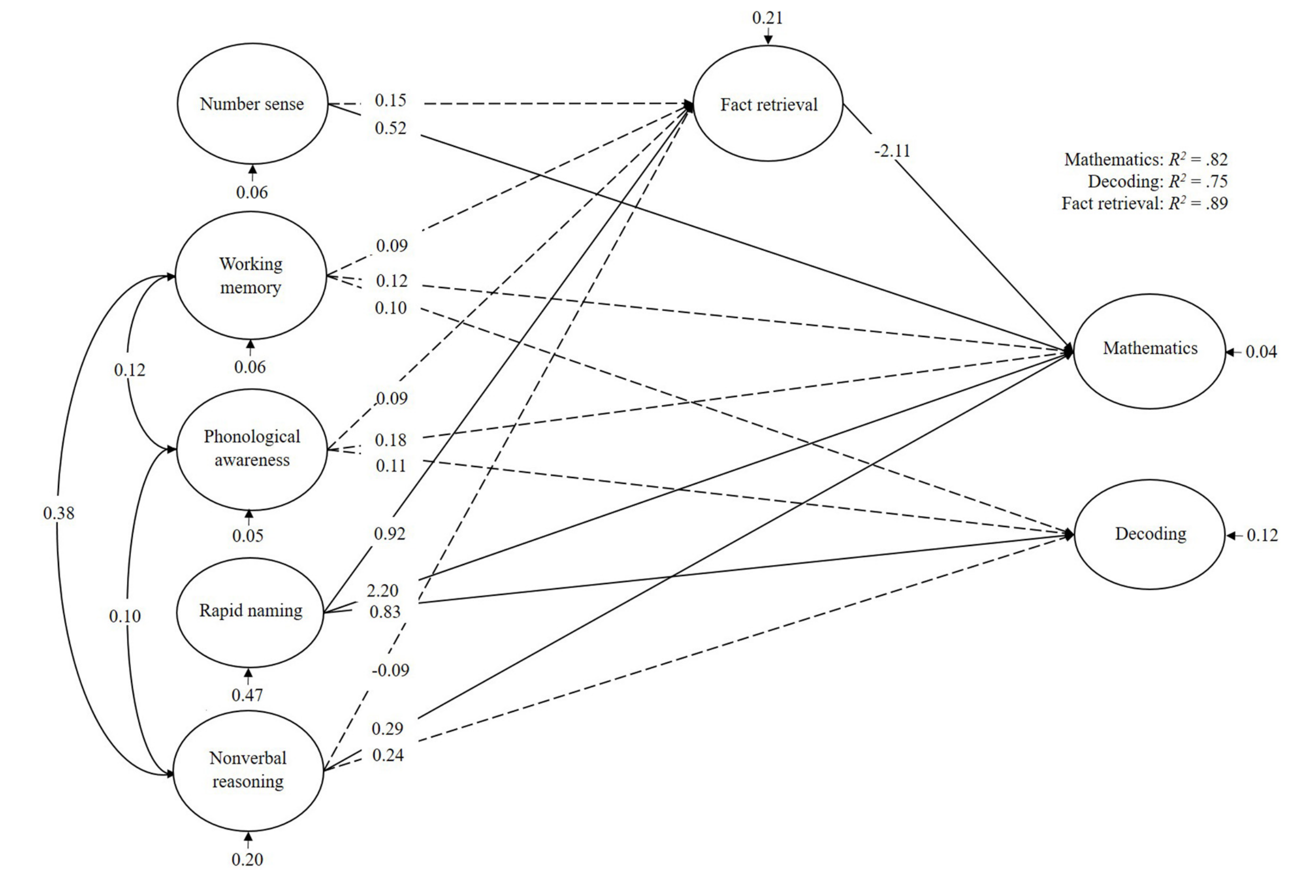

FIGURE 4 | Bayesian structural equation model for children with weak decoding abilities (RLD). Denoted values are beta weights.

examined on a continuous dimensional scale for children with strong performance on this cognitive skill compared to children with weak performance on that same skill. The exploratory Bayesian *t*-tests in our full sample indeed confirmed our hypothesis that children with strong rapid naming (and a weak number sense as marker for mathematical difficulties) performed slightly better on mathematics and fact retrieval than children with weak rapid naming. Mean differences were small and standard deviations were large, thus cognitive compensation is not considered a mechanism that can resolve learning difficulties, and it may not apply to all children. Nevertheless, small gains in mathematics performance can be very meaningful for children with MLD. These results therefore point into the direction that rapid naming as a compensatory mechanism can reduce the severity of MLD.

For reading, a cognitive compensatory mechanism was not identified in the present study. It was hypothesized that strength in working memory might be a candidate for compensation, because previous research has shown that working memory is a less consistent predictor of reading compared to for example phonological awareness and rapid naming (Baddeley, 2003). However, this hypothesis was not supported. Working memory evidently is a prerequisite for reading (Savage et al., 2007), just like the other cognitive skills phonological awareness and rapid naming. Proficiency in certain (cognitive) skills may be essential for a child in order to be able to read. In contrast, MLD is a more heterogeneous learning disability (e.g., Price and Ansari, 2013), and for mathematics one may take alternative routes to acquire a minimum level of performance. Thus, there may be more possibilities for cognitive compensation in mathematics as opposed to reading. Nevertheless, strengths in other variables such as vocabulary (Haft et al., 2016), or affective variables such as motivation and self-esteem (Durlak et al., 2011) may be possible candidates for compensation of weaknesses related to reading. An alternative explanation for the lack of a compensatory mechanism for reading in the present study is the outcome measure that has been used. Reading was operationalized by (pseudo-)word decoding in the present study. However, a more complex task such as reading comprehension might appeal upon more cognitive skills, and may thus be more comparable with the complex problem solving task for mathematics. Indeed, previous research has shown that decoding is more associated with fact retrieval (De Smedt et al., 2010; Jordan et al., 2010), whereas reading comprehension is more associated with math problem solving (Pimperton and Nation, 2010; Björn et al., 2016). Thus, we cannot rule out the possibility that when a measure of reading comprehension had been included, a compensatory mechanism for reading could have been obtained.

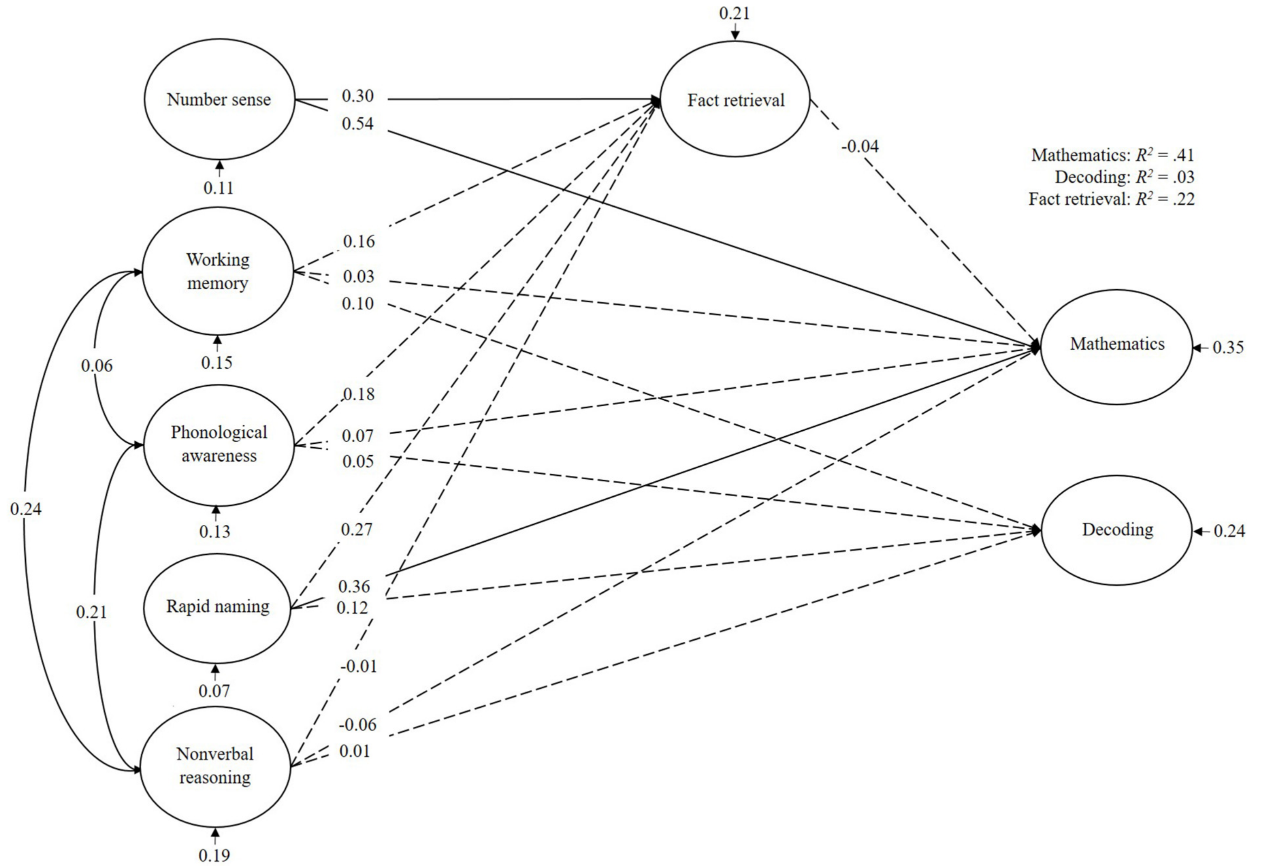

FIGURE 5 | Bayesian structural equation model for children with comorbid learning difficulties (MRLD). Denoted values are beta weights.

TABLE 7 | Indirect and total effects (marked bold) for fact retrieval as mediator in the effects of the cognitive skills on mathematics.

	TD		MLD		RLD		MRLD	
	Indirect	Total	Indirect	Total	Indirect	Total	Indirect	Total
Number sense	0.18	**0.38**	–0.05	0.16	**–0.32**	0.20	–0.01	**0.53**
Working memory	–0.13	**0.32**	–0.05	0.05	–0.20	–0.08	–0.01	0.02
Phonological awareness	0.11	0.19	–0.07	0.20	–0.18	–0.01	–0.01	0.06
Rapid naming	0.12	0.10	**–0.35**	**0.55**	**–1.93**	0.26	–0.01	**0.35**
Non-verbal reasoning	0.07	**0.49**	0.05	0.21	0.18	**0.47**	0.00	–0.06

Furthermore, there was a strong effect of number sense on mathematics within the children with reading difficulties. As not every child with a specific learning deficit develops a comorbid learning difficulty (i.e., children with reading difficulties performed better on mathematics than children with either specific or comorbid mathematical difficulties in the present study), we would like to suggest to the reader that the effect of number sense may be interpreted as a preventive mechanism for developing comorbid math difficulties. A strength in number sense might not compensate for cognitive weaknesses related to RLD *per se* (Moll et al., 2015a,b), but we speculate that it might prevent these children from the adverse effects of for example a phonological deficit. Such a deficit is of course related to reading difficulties and generally is also related to mathematical difficulties (Wilson et al., 2015). Due to a strong number sense, however, children may be able to avert this disadvantage by developing specific reading problems instead of a comorbid mathematics and reading learning difficulty.

With respect to children with a comorbid mathematical and reading learning difficulty (MRLD), results should be interpreted carefully. Although one of the advantages of Bayesian analyses is that it can be applied in small samples, any analyses with less than twenty children may be too small to detect an effect, especially for a complex model such as a multigroup mediation SEM (De Santis, 2007). We could therefore not confirm our hypothesis that compensation is not possible for children with MRLD.

TABLE 8 | Background characteristics for the follow-up analyses.

	Weak number sense, strong rapid naming (n = 54)	Weak number sense, weak rapid naming (n = 61)
#MLD	9	2
#RLD	5	15
#MRLD	3	7
Working memory	0.65 (0.10)	0.62 (0.09)
Non-verbal reasoning	39.28 (7.75)	40.53 (5.81)

Bayesian t-tests for working memory and non-verbal reasoning revealed that there were no initial group differences (BFs < 3). However, Bayesian Chi-square tests revealed that the number (#) of children with MLD, RLD, or MRLD per group was different (BFs > 3).

Nevertheless, there was little variance on the cognitive measures in the present study, as well as in previous research (Andersson, 2010), which demonstrates that children with MRLD are weak across the board. As these children show weaknesses on (almost) all cognitive skills related to their mathematics and reading performance, we carefully suggest that children with MRLD, who are known to have the most serious learning problem (Kaplan et al., 2006), are unable to compensate with a cognitive strength. This hypothesis should be tested in future research in a larger sample of children with MRLD.

The MRLD model also showed a relatively strong effect of number sense. Although this finding too should be interpreted with care, this is in line with the existing body of literature. It has previously been suggested that number sense can mainly be used to differentiate within children who are at the lower end of the continuum for mathematics (Geary et al., 2012). Variability in number sense skills cannot be used to distinct between children with strong math skills, because apparently all of them are able to solve these relatively simple numerical tasks. A child with very weak overall cognitive skills related to developing a mathematical and reading learning difficulty (i.e., the lower extreme of the continuum), might still benefit from slightly better number sense skills (compared to peers) when learning mathematics. Then again, the MRLD sample was quite small, thus future research should attempt to confirm this hypothesis by comparing children with MRLD with different levels of number sense in a larger sample size.

Previous research has demonstrated that the comorbidity between MLD and RLD likely occurs because of an overlap in the predictors of mathematics and reading. For instance, a child with weak phonological skills likely suffers from both mathematical and reading difficulties (Wilson et al., 2015). With respect to the cognitive compensation theory—as proposed in the present study—even children with comorbid learning difficulties might have a small cognitive strength. Low achievers could still perform slightly better on one of their cognitive skills compared to peers, despite limited variance in these cognitive skills, which can make their learning difficulty slightly less detrimental.

Finally, it is interesting to note that the Bayesian multigroup mediation SEM analyses showed the effect of several cognitive skills on mathematics to be mediated by fact retrieval. However, direct effects for most of the cognitive skills on mathematics (especially for working memory and non-verbal reasoning) were stronger than indirect effects via fact retrieval for TD-children. A potential explanation for this finding is that TD fourth-graders have already internalized the relatively simple arithmetic (fact retrieval) calculations (Mullis et al., 2016). Thus, when performing more complex math problem solving tasks, they might not need to rely much on their fact retrieval skills as these have already been automatized sufficiently. During these tasks, TD-children might instead invoke their cognitive resources such as working memory and non-verbal reasoning, because they are still learning new skills such as multiplying fractions. In line with a developmental framework, shifts may indeed occur over time within the relationship between various cognitive skills and mathematics (Van der Ven et al., 2013; Van de Weijer-Bergsma et al., 2015b).

While the mediation effect was positive for typical developing children, the effect was reversed for children with mathematical or reading difficulties in the multigroup model. Fact retrieval appeared to negatively mediate the effect of rapid naming on mathematics in children with MLD as well as in children with RLD. A similar negative mediation effect was obtained for number sense in children with RLD. This finding is surprising as correlations between fact retrieval and mathematics typically are strong and positive (see e.g., Träff, 2013), even in samples consisting of children with learning difficulties (see e.g., Träff and Samuelsson, 2013). Although this was not the main question of the present study, we would like to take the liberty to speculate about this unexpected negative mediation effect for fact retrieval. The correlation matrix provided no explanation as to why the effect was negative, thus this was probably a statistical artifact in the analyses due to the complexity of the model and given that this effect waned in the sensitivity analysis. It could also be speculated about a more conceptual explanation. The negative indirect effect could be interpreted as if stronger rapid naming (or number sense) is related to better fact retrieval skills, whereas better fact retrieval in turn appears to be related to worse math performance in children with specific learning difficulties. Number sense, rapid naming, and fact retrieval were all timed measures, thus a plausible explanation for this mediation can possibly be found in children's processing speed. The finding that better fact retrieval is related to worse math performance might indicate that some children are able to perform quick numerical calculations because they have adequate processing speed skills (e.g., memorized knowledge, such as '3 * 5 = __'), even though they do not grasp the meaning of problem solving tasks (e.g., understanding, such as 'calculate the surface in millimeters of a 3 cm by 5 cm rectangle). Previous research has indeed shown that individual differences exist in children's math performance. Some of them perform better on fact retrieval, whereas others are better in math problem solving (Huijsmans et al., under review). To add to that, it has been suggested that whereas typical math development involves progression from fact retrieval toward more procedural mathematics, some children with MLD tend to lag behind in this conceptual step (Thevenot, 2017; De Chambrier and Zesiger, 2018). This speculative explanation appears to be supported by the present study's finding that rapid naming (and number sense) is positively related to fact retrieval for children with MLD. Thus, faster processing speed within children with specific learning difficulties (i.e., rapid naming for MLD, and rapid naming and number sense for RLD in the present study) might positively interfere with these children's ability to quickly solve arithmetic facts, whereas it does not facilitate their procedural understanding of more complex problem solving tasks. However, conclusions regarding this finding should be investigated more thoroughly in future research considering the unexpected direction of the effects in comparison with previous literature.

To summarize, rapid naming is a likely candidate for cognitive compensation of number sense and possibly working memory weaknesses that are related to mathematical difficulties. Rapid naming is moderately related to mathematics (Berch and Mazzocco, 2007), which might explain why a strength in rapid naming takes on the role of a compensatory mechanism for mathematics for children with MLD as opposed to TD children. Regardless of children's persistent difficulties with number sense and working memory, strength in rapid naming might enable children with MLD to partly overcome the possible negative effects of a cognitive deficit by taking an alternative route to learning mathematics compared to TD children. At this point we would like to take the liberty to speculate that a possible alternative route via rapid naming might call upon children's general ability to retrieve facts from their long-term memory. These facts do not have to be numerical in nature *per se* (and they most likely are not entirely numerical because of those children's weak number sense), but instead one might argue that they make more use of procedural facts. Fast and accurate retrieval (i.e., rapid naming) of procedural facts such as 'when multiplying a rational number by ten, the decimal point is moved one place to the right' might be initialized in some children with MLD, even when his conception of the magnitude of a series of numbers is imperfect. One possible interpretation thus is that children with weak number sense but strong rapid naming rely more on procedural strategies compared to children without a weak number sense. An alternative explanation for the strong association between rapid naming and mathematics for children with MLD is the role of language skills, such as grammar, vocabulary, decoding, and reading comprehension. Such language skills rely in part on rapid naming (Norton and Wolf, 2012), and have also been directly and indirectly related to mathematics (Björn et al., 2016). Direct associations with mathematics have been obtained for vocabulary (Kleemans et al., 2018) and reading comprehension (Björn et al., 2016), and can be explained by the fact that children apply their knowledge of math-words (such as 'larger,' 'half,' and 'multiply') when inferring the appropriate calculation from a word problem in the upper grades of primary school. Decoding has indirectly been associated with mathematics via fact retrieval, because children rely on retrieval of verbal codes from long-term memory during decoding and fact retrieval tasks, which is supported by rapid naming skills (Norton and Wolf, 2012; Koponen et al., 2017). As reading performance of the children with MLD is adequate, this might show that they have relatively strong cognitive skills related to reading. Proficiency in common precursors of mathematics–such as number sense–therefore does not seem to be a requirement for reaching a sufficient level of mathematics in primary school. Part of the delay in mathematics performance can be circumvented by a strength in related cognitive skills. Thus, children may to be able to partly reduce their mathematical learning disability.

This finding leads to a new direction in research on specific (mathematical) learning difficulties by suggesting that primary school children are to some extent able to compensate for their learning difficulties in the domains of mathematics. Likewise, similar mechanisms may exist in other academic domains such as reading and science. Equivalent to the theory of neural plasticity (Nelson, 1999), the conceptualization of cognitive compensation posits that a child who experiences a deficit in one process will rely more on another closely-related process to facilitate learning. The cognitive compensation theory leads to a different interpretation of the multiple deficit model of Pennington (2006) by including strengths beyond weaknesses. Strengths in this fashion were defined as relative to children with comparable characteristics (e.g., a group of children with math difficulties). Different conceptualizations, such as a relative strength within a child (e.g., average performance on a skill when performance on related skills is below average), are interesting to study in future research, because they might reflect individual variation even better. Nevertheless, this new multifactorial model re-conceptualizes our understanding of individual differences in learning: Each child with a specific learning difficulty has a unique profile of cognitive strengths and weaknesses with the goal to maximize their learning outcomes.

Limitations and Suggestions for Future Research

At this point it should be mentioned that some of the measures used in the present study conveyed somewhat unexpected outcomes. First, fact retrieval skills were comparable across children with mathematical and/or reading difficulties. This may be a consequence of the speeded character of the test (i.e., processing speed; Berg, 2008), or underlying linguistic skills (Berch and Mazzocco, 2007). Secondly, children with mathematical difficulties surprisingly had the highest performance (i.e., quickest reaction times) on the non-symbolic number sense task. From the existing body of literature, however, it is evident that children with MLD at best perform equally to TD-children (Desoete and Grégoire, 2006). We hypothesize that the children with mathematical difficulties in the present study—possibly due to a lack of understanding—merely pressed one of the two buttons during the task, and therefore have faster reaction times compared to the other groups. Lastly, visuospatial working memory did not differ across groups, which contradicts the literature, wherein weaker visuospatial working memory usually is associated with lower math performance (Kroesbergen and Van Dijk, 2015). However, verbal working memory did differ across groups, which is in line with the notion that the effect of verbal working memory on mathematics performance increases as grade level progresses, while the effect of visuospatial working memory decreases (Van de Weijer-Bergsma et al., 2015b).

To add to the previous point, the BSEM model elicited some unexpected results as well. Some of the path coefficients for children with reading difficulties are inflated. This can likely be ascribed to the complexity of the model in relation to the sample size, and may be a statistical artifact (Lei and Wu, 2007). Even though the size or direction of some of the effects in the BSEM model were somewhat extreme, we are confident with our results given that these are mostly in line with previous studies. Nevertheless, future research might consider replicating these findings.

Third, it should be acknowledged that the present study consisted of a single measurement, and that we did not take a process measure of compensation into account. Causal inferences about the direction of the effects of cognitive strengths cannot be drawn from concurrent data (Hill and Stuart, 2015). Instead of using strong rapid naming skills to compensate for the detrimental consequences of weaknesses in cognitive predictors of mathematical difficulties (such as number sense), it might be the case that this strength arises from or co-occurs with reading proficiency in children with specific mathematical learning difficulties. Despite the reason for the strength of rapid naming in some children with mathematical difficulties, it seems plausible that children with weak mathematics performance might benefit from strong rapid naming skills. Future longitudinal research might shed light on the underlying mechanisms. For example, by using process measures during mathematics tasks (see e.g., Gidalevich and Kramarski, 2017), and by studying the patterns of correct and incorrect responses in mathematics tasks (see e.g., Koriakin et al., 2017). Children who use rapid naming to compensate for cognitive deficits will probably show patterns of correct responses on items that rely more on rapid naming (such as fact retrieval), whereas items that involve less rapid naming (but for example more number sense) may still be answered incorrectly.

A final point worthy of consideration is the question whether the compensatory effect is method-induced. To elaborate, variation within predictors may have shrunken substantially by selecting subsamples based on the outcome measures mathematics and reading. We considered the fact that this approach would be a restriction of range, but looking into the variance in minimum and maximum scores of the predictors lifted our concerns, because variance was substantial within groups as well as across groups. Group membership thus did not induce an artifact that could explain the compensatory effect in the present study. Nevertheless, it would be wise to replicate these findings in future research. Preferably first with a similar research design as proof of concept, and thereafter with different groups and variables related to learning, because compensation likely occurs in other domains as well.

CONCLUSION

To conclude, the severity of mathematical learning difficulties might be reduced trough compensatory cognitive mechanisms, despite etiological factors (e.g., genes and environment) that confer risk for developing a specific learning disability. This leads to a more extensive view on learning difficulties (i.e., the cognitive compensation theory) compared to the multiple deficit model by Pennington (2006): Learning difficulties do not only result from several (cognitive) weaknesses, but seem to exist in combination with strengths in other skills. This is especially true for specific learning difficulties, but might apply to children with a comorbid learning difficulty as well. Mathematical performance is probably affected by cognitive strengths (i.e., rapid naming) in a reciprocal manner, which contributes to the individual's ability to compensate to suboptimal circumstances. With the cognitive compensation theory, learning disability research is anticipated to shift from a restricted view of emphasizing an individual's weaknesses toward the vision that each child has a unique profile of cognitive strengths and weaknesses, and that these strengths in one way or another may compensate for their weaknesses.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://dx.doi.org/10.6084/m9.figshare.12122850.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee Social Science, Behavioural Science Institute, Radboud University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

MH, TK, and EK designed the research, analyzed and/or interpreted the data. MH performed the data-collection and wrote the manuscript. TK and EK gave feedback on draft versions. All the authors read and approved the final manuscript.

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APPENDIX

TABLE A1

Effect (X-Y)	Beta	N	SE	SD	Var	Precision	Source	Reason	Sample
NS-FR	*0.38*	154	0.07	0.86	0.74	*1.36*	Kroesbergen and Van Dijk, 2015: Table 3, model 3 (p. 106)	Same tasks were used for NS and BA	Grade 2–5; TD + MLD
WM-FR	*0.36*	154	0.07	0.87	0.76	*1.31*	Kroesbergen and Van Dijk, 2015: Table 3, model 3 (p. 106)	Similar tasks were used for WM and BA	Grade 2–5; TD + MLD
PA-FR	*0.20*	167	0.07	0.96	0.93	*1.08*	Kleemans et al., 2018: Figure 1 (p. 410)	Comparable task was used for PA; same task for BA	Grade 5; TD
RAN-FR	*0.08*	103	0.10	1.00	1.00	*1.00*	Donker et al., 2016: data simulated based on paper	Same tasks were used for RAN and BA	Grade 1–5; TD + MLD + RLD + MRLD
NVR-FR	*0.11*	118	0.09	0.99	0.98	*1.02*	Filippetti and Richaud, 2017: Figure 4 (p. 877)	Comparable tasks were used for NVR and BA	Grade 2–6; TD
NS-Math	*0.34*	154	0.07	0.89	0.79	*1.27*	Kroesbergen and Van Dijk, 2015: Table 3, model 3 (p. 106)	Same task was used for NS; similar for AM	Grade 2–5; TD + MLD
WM- Math	*0.27*	154	0.08	0.93	0.87	*1.16*	Kroesbergen and Van Dijk, 2015: Table 3, model 3 (p. 106)	Similar tasks were used for WM and AM	Grade 2–5; TD + MLD
PA- Math	*0.33*	148	0.07	0.89	0.80	*1.25*	Slot et al., 2016 – Figure 1 (p. 7)	Similar tasks were used for PA and AM, but incl. BA	Grade 1–5; TD + MLD + RLD + MRLD
RAN- Math	*0.23*	103	0.09	0.95	0.91	*1.10*	Donker et al., 2016: data simulated based on paper	Same task was used for RAN; similar tasks for AM	Grade 1–5; TD + MLD + RLD + MRLD
NVR- Math	*1.20*	167	–0.03	–0.44	0.19	*5.13*	Kleemans et al., 2018: Figure 1 (p. 410)	Same tasks were used for NVR and AM	Grade 5; TD
FR- Math	*1.65*	167	–0.13	–1.73	2.98	*0.34*	Kleemans et al., 2018: Figure 1 (p. 410)	Same tasks were used for BA and AM	Grade 5; TD
WM-Dec	*–0.57*	91	0.07	0.68	0.46	*2.17*	Swanson et al., 2009: Tables 4, 5A,B (p. 268)	Meta-analysis	5-to-18-years-old; TD + RLD
PA-Dec	*0.74*	148	0.04	0.45	0.21	*4.85*	Slot et al., 2016: Figure 1 (p. 7)	Similar task was used for PA; same for Read	Grade 1–5; TD + MLD + RLD + MRLD
RAN-Dec	*0.44*	103	0.08	0.81	0.66	*1.52*	Donker et al., 2016: data simulated based on paper	Same tasks were used for RAN and Read	Grade 1–5; TD + MLD + RLD + MRLD
NVR-Dec	*0.11*	1335	0.03	0.99	0.98	*1.02*	Korpipää et al., 2017: Figure 2 (p. 136)	Comparable tasks were used for NVR and Read	Grade 1-7; TD

Endogenous latent variables (Y's): FR = Fact Retrieval; Math = Mathematics; Dec = (non-)word decoding. Exogenous latent variables (X's): NS = Number Sense; WM = Working Memory; PA = Phonological Awareness; RAN = Rapid Automatized Naming; NVR = Nonverbal Reasoning.
Values displayed in italics were used as priors.
Explanation reasons. Same task, the source paper used the exact same task (or an older version) as the present study. Similar task, the task in the present study was based on/contained elements of the source task. Comparable task, the same construct was measured in both the source paper and in the present study.

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The Relationship of Reading Abilities With the Underlying Cognitive Skills of Math: A Dimensional Approach

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Math and reading are related, and math problems are often accompanied by problems in reading. In the present study, we used a dimensional approach and we aimed to assess the relationship of reading and math with the cognitive skills assumed to underlie the development of math. The sample included 97 children from 4th and 5th grades of a primary school. Children were administered measures of reading and math, non-verbal IQ, and various underlying cognitive abilities of math (counting, number sense, and number system knowledge). We also included measures of phonological awareness and working memory (WM). Two approaches were undertaken to elucidate the relations of the cognitive skills with math and reading. In the first approach, we examined the unique contributions of math and reading ability, as well as their interaction, to each cognitive ability. In the second approach, the cognitive abilities were taken to predict math and reading. Results from the first set of analyses showed specific effects of math on number sense and number system knowledge, whereas counting was affected by both math and reading. No math-by-reading interactions were observed. In contrast, for phonological awareness, an interaction of math and reading was found. Lower performing children on both math and reading performed disproportionately lower. Results with respect to the second approach confirmed the specific relation of counting, number sense, and number system knowledge to math and the relation of counting to reading but added that each math-related marker contributed independently to math. Following this approach, no unique effects of phonological awareness on math and reading were found. In all, the results show that math is specifically related to counting, number sense, and number system knowledge. The results also highlight what each approach can contribute to an understanding of the relations of the various cognitive correlates with reading and math.

Keywords: math, reading, working memory, approximate number system, phonological awareness

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INTRODUCTION

The Triple Code Model (Dehaene, 1992, 1997) suggests that numbers are expressed in three different codes that are at the base of our ability to count and process numerosity. They have distinct functional neuroarchitectures and are related to performance on particular tasks (Van Harskamp and Cipolotti, 2001). The first one is a verbal code, connected to the linguistic system, that is used to recover well-learned arithmetic facts using memory, such as simple addition and multiplication tables (González and Kolers, 1982). The second one is a visual code that represents and spatially manages numbers in Arabic format (Ashcraft and Stazyk, 1981; Dahmen et al., 1982; Dehaene and Cohen, 1991; Weddell and Davidoff, 1991). Finally, the third code is the analog magnitude representation, which gives a representation of analogical quantity on a mental number line (approximate calculation and magnitude comparison) (Chochon et al., 1999; Spelke and Dehaene, 1999). According to this model, the verbal code is used in particular for counting, addition, and easy multiplication, while approximate calculation and comparison are sustained more by the non-verbal codes.

From a developmental perspective, some studies proposed that language is essential for the growth of numerical competencies (Hauser et al., 2010), and mathematical language was found to be a unique significant predictor of numeracy performance (Purpura and Logan, 2015). There is also evidence that the structure of the language system in which one grows up shapes the development of numerical concepts. For example, Chinese children have been found to have an advantage in arithmetic tasks because in Chinese the base 10 number system is transparently represented in the structure of the number words (Geary et al., 1996). On the counterpart, speakers of Munduruku̇, who lack words for numbers beyond 5, are able to compare and add large approximate numbers, but they fail in exact arithmetic for large numbers (Pica et al., 2004). Others, however, argue that numerical competence, at least for some aspects, can develop independently from linguistic skills (Landerl et al., 2004). Landerl et al. (2004) support the theory that the number system is able to develop independently from the language domain. However, the relationship between linguistic and numerical skills is still under debate as well as the role of domain general cognitive markers as possible shared cognitive underpinning of reading and math skills. In the present study, we addressed the issue of the specificity of cognitive markers of math abilities and whether reading ability might also affect numerical competencies.

It is known that math and reading skills are related (Cirino et al., 2018; Koponen et al., 2020), and the co-occurrence of reading and math disorders can be between 2.3% and 40% (Lewis et al., 1994; Landerl and Moll, 2010; Moll et al., 2015; Koponen et al., 2018). In a recent meta-analysis, Joyner and Wagner (2020) reported that children with math disorders have a two times greater chance of having reading disability. According to the multiple deficit model (Pennington, 2006; McGrath et al., 2020), the relationship between math and reading can be accounted for by shared factors, which may act at different levels (genetics, cognitive, and behavioral).

A first candidate shared cognitive factor underlying reading and math is phonological processing, which might explain problems with the verbal code. Many studies have found that phonological processing difficulties predict early numeracy skills (Bonifacci et al., 2016) and the emergence of mathematical difficulties (Leather and Henry, 1994; Hecht et al., 2001; Rasmussen and Bisanz, 2005) and suggest that phonological awareness might be a shared underlying deficit of both disorders (Slot et al., 2016). Rapid automatized naming (RAN) is another important shared factor and is clearly distinct from phonological awareness (e.g., de Jong and van der Leij, 1999; Kirby et al., 2010). Naming speed has been found to explain a significant portion of the common variance of reading and math (Geary, 2011; Koponen et al., 2007, 2019, 2013; Fuchs et al., 2016; Balhinez and Shaul, 2019) and, together with timed counting, the largest amount of the overlap between the fluency of reading and math (Koponen et al., 2007, 2020). Also, domain-general processes, such as processing speed or working memory (WM), have been proposed to account for the relationship between math and reading as well as the comorbidity of math and reading problems (Bull and Johnston, 1997; Willcutt et al., 2013). A meta-analysis by Daucourt et al. (2020) suggested that domain-general risk factors underlie the co-occurrence of reading and math to a greater extent compared to the co-occurrence of reading and ADHD. Also, the genetic correlation between reading and math was higher than between reading and ADHD. In particular, there is evidence that a weakness in verbal WM leads to difficulties in storing and remembering arithmetic facts (Swanson and Sachse-Lee, 2001; Koponen et al., 2007, 2013; Simmons and Singleton, 2008; Vanbinst et al., 2015). Whereas some authors suggested that specific components of WM are related differentially to mathematics (Wilson and Swanson, 2001; Simmons et al., 2012), other studies note that the whole WM system is linked to mathematical knowledge development (Simmons et al., 2008; Zhang and Lin, 2015).

Two approaches have been used to enhance the understanding of the cognitive factors that underlie the common and specific aspects of reading and math. In one approach, underlying cognitive deficits of reading and math disorders are examined, with a particular emphasis on the shared and distinct markers of comorbid conditions and single deficits. In the other approach, underlying cognitive factors are used to predict common and unique variance in individual differences in reading and math in unselected samples. Hereafter, we will discuss main evidence deriving from the two approaches.

Studies on Cognitive Deficits Underlying Reading and/or Math Disorders

The main aim of these studies is to examine the various deficits that are characteristic of the single- and comorbid-deficit groups. The results of these studies might have implications for the diagnosis and treatment of disorders in reading (RD) and math (MD). Of particular interest is whether the deficits of the comorbid group, MD + RD, can be characterized as an additive combination of the deficits found in the single MD and RD group. From a methodological point of view, the disorder conditions are dichotomous independent variables on which each deficit variable is regressed as a function of the cognitive skill and importantly both main effects of reading and math as well as their interaction are tested. The test of the interaction effect reveals whether the deficit in the comorbid group is an additive or non-additive combination of the deficits in the single-deficit groups.

The approximate number system (ANS) has been proposed as a specific deficit underlying math impairments

(Butterworth and Laurillard, 2010; Piazza et al., 2010). ANS involves an automatic, non-symbolic, approximate sense of number that is available before the start of schooling, and that survives beyond the lifespan. Others propose a deficit in accessing numerosities from symbols (Noël and Rousselle, 2011; De Smedt et al., 2013). Schneider et al. (2017), in a meta-analysis, found that symbolic magnitude comparison skills were more strongly related to broader mathematical competence, e.g., counting, arithmetic, or algebra, compared to non-symbolic tasks. Within this view, symbolic numerical magnitude processing is thought to be as important to arithmetic development as phonological awareness is to reading (Vanbinst et al., 2016), as also documented by studies on children with math and reading disorder (MD-RD) (Landerl et al., 2004, 2009).

As said, a main issue is whether the two disorders and their comorbid phenotype might have distinct or common causes. Considering children with reading impairments, Simmons and Singleton (2008) hypothesized a weakness in the verbal code and, in particular, in recalling numerical facts. Indeed, several studies reported that children with dyslexia are slow in calculation, arithmetic fact retrieval, and, in particular, have difficulties with multiplication (Simmons and Singleton, 2006; Boets and De Smedt, 2010; De Smedt and Boets, 2010).

Most studies show that the MD + RD can be characterized by an additive combination of the deficits found in the single MD and RD group; this means that children with comorbid MD and RD usually show a summation of symptoms from the two disorders (e.g., phonological deficit and counting). van der Sluis et al. (2004) found that MD-only children were impaired in naming of digits and quantities, whereas RD-only children were impaired in digit and letter naming. The MD-only group also showed problems in executive functioning. The performance of the group with double deficits could best be described as an additive combination of the deficits underlying each disorder (see for similar results Willburger et al., 2008). Also, Landerl et al. (2009) found distinct cognitive profiles for RD and MD groups, with weaknesses in phonological awareness for the first, deficits in the processing of symbolic and non-symbolic magnitudes for the second, and additive cognitive deficits for the RD + MD group. Other studies (Cirino et al., 2007; Jordan et al., 2003) found that the RD-only group outperformed the RD + MD and MD-only group, with the latter groups showing a similar math profile. Finally, Moll et al. (2015) examined deficits in the underlying factors of reading and math. They found that factors underlying numerical difficulties in children with RD were different from the factors underlying numerical problems in children with MD. Children with RD were impaired in phoneme awareness and in RAN but not in simple reaction time (Bonifacci and Snowling, 2008). Furthermore, RD-only children performed more weakly on all tasks tapping verbal number skills, but they had no difficulty with either the non-symbolic number comparison or in locating numbers on the number line. Their weaknesses were particularly marked when numbers had to be transcoded. The MD group, instead, showed deficits in processing numerosities and in all math tasks. The cognitive profile of the RD + MD group did not differ from the single-deficit groups in mathematics and literacy skills but manifested a weaker performance than the RD group in some language measures (phonological awareness and verbal IQ). Importantly, none of the RD-by-MD interactions were significant, demonstrating again that the cognitive deficits of the comorbid group were simply the sum of the deficits of the single-disability group.

In summary, studies on cognitive deficits show that children with math problems have deficits in the processing of numerosity, both non-symbolic and symbolic, whereas children with a reading disorder tend to have deficits in those math-related abilities that require the use of the verbal code. Moreover, the deficits in the comorbid group were mainly found to be an additive effect of the deficits underlying each single disorder, suggesting that each disorder has specific markers that concur in comorbid conditions.

Studies on Shared and Distinct Predictors of Reading and Math in Typical Populations

The main aim in the studies with unselected samples has been to examine the unique effects of a range of underlying cognitive abilities on reading and math. Shared abilities, having an effect on both reading and math, can account for their relation or overlap (e.g., McGrath et al., 2011; Koponen et al., 2020). Cognitive abilities that are specifically related to either math or reading are responsible for their differentiation. From a methodological point of view, all variables in these studies are usually considered to be continuous, and reading and math are simultaneously regressed on all the cognitive abilities.

A range of studies has focused on the shared and specific predictors of math and reading. In some of these studies, reading and math were specified as indicators of a common latent variable. In one of the first of this type of studies, Koponen et al. (2007) showed that letter knowledge and counting ability in kindergarten together with RAN in grade 4 predicted the common variance of reading and math fluency. This study did not include measures of number sense. In a more recent longitudinal study by the same group (see also Koponen et al., 2013, 2020), from first to second grade, the shared variance of reading and math fluency was almost fully explained by serial retrieval fluency, a latent variable which, in their structural equation model, was formed by RAN and counting. Also, phonological awareness, number comparison, and processing speed were predictors of shared reading and math fluency. Surprisingly, Koponen et al. (2020) did not find a specific relation of number sense, number comparison, and number writing with math. In an earlier longitudinal study from first to third grade, Fuchs et al. (2016) also observed that RAN had an effect on both reading and math skills, alongside with attentive behavior, reasoning, and visuospatial memory, albeit through retrieval measures. However, unlike Koponen et al. (2020), Fuchs et al. also found distinct predictors for reading (language, phonological memory, and RAN) and math (attentive behavior, reasoning, and WM). In a cross-sectional study with children from first to third grade, Balhinez and Shaul (2019) showed that the common predictors of reading and math might change over time. In particular, RAN was specific to math in first grade but predicted both reading and math fluency in later grades, whereas WM predicted both abilities in first and second grade but no longer in third grade. Finally, in a recent study, Vanbinst et al. (2020) examined the common and unique predictors of reading and math in kindergarten children. Interestingly, they included a range of cognitive abilities deemed to be specifically related to reading and math. Their results showed that non-symbolic and symbolic magnitude comparisons were unique predictors of math, whereas numeral recognition and phonological awareness were related to both reading and math. Similarly, Child et al. (2019) found in second grade children that numerosity, tested through a non-symbolic magnitude comparison task, was uniquely related to math, whereas phonological awareness and WM were related to both reading and math.

In summary, the studies adopting a continuous approach suggest a number of candidate shared predictors of reading and math, in particular phonological processing, RAN, counting, and WM. In contrast, some studies suggest that symbolic and non-symbolic number processing skills are unique predictors of math skills. However, most of these studies were conducted on young children, mainly from the end of the preschool to the first years of primary school. Little is known on the relations of the cognitive correlates of math with reading in older children who already mastered the first stages of reading and math acquisition.

Present Study

In this study, we aimed to assess the relationship of reading and math with the cognitive skills assumed to underlie the development of math. We hypothesized that tasks related to the number sense domain would be related only to math and not to reading. In addition, we expected that cognitive skills related to the phonological domain (phonological awareness) and domain-general abilities, in particular WM, would be related to both math and reading.

We used both approaches mentioned above to examine these relationships. In the cognitive deficit approach, our main question was whether the effects of math and reading on the various cognitive correlates were additive or, alternatively, whether the combination of skills in reading and math had additional positive or negative effects on the performance of the cognitive skills presumed to underlie the development of math.

Previous studies on the relations of math and reading with underlying cognitive skills have adopted a design with four groups: two single (MD and RD) and a double (MD + RD) deficit group and one group of typically developing children. The analysis of the data in such a design is straightforward: (multivariate) analysis of variance to examine the main effects of RD (yes or no) and MD (yes or no) and the MD-by-RD interaction effect. In principle, this means that each cognitive skill is regressed on three independent variables: the RD factor, the MD factor, and a factor for the RD-by-MD interaction. However, the deficit groups in such a design are the result of cut-offs on math and reading ability, which are generally considered as continuously distributed abilities. Such cut-offs are always somewhat arbitrary, and the outcomes of the study might be affected by the chosen cut-off (e.g., Landerl and Moll, 2010). Moreover, the use of extreme groups requires extensive screening, and it is therefore not very efficient. In this study, we adopted a continuous perspective, but following the approach in previous studies with various deficit groups, we examined the effects of reading and math skills as well as their interaction on the cognitive skills believed to underlie math development.

In the second approach, the cognitive abilities were used to predict math and reading ability. One question here was whether the various cognitive abilities contribute independently to individual differences in math and reading ability. A further question was whether the cognitive abilities are uniquely related to math and reading or related to what math and reading have in common.

The study was conducted with Italian fourth- and fifth-grade children. We administered measures of reading and arithmetic, non-verbal IQ, and various underlying cognitive abilities of arithmetic (counting, number sense, and number system knowledge). We also included measures of WM and phonological ability.

MATERIALS AND METHODS

Participants

The sample consisted of 97 children (mean age = 9.8, *SD* = 0.6, 55.7% females), attending the 4th (57 children) and the 5th (40 children) grades of primary school, selected from five classes.

Participants were selected from schools in suburban areas in the north of Italy. From an initial sample of 126 children, we included in the study only participants with a complete dataset collected (29 children were excluded). All the remaining children met the following inclusion criteria: intellectual functioning within the normal range (>70 standard score), as measured through the matrix task of the Kaufman Brief Intelligence Test (KBIT-2, Kaufman and Kaufman, 2014; Bonifacci and Nori, 2016) and the absence of neurological impairment, sensory deficits, and neurodevelopmental disorders. Families were from a low to high socio-economic status (6.8% low, 23% medium-low, 43.2% medium, 23% medium-high, and 4% high), measured through the Hollingshead Four-Factor Index.

Parents provided written informed consent prior to the experiment. The Ethical Committee of the University of Bologna approved the study design.

Measures

Children were administered tests assessing intellectual functioning, formal math skills, and reading tasks. A detailed description of the task is detailed below.

Non-verbal IQ

Children were administered the Matrices subtest of K-BIT 2 (Kaufman and Kaufman, 2014; Bonifacci and Nori, 2016). The test is a measure of non-verbal IQ. Depending on the age range, children were shown pictures (starting from one up to a matrix of 12 elements) and they were asked to choose among five to six images the one that best fitted with the target picture. For example, on top, there might be a picture of rain associated with an umbrella and the sun associated with a question mark and then pictures below that include gloves, socks, sunglasses, and shoes. The correct answer is that the sun goes with sunglasses. There are different starting points based on the participant's age, and the task stops after four consecutive wrong responses. There are 46 items; a score of 1 is given for each correct answer and the maximum score is 46. Split-half reliability coefficient in developmental age (4–18 years) was 0.87.

Working Memory

Children were administered the digit span task (forward and backward) sequencing test (memory) of the subtest of the WISC-IV (Wechsler, 2003; Italian adaptation, Orsini et al., 2012). Children were required to repeat forward and backward series of numbers of increasing length. The task was stopped after two failures on a series of the same length. The score is the number of digits' series that they can repeat correctly. The maximum score is 16 for the forward and 16 for the backward. The test–retest reliability was 0.79 for digits forwards and 0.74 for digits backward (Orsini et al., 2012). We added the scores of the forward and backward span into one score for WM.

Phonological Awareness

Children were administered the phonological processing, a subtest of the NEPSY-II battery (Korkman et al., 2007). Phonological processing is designed to assess phonological awareness through different tasks, with different starting points according to participants' age. The task starts with syllables blending [Me-la → Mela (apple)], then with recognition of syllables within different words [e.g., which words contain the sound "aci" → "Bacio" (kiss)]. For age 9–11, tasks of elision of syllables within a word (say "stop" but without "p") or by substituting one phoneme in a word with another (say "roba" with "s" instead of "b") were administered. There are 53 items and the maximum score is 53. Reliability scores are not reported in the Italian test manual, but a good internal reliability ($r > 0.80$) and test–retest reliability = 0.78 were reported in the original manual (Brooks et al., 2009).

Mathematical Knowledge

The BDE-2 (Biancardi et al., 2016), developmental dyscalculia battery, was administered. The BDE-2 is composed of nine tests plus three optional tests (of which only "repetition of numbers" was administered) for the fourth and fifth primary classes. We performed Cronbach's alpha and factorial analysis to test the internal consistency, and for the purpose of the present study, tasks were grouped in four main areas: counting, number sense knowledge, number system knowledge, and math.

Counting

In this task, the examiner asks the children to count aloud from 80 to 140 and records the time. Then, the experimenter asks the child to count backward from 140. The time given to do so is the time that the child needed to count forward from 80 up to 140. The score is the total of numbers the child said correctly backward within the allotted time.

Number Sense

This was evaluated using two different subtests: triplets and insertion. On the triplet task, children have 2 min to indicate on a paper record form the largest number in 18 sets of three numbers (e.g., 30,100, 31,000, and 30,009). The score is the total number of answers they give correctly in 2 min. The maximum score is 18. On the insertion task, children have 2 min to place a target number at the correct place in a series of three numbers arranged in ascending order. For example, they have to put on a paper record form the number 10 in the correct position between the numbers 5, 8, and 15. The number of items is 18. The score is the total number of correct items done in 2 min. The maximum score is 18. Cronbach's alpha based on the two scales was 0.64.

Number System Knowledge

This task was evaluated using three different subtests: number reading, number writing, and repetition of number. In the number reading task children have 1 min to read aloud a list of numbers of increasing difficulty (three to six digits). The score is the total number of Digits they read correctly. Number writing and repetition give two scores. First, the child has to repeat the number (repetition of numbers), and then, the child has to write the number (number writing). There are 18 numbers, among which there are numbers with the 0 (e.g., 807 or 5,010) and numbers with 4, 5, and 6 digits (e.g., 27,463 or 346,879). A score of 1 is given for each number that the child repeats (repetition score) or writes (writing score) correctly. The maximum score for both scales is 18. Each of the three scores was converted to a z-score. Then, the three scores were added to obtain one score for number system knowledge. Cronbach's alpha based on the three scales was 0.78.

Math and Reading Ability

Standard tests for math and reading fluency were administered.

Math

This task was evaluated using four subtests of the BDE-2 (Biancardi et al., 2016) referred to the calculation ability and speed: multiplication, mental calculation, quick calculation, and approximate calculation. Multiplication—the examiner reads 18 items in random order (e.g., 3×4, 7×9...). Children have 3 s to give an answer to each operation. The score is the total number of answers they give correctly within 3 s. The maximum score is 18. Mental calculation—the examiner reads 18 operations (nine additions and nine subtractions), and children have 30 s to answer each operation with the correct result. The score is the total of answers they give correctly. The maximum score is 18. Quick calculation—children have 2 min to write the correct results of as many mixed operations as possible (additions, subtractions, multiplications, and divisions) up to a maximum of 40. The score is the total of answers they give correctly in 2 min. Approximate calculation—children have 2 min to indicate the correct result of 18 operations, indicating it from the four options. For example, the operation is 75:5 and they have to choose between 80, 375, 15, and 5. The score is the total of answers they give correctly in 2 min. The maximum score is 18. Cronbach's alpha of the sum score, calculated over the four tests, was 0.79.

Reading

The reading materials were two texts taken from the MT reading test, the Italian battery used to assess text reading speed and accuracy (Cornoldi et al., 2017). Children were required to read as fast and accurate as possible, and reading comprehension was not tested. The texts were different for the two different grades of primary school. The text used to assess children from the fourth grade of elementary school has 141 words, while that for children from the fifth grade has 236 words. For the purpose of the present study, we calculated reading fluency, that is, the number of words read aloud correctly in 1 min. Then, we compute the z-score within each grade using the reading fluency in order to have a unique score of this variable by grade. The test manual reports reliability coefficients between 0.75 and 0.87 for accuracy scores and between 0.94 and 0.97 for reading speed.

RESULTS

Descriptive Statistics

We considered scores with a mean of more than 3.3 standard deviations from the grade mean as outliers. There were eight of such scores, three in fourth and five in fifth grade. Each outlier score belonged to a different child. There were three children with very low scores on number sense and two on number system knowledge. Three children had very high scores on math or reading fluency. All outliers were coded as missing.

Descriptive statistics for the children's variables, separated by grade, are reported in **Table 1**.

Next, we computed the correlations among the variables. To control for grade, we computed within-grade standardized scores. Then, the eight missing scores, less than 1% of the total number of data points, were estimated using the EM method in SPSS. Correlations among the variables for the full sample, controlling for grade, are reported in **Table 2**.

As expected, the correlation between phonological awareness and WM was substantial [$r(95) = 0.521$, $p < 0.01$]. Also, a high correlation was found between counting and number system knowledge [$r(95) = 0.545$, $p < 0.01$]. Of most interest were the correlations of the cognitive skills with math and reading. As expected, the relations of math with its underlying cognitive skills, counting, number sense, and number system knowledge, were highly significant [all $r(95) > 0.5$, $p < 0.01$). We found moderate relations of reading with counting [$r(95) = 0.418$, $p < 0.01$] and number system knowledge [$r(95) = 0.315$, $p < 0.05$], whereas its correlation with number sense was not significant.

Prediction of Cognitive Abilities From Math and Reading

In this approach, we conducted regression analyses on the within-grade standardized scores to examine the unique contributions of arithmetic and reading ability, as well as their interaction, in the prediction of phonological awareness, WM, and the cognitive correlates of math. Note that in these analyses, reading, math, and the interaction of reading and math were the independent variables, although this does not imply that they act causally. In these analyses, we controlled for IQ. The results of the analyses are presented in **Table 3**.

We found an effect of math on phonological awareness. The effect of reading just missed significance ($p = 0.085$). We also found an interaction effect of math by reading. For a better understanding of the interaction effect, we formed groups of lower (score below the mean) and higher (score above the mean) performing children in math and reading. Cross classification of math (below or above average) and reading (below or above average) resulted in four groups. The mean scores of these groups are displayed in **Figure 1**.

The figure clearly shows that the lower performing children on both math and reading obtained a disproportionately lower score in phonological awareness.

Unexpectedly, we found no significant effects of reading or math on WM. Separate analyses for forward and backward memory span gave similar results.

TABLE 1 | Descriptive statistics for grade 4 and grade 5.

		Grade 4				Grade 5			
	Max	Mean	SD	Skew	Kurt	Mean	SD	Skew	Kurt
Age (years)		9.52	0.48	0.07	−2.06	10.24	0.45	0.47	0.97
General cognitive ability (*n* correct items)	46	28.61	6.72	−0.03	0.50	31.48	6.63	−0.59	−0.62
Phonological awareness (*n* correct items)	53	46.44	3.19	−0.58	−0.01	47.65	3.28	−0.70	−0.28
Working memory (*n* correct items)	32	14.00	1.91	0.53	−0.26	15.03	2.79	0.31	−0.51
Counting	[a]	−0.27	1.69	0.26	0.81	0.38	2.02	−0.02	−0.47
Number sense	[a]	−0.07	1.37	−0.86	0.68	0.57	1.22	−1.04	0.68
Number system knowledge	[a]	−0.81	2.12	−0.53	0.05	1.57	1.97	−1.42	1.98
Math (*n* correct items)	94	50.17	12.21	0.80	1.71	67.97	14.45	−0.44	−1.00
Reading (words per minute)	141/236	85.34	21.16	0.62	−0.21	114.17	28.43	−0.27	0.45

Means for reading fluency cannot be compared between grades because different (grade-appropriate) texts were used to assess words read per minute.
[a]*z-scores over grades.*

TABLE 2 | Pooled within-grade correlations among the variables.

Measure	1	2	3	4	5	6	7
General cognitive ability							
Phonological awareness	0.310**						
Working memory	0.229*	0.521**					
Counting	0.268**	0.431**	0.193				
Number sense	0.402**	0.269*	0.174	0.276**			
Number system knowledge	0.241*	0.547**	0.353**	0.545**	0.310**		
Math	0.322**	0.459**	0.183	0.622**	0.515**	0.629**	
Reading	0.149	0.304*	0.104	0.418**	0.193	0.315*	0.310*

*$p < 0.01$. **$p < 0.001$.

The results with respect to the math-related cognitive skills were clear. Math was uniquely related to number sense and number system knowledge, whereas reading did not make a significant contribution. For counting, however, both math and reading made an independent contribution. The effect of math was about twice as large as the effect for reading. There were no math-by-reading interactions on the math-related cognitive skills.

Prediction of Math and Reading by the Cognitive Abilities

In this approach, we also used the within-grade standardized scores, but now, we regressed math and reading ability on the cognitive abilities. In these analyses, we also controlled for IQ but omitted WM as we did not find any relationships with math and reading in the previous analyses. To examine the specific contributions of the cognitive abilities, we also conducted a set of regression analyses in which we controlled for reading ability in predicting math and for math in predicting reading. The results are reported in **Table 4**.

The main results of these analyses were that counting made a specific contribution to both reading and math. Number sense and number system knowledge were specifically related to math. In addition to our previous analysis in which each cognitive skill was regressed on reading and math (see **Table 3**), this approach revealed that counting, number sense, and number system knowledge made independent, that is, unique contributions to math. These analyses also show that phonological awareness did not describe independent variance in reading and math, although its correlation with both academic abilities was significant (see **Table 2**).

TABLE 3 | Results of the regression analyses predicting the cognitive abilities from math, reading, and the interaction of math and reading: standardized regression coefficients and R^2.

Predictor	PA	WM	Count	NS	NSK
IQ	0.189*	0.195+	0.054	0.263**	0.041
Math	0.365**	0.116	0.520**	0.423**	0.582**
Reading	0.161+	0.038	0.249**	0.023	0.128
Math by reading	−0.176*	−0.073	0.076	0.000	−0.056
R^2	0.297	−0.073	0.452	0.328	0.416

PA, phonological awareness; WM, working memory; Count, counting; NS, number sense; NSK, number system knowledge.
+$p < 0.10$. *$p < 0.05$. **$p < 0.01$.

DISCUSSION

We examined the relationship of various proximal markers of math development with the common and unique aspects of math and reading. We also investigated the relations of math and reading with a domain-general ability, WM, and phonological awareness, a cognitive skill generally associated with reading development (e.g., Landerl et al., 2019). Unlike previous studies, we used two approaches to elucidate these relationships. The first is the deficit approach but here with math and reading as continuous predictors. Although in the present study we actually did not consider children with deficits, we kept the same term in continuity with previous research. In the other approach, regularly used in unselected samples, the cognitive abilities were taken to predict math and reading.

We considered counting, number sense, and number system knowledge as cognitive markers of math. As expected, all markers were moderately to highly related to math ability. Two math-related cognitive skills were also related to reading, that is, counting and number system knowledge, although their relationship with reading was lower than with math.

Next, we conducted two types of regression analyses. In the first type of analysis, the "deficit" approach, each cognitive skill was regressed on math and reading as well as their interaction. The outcomes denote the unique relations of math and reading with each math-related cognitive skill. We found here that the relation of number system knowledge with reading was no longer significant when math was included in the regression model. Thus, number system knowledge and number sense both had a specific relation with math, but not with reading. In contrast, counting had a unique relation with both reading and math. Finally, in the analyses on the cognitive markers of math, none of the math-by-reading interactions were significant. Thus, our continuous approach in this respect led essentially to the same results as studies that used a categorical approach, including groups that were weak in math, reading, or both (e.g., Moll et al., 2015).

In the second type of analysis, reading and math were regressed on the cognitive markers of math together with

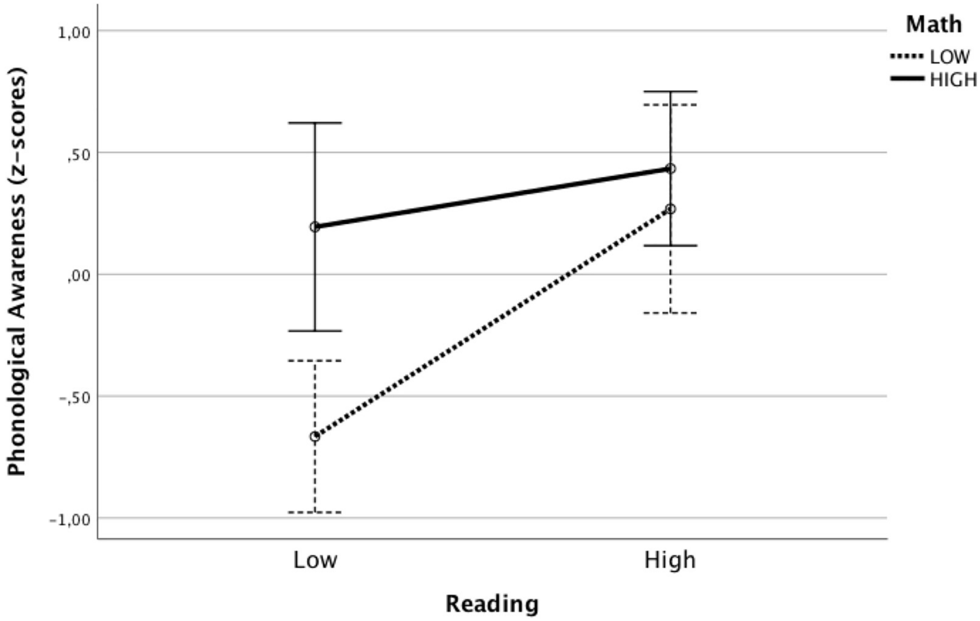

FIGURE 1 | Interaction of math and reading for groups of lower and higher scoring children. Error bars: 95% confidence interval (CI).

phonological awareness. The results here showed that all cognitive markers were independently related to math, even when reading was controlled. Counting was the only math-related skill that was also associated with reading. In all, both types of analyses clearly suggest that math is specifically related to counting, number sense, and number system knowledge. The second set of analyses adds here that each of these cognitive skills is independently related to math. Counting was found to be specifically related to both math and reading.

The specific relation of number sense to math seems understandable and aligns with previous findings in younger children (Child et al., 2019; Vanbinst et al., 2020). Following the Triple Code Model (Dehaene, 1992, 1997), number sense does not involve any verbal code and heavily taps numerosity and, in this study, particularly the representation of the number line. The finding seems in accordance with proposals to regard number sense as the prime characteristic of a math disorder (e.g., Piazza et al., 2010). Some authors suggested that number system knowledge might be a meaningful mediator of the relationship between approximate number system (ANS) skills and math competence (van Marle et al., 2014; Chu et al., 2015). Although it requires verbal skills, it might be cognitively conceptualized as a bridge function that, starting from basic ANS skills, allows to achieve higher order math competencies such as representing large quantities precisely and also facilitating the acquisition and storage of complex relations between numbers, more efficiently and precisely than does the ANS alone (Peng et al., 2017). However, note that other studies showed the selective contribution of transcoding to math performance over and above ANS skills (Göbel et al., 2014; Habermann et al., 2020). As expected, counting was specifically related to both math and reading. This finding is in line with the results reported in previous studies (e.g., Moll et al., 2015; Koponen et al., 2018). Counting requires, as reading, the activation of verbal labels and, as reading, is related to phonological awareness.

TABLE 4 | Results of regression analyses predicting reading and math from underlying cognitive abilities: standardized regression coefficients and R^2.

	Math	Math	Reading	Reading
Reading/math	–	−0.010	–	−0.020
IQ	0.017	0.017	−0.012	−0.012
PA	0.053	0.055	0.122	0.123
Count	0.337**	0.340**	0.320*	0.327*
NS	0.302**	0.302**	0.059	0.065
NSK	0.319**	0.320**	0.059	0.065
R^2	0.595	0.596	0.199	0.199

*PA, phonological awareness; Count, counting; NS, number sense; NSK, number system knowledge. *p < 0.05. **p < 0.01.*

The results with respect to phonological awareness were less clear. As in previous studies, both math and reading, although the latter just missed significance, contributed to phonological awareness (Child et al., 2019). But, in this study, we found an interaction effect of math and reading. The effect of math became stronger when reading abilities decreased. In the group of relatively weak readers (below the mean in the sample), those who also had relatively low math skills had the worst performance in phonological awareness. Children with weak reading skills and good math skills had relatively spared phonological skills. These results are in line with previous findings that phonological processes might be important in some aspects of arithmetic skills and, particularly, for the comorbidity of math and reading disorders (Cirino et al., 2015; Slot et al., 2016). In the present study, phonological awareness might be viewed as a marker of the interaction of math and reading when these abilities are observed in a dimensional and continuous perspective. However, in the other type of regression analyses, phonological awareness did not contribute in the prediction of reading or math (see **Table 4**). Especially, the relation with math was fully captured by the math-specific cognitive markers, which also shared variance with phonological awareness. These results suggest that the role of phonological awareness may fade when stronger predictors of reading and math are considered in the regression model. Similarly, Koponen et al. (2020) found that the contribution of PA to the shared variance in reading and math was only very moderate; when RAN and counting were included in the prediction, they accounted for a higher amount of variance. Overall, however, it was striking that phonological awareness was hardly related to reading and even higher with math. A difference with earlier studies is that the current study involved older children. Especially in a transparent orthography like Italian, phonological awareness seems less relevant for reading in older children and thereby the relationship between these abilities might decrease (e.g., Landerl and Wimmer, 2000; de Jong and Van der Leij, 2003; Brizzolara et al., 2006). Another reason for the rather low relation between phonological awareness and reading could be that the measure of reading in this study concerned text reading and not the reading of a list of unrelated words. Finally, it might be that the phonological awareness task used was not sufficiently hard, as children's performance was generally high (88% and 90% correct in grades 4 and 5, respectively), although not at ceiling, suggesting that there was relatively little variation on this task.

Somewhat to our surprise, we did not find relations of math and reading with WM. Also, relations were absent when memory span forward, usually more related to reading, and memory span backward, involving more executive functioning, were considered separately. It is not entirely clear why effects of reading and math on WM were not found. Possibly, the particular tasks used to assess math, mainly very simple calculations, and reading, texts, did not very heavily depend on WM. The absence of a relationship between WM and reading might be interpreted in the light of the debate as to whether phonological WM is a direct predictor of reading skills or, rather, involves access to representations that underlie phonological awareness tasks (Melby-Lervåg et al., 2012). Concerning math, many studies evidenced a primary role of the visuo-spatial WM component (Simmons et al., 2012; Zhang and Lin, 2015), and therefore, verbal WM might play a minor role. Furthermore, WM tasks and domain-general factors seem to be more strongly related to complex math outcomes such as problem solving tasks (Swanson and Beebe-Frankenberger, 2004; Fuchs et al., 2008, 2010) and procedural computations (Fuchs et al., 2010). These results are in line with previous evidence suggesting that domain-general skills might act indirectly via more proximal predictors (Cirino et al., 2018; Zoccolotti et al., 2020).

The present study has some limitations that could be addressed in future investigations. First, a larger sample size would have strengthened the generalizability of the findings. More specific limitations are referred to the tasks adopted in the study. The task used to assess ANS skills are not standard ANS tasks as they involve, at least in part, transcoding skills and number ordering. Symbolic order processing is related to a certain degree to number sense (magnitude processing) but does not completely overlap with it (Lyons et al., 2014; Sasanguie et al., 2017; Sasanguie and Vos, 2018). We also have to acknowledge that we did not include rapid automatized naming (RAN), which is known to be an important common predictor of reading and math. However, our main interest was in the relation of reading ability to the cognitive markers of math as derived from the Triple Code Model. There is already an abundant number of studies to show the relation of RAN to both math and reading. Finally, although we tested regression models in order to understand different patterns of predictors, we cannot infer causal relationships; longitudinal studies would be necessary at this regard.

In sum, we used two approaches to examine the relationship of reading ability with the main cognitive markers of math. The main findings were that predicting each cognitive marker from reading and math ability, we found that number sense and number system knowledge were specifically related to math, whereas counting was related to both math and reading. There were no math-by-reading interactions. In the second approach, all markers of math were used simultaneously to predict math and reading, respectively. The results confirmed the previous results on the relations of the various markers to reading and math, but these analyses also showed that counting, number sense, and number system knowledge independently contributed to individual differences in math.

A potential implication of this study for research is that the "deficit" approach can be adopted with the use of continuous indicators of individual differences in math and reading. The approach is fully compatible with the use of deficit groups, and the results of the present study seem to be in line with those of previous studies focusing on children with math and/or reading disorders. Moreover, from an educational perspective, a deficit approach might sometimes be too strict. Children with low reading skills, although not in the clinical range, might encounter subtle weaknesses also in the math domain and the other way around. A more comprehensive awareness of shared mechanisms underlying learning skills would allow to better promote scholastic well-being and achievements.

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 Bioethics Commmitte, University of Bologna. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

LB carried out the study, collected and analyzed data, and wrote a preliminary version of the manuscript. PJ designed and supervised manuscript structure. PJ and LB performed statistical analysis. PJ and PB revised and significantly contributed to the final version of the manuscript. All authors discussed the results and contributed to the final manuscript.

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Two Dyscalculia Subtypes With Similar, Low Comorbidity Profiles: A Mixture Model Analysis

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Several studies have aimed to identify subtypes of dyscalculia. In many of these studies, either pre-defined groups (e.g., children with reading and mathematical difficulties vs. children with isolated mathematical difficulties) were analyzed regarding their cognitive profiles (top-down approach), or clusters of children with dyscalculia (CwD) were identified based on a narrow range of cognitive and mathematical skills (data-driven or bottom-up approach). However, it has remained difficult to establish robust subtypes of dyscalculia across studies. Against this background, we conducted a mixture model analysis in order to explore and identify subtypes of dyscalculia based on a broad range of variables (intelligence, reading fluency, working memory, attention, and various mathematical skills). The total sample comprised 174 elementary school CwD (IQ > 70; mathematical abilities: percentile rank <10), which consisted of two subsamples. The first subsample was based on a diagnostic test focusing on calculation (HRT 1–4; n = 71; 46 girls, 25 boys; age: M = 9.28 years, SD = 0.94) whereas the second subsample was based on a diagnostic test with a strong focus on basic numerical capacities (ZAREKI-R; n = 103; 78 girls, 25 boys; age: M = 8.94 years, SD = 1.05). Results provided convincing evidence for the existence of two subtypes in CwD: A slightly impaired subtype and a strongly impaired subtype. Subtypes differed most strongly regarding mathematical abilities, but the analyses suggest that differences in attention could also be a key factor. Therefore, comorbid attention difficulties seem to be a relevant factor that needs to be considered when establishing subtypes. Substantial intelligence differences between dyscalculia subtypes could not be found. Differences in working memory and reading fluency were negligible. Overall, the results seemed to be robust regardless of the diagnostic test used for assessing dyscalculia. When planning interventions for CwD, the existence of a subtype with substantial attention problems should be kept in mind.

Keywords: subtypes, mathematical skills, mathematical abilities, mixture model analysis, comorbidity, dyscalculia, developmental dyscalculia

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INTRODUCTION

Mathematical skills are important for a successful biography: For example, there is a strong connection between mathematical skills in childhood and adult socioeconomic status (Ritchie and Bates, 2013). Therefore, children with difficulties in mathematics face the risk of serious consequences. Dyscalculia is defined as an impairment of basic arithmetic skills (addition, subtraction, multiplication, division), which cannot solely be explained by a general intelligence deficit nor by inadequate learning environment (ICD-10: Dilling et al., 1993). In the ICD-11, (developmental) dyscalculia is described as a developmental learning disorder that is characterized by a lack of "skills related to mathematics or arithmetic, such as number sense, memorization of number facts, accurate calculation, fluent calculation, and accurate mathematic reasoning" (World Health Organization, 2020). In any case, mathematical skills and mastery of mathematical procedures, along with mathematical fact retrieval, are strongly impaired in children with dyscalculia (CwD) (Geary et al., 2012; Kuhn et al., 2013; Mazzocco et al., 2013). Landerl et al. (2004, p. 99) "conclude that dyscalculia is the result of specific disabilities in basic numerical processing rather than the consequence of deficits in other cognitive abilities." *Basic numerical processing* (BNP) has also been referred to as core number competencies and is assessed using simple tasks such as dot enumeration and comparison of single digits (Reeve et al., 2012). In addition, there are more complex mathematical precursor skills (*complex number processing*, CNP): For example, mental number line tasks, which require participants to locate a given number on a number line, or the ability to convert auditorily presented numbers into written Arabic symbols (transcoding; Nuerk et al., 2006; Kuhn et al., 2013, 2017). Deficits in the processing of numbers and/or magnitudes are discussed as the main causes of dyscalculia (Butterworth, 2005; Noël and Rousselle, 2011; Moll et al., 2015). Overall, different mathematical skills can be impaired in CwD: Individual profiles and therefore problem areas and needs can vary substantially across individuals (Haberstroh and Schulte-Körne, 2019). Therefore, different subtypes of CwD might exist which display different profiles concerning BNP, CNP, and calculation skills.

In fact, arithmetic errors of CwD vary with their cognitive profile (Rourke, 1993, p. 218). Because error patterns, at least partially, reflect strategy use or selective deficits and thus can be relevant starting points for interventions, several studies have aimed to identify subtypes (or subgroups) of CwD (e.g., Geary, 1993; Von Aster, 2000; Bartelet et al., 2014; Skagerlund and Träff, 2016). When trying to identify subgroups of CwD, a broad range of cognitive abilities has to be taken into account because mathematical skills rely on many different cognitive abilities.

Although some etiological views (e.g., Landerl et al., 2004) focus on domain-specific causes of dyscalculia, mathematical deficits in the heterogeneous population of CwD can be based on additional, domain-general causes. For example, the mathematical deficits of some CwD seem to be associated with impairments in verbal short-term memory (Szücs, 2016). Further, it is widely known that a large number of children with mathematical deficits also display impairments in reading or attention (Gross-Tsur et al., 1996; Willburger et al., 2008; Haberstroh and Schulte-Körne, 2019). In addition, many CwD display difficulties in working memory (e.g., Keeler and Swanson, 2001; Schuchardt et al., 2008; Mähler and Schuchardt, 2011). According to Baddeley's (1992) framework, on which the majority of working memory assessments are based, working memory is divided into three structural parts. One part (the central executive) coordinates the storage and manipulation of the information, whereas two other parts (slave systems) are responsible for storing (1) auditory (phonological loop) or (2) visuo-spatial information (visuo-spatial sketchpad; Baddeley, 1992; Cragg et al., 2017). Many studies report that CwD display deficits in the visuo-spatial sketchpad (e.g., Schuchardt et al., 2008). However, not all studies replicated that CwD have significant difficulties in working memory (e.g., Landerl et al., 2009; Kißler et al., 2021). Specifically, Landerl et al. (2009) did not find significant deficits regarding block tapping tasks (*Corsi block* tapping task: e.g., Berch et al., 1998) when comparing CwD with a control group. However, children with dyscalculia and comorbid reading difficulties performed significantly lower than a control group. Hence, stronger or more diverse working memory difficulties could be linked to comorbidity, i.e., to different subtypes of CwD with or without comorbid impairments. Correlative findings corroborate this assumption (e.g., Peng et al., 2016). In sum, there is some evidence for different subtypes of CwD that are characterized by varying deficits in working memory.

As mentioned earlier, attention problems and reading difficulties are often associated with dyscalculia, but not all CwD seem to have these problems (e.g., Gross-Tsur et al., 1996; Haberstroh and Schulte-Körne, 2019). Correspondingly, attention deficits and dyslexia could also be factors that need to be considered when discussing dyscalculia subtypes. In the past, it was common to differentiate between children who showed a discrepancy between general intelligence and individual calculation or reading performance, and children who did not show such an intelligence discrepancy (e.g., Dilling et al., 1993). Even if the intelligence discrepancy criterion is no longer recommended for diagnosing CwD because of methodological and content-related reasons (e.g., Ehlert et al., 2012; Kuhn et al., 2013), intelligence should still be taken into account as a further factor in a holistic typification of CwD.

After describing cognitive features (attention, intelligence, reading skills, working memory, and different arithmetic abilities and skills as BNP, CNP, and calculation) that are often associated with dyscalculia and that may vary across subtypes of CwD, the next part of this introduction focuses on different methodological approaches and conclusions of studies conducted in this field. In order to identify subtypes of dyscalculia, two different approaches have been pursued: Some studies analyzed predefined subtypes based on specific theoretical expectations, whereas others used a data-driven approach and therefore tended to be more exploratory.

Some of the first studies analyzing predefined subtypes were conducted by Rourke and his research team (e.g., Ozols and Rourke, 1988; Rourke, 1993). These authors divided CwD into three groups: (1) children with problems in arithmetic, reading and spelling, (2) children with deficient reading and spelling abilities who displayed higher (albeit still deficient) arithmetic skills, and (3) children with average or above reading and spelling performance, but with mathematical problems. Arithmetic errors of these groups varied in a qualitative way: For example, while children in group 2 mostly made mistakes that could be related to their reading problems, children in group 3 showed a broad range of mechanical arithmetic errors (Rourke, 1993). Children in group 3 had problems to calculate correctly because of their poor handwriting; they misread the mathematical signs, they performed arithmetic operations incorrectly and they had problems to access the needed calculation rules from long-term memory (Rourke, 1993). Thus, this line of research provided evidence that subtypes of children with problems in arithmetic differ depending on their reading skills. This finding underscores the importance of reading skills when describing subtypes of dyscalculia.

In an early review, Geary (1993) also described three different subtypes of CwD. In contrast to Rourke (1993), Geary (1993) did not focus on the comorbidity of dyscalculia and reading/spelling disorder: One of these subtypes displayed "difficulties in arithmetic fact retrieval and problems in the memorization of arithmetic tables even with extensive drilling" (Geary, 1993, p. 357). Furthermore, he described a second subtype with "difficulties in the use of arithmetical procedures" (p. 357). The third subtype described by Geary (1993) had visuospatial difficulties and consequently, this subtype had problems with the processing of numerical information. The subtypes suggested by Geary (1993) relate to difficulties in memory, visuospatial skills, and procedural calculation, thus focusing more strongly on general cognitive abilities when identifying subtypes of dyscalculia.

In a more recent study, Skagerlund and Träff (2016) divided CwD into two subgroups (based on theoretical assumptions) and analyzed them by focusing on different mathematical abilities. These authors described a subtype (*general dyscalculia subtype*) with problems in the innate approximate number system (ANS). In addition, they postulated and found a second subtype with *arithmetic fact dyscalculia*. The latter subtype showed no difficulties in non-symbolic number processing but had difficulties in symbolic number processing. Skagerlund and Träff (2016) concluded that this second subtype is characterized by suffering from a deficit in accessing information from symbols which has been referred to as *access deficit* in the literature (Rousselle and Noël, 2007). In summary, the results of Geary (1993) and Skagerlund and Träff (2016) suggest the existence of subtypes in CwD that differ in their profiles of numerical and arithmetic skills.

Next, studies that used data-driven methods to identify subtypes of dyscalculia are presented. In contrast to the studies analyzing predefined subtypes of dyscalculia, Von Aster (2000) used a data-driven approach (cluster analysis) for subtyping 93 children with poor achievement in school mathematics. In line with the results reported by Rourke (1993), Von Aster (2000) characterized a *verbal subtype* with language-based problems. Von Aster (2000) differentiated this subtype from two other subtypes specific to his study: An *Arabic subtype* with difficulties in understanding and using the Arabic notation system as well as a *pervasive subtype* with strong problems in most mathematical subareas (e.g., a lack of basic numerosity and number concepts).

Similar to Von Aster (2000), Bartelet et al. (2014) also used a data-driven approach. Bartelet et al. (2014) focused on various variables that represent specific cognitive abilities and skills: Spatial short-term working memory, verbal short-term working memory, intelligence, Arabic numeral knowledge, number line estimation, approximate numerical knowledge (e.g., dot comparison task), and counting. Bartelet et al. (2014) identified and described six subtypes of dyscalculia with different cognitive profiles: (1) the *weak mental number line subtype* with a low performance in number line tasks but a high performance in approximate numerical knowledge and Arabic numeral knowledge, (2) the *weak ANS subtype* with problems in approximate numerical knowledge and number line tasks, but with a strong performance in spatial short-term working memory and with a higher IQ in comparison to other subtypes—the characteristics of this subtype resemble the general dyscalculia subtype described by Skagerlund and Träff (2016), (3) the *spatial difficulties subtype* with particular difficulties in spatial short-term working memory and in approximate numerical knowledge, but also difficulties in verbal short-term working memory and number line tasks, (4) the *access deficit subtype* with problems in counting and Arabic numerical knowledge, (5) the *no numerical cognitive deficit subtype* with no deficits in any area and very high verbal short-term working memory, and (6) the *garden variety subtype* with many smaller deficits in different areas, a high performance in number line tasks and a lower IQ. These results suggest a large (and almost confusing) variety of subtypes. It is also noticeable that the characteristics of some subtypes overlap, and that IQ seems to be an important domain-general factor which helps to characterize different subtypes.

In another data-driven subtyping study, Chan and Wong (2020) used a cluster analysis for subtyping CwD over the first 2 years of elementary school to compare the cognitive profiles of the identified subgroups. These authors assessed a broader range of variables compared to many prior studies (working memory and mathematical abilities): Backward digit span, backward block span, the acuity of the ANS, number comparison, number line estimation, number fact retrieval, accuracy in calculation, strategic counting, arithmetic word problems, and a general learning achievement test in mathematics (based on the curriculum of Hong Kong). Moreover, dot enumeration tasks were used to assess both the ability to subitize (1–3 dots) and to enumerate (4–9 dots). Chan and Wong (2020) described five different subtypes of CwD: (1) the *numerosity coding deficit subtype*, (2) the *symbolic deficit subtype*, (3) the *working memory deficit subtype*, (4) the *number sense deficit subtype,* and (5) the *mild difficulty subtype* with almost no deficits in the cognitive areas examined but with some problems in mathematics. The subtypes presented by Chan and Wong (2020) seem to differ from the subtypes described by Bartelet et al. (2014), with some overlaps. The *mild difficulty group* shares some features with the *garden variety subtype* identified by Bartelet et al. (2014), for example—but they are far from being identical. Both studies have in common that they present at least one subtype that is characterized by substantial deficits in working memory.

A recent data-driven study of Huijsmans et al. (2020) aimed to identify different cognitive profiles of 281 fourth graders by examining basic arithmetic and advanced mathematic skills. In contrast to Bartelet et al. (2014) and Chan and Wong (2020), this study did not exclusively focus on CwD. Huijsmans et al. (2020) found four different profiles. Three of those profiles did not seem to have significant mathematical difficulties (a *high-achieving profile*, an *average profile,* and a *divergent profile*). Another profile seemed to have mathematical difficulties in some way (a *low-achieving profile*), but none of the detected profiles met the criteria for dyscalculia. No subgroups of CwD were found. Huijsmans et al. (2020) concluded that the group of CwD could be "too heterogeneous to distinguish subgroups" (p. 9).

The assumption that there are many and very heterogeneous cognitive profiles in CwD (Huijsmans et al., 2020) is in line with the fact that other studies (Bartelet et al., 2014; Chan and Wong, 2020) found a relatively large number of subtypes in CwD. In summary, Bartelet et al. (2014) and Chan and Wong (2020) assessed children's mathematical performance and their working memory capacity, but only Bartelet et al. (2014) took intelligence into account. In contrast to Rourke (1993), data-driven approaches often neglected reading deficits when subtyping CwD. Therefore, important information for subtyping CwD may have been overlooked. However, as mentioned before, CwD have difficulties in many cognitive areas. The studies by Bartelet et al. (2014) and Chan and Wong (2020) present different typologies, and these differences could be due to the fact that the cognitive profiles of CwD were not considered exhaustively. To systematically overcome heterogeneous, and therefore inconclusive, evidence, it is necessary to consider a broader range of variables and cognitive areas when following data-driven approaches to subtype CwD. Therefore, the present study includes attention, reading fluency, and intelligence beyond working memory and mathematical skills.

It is important to bear in mind that different tests and assessments are used to assess dyscalculia. This may affect results because different groups of children are identified as dyscalculic, depending on the structure of the test used. There is no "gold standard" test for dyscalculia; instead, instruments and diagnostic thresholds depend on (dynamic) consent. Hence, in order to provide more robust results, two different assessments of dyscalculia were used in this study, with an emphasis on different aspects of mathematical difficulties. The first assessment, ZAREKI-R (von Aster et al., 2006), mainly focuses on basic numerical processing (such as the comparison of quantities) and complex number processing (such as number line estimation, or transcoding). In contrast, HRT 1–4 (Haffner et al., 2005) mainly focuses on calculation and arithmetic (e.g., basic arithmetic operations), i.e., on a higher level of mathematical skills. Both tests include addition and subtraction tasks, but only the HRT 1–4 includes tasks where children have to divide and multiply. While ZAREKI-R tests mathematical precursor abilities such as number line estimation, HRT 1–4 includes tasks on visual/geometrical skills such as lengths estimation. In this study, therefore, two different dyscalculia assessments in two different samples of CwD were used to assess the robustness of dyscalculia subtypes across measurement instruments.

To summarize, several studies have assessed subtypes of dyscalculia. However, results vary across studies, possibly due to the narrow range of skills assessed and different diagnostic tests used. The present study pursues the following questions: (1) Which subtypes in CwD can be identified by taking a broad range of mathematical skills (BNP, CNP, and calculation) and more general cognitive skills (attention, intelligence, reading skills, working memory) into account? (2) Is the identified pattern of dyscalculia subtypes robust? (3) Are there different subtypes in CwD that are related to specific comorbidity profiles?

In this study, the research questions outlined above were not analyzed assuming predefined (comorbid) groups. Rather, this study analyzed CwD (percentile rank <10 in standardized math assessments) and used a data-driven approach to identify subtypes. In summary, an exploratory approach was used to check whether subtypes of CwD which are characterized by comorbid cognitive profiles could be identified. To take the high comorbidity of dyscalculia and reading disorder into account, we also checked whether children with a comorbid reading disorder could be assigned to a specific subtype of CwD.

MATERIALS AND METHODS

Sample

The total sample consisted of 174 CwD (mathematical abilities: percentile rank (PR) < 10; IQ > 70; level of education: grade 2, 3, and 4). The sample was part of a large-scale investigation of mathematical skills comprising 1,211 elementary school children. Data were collected in two separate contexts with partly different tests: 103 children (age: $M = 8.94$ years, $SD = 1.05$; 78 girls, 25 boys; grade 2: 34 students, grade 3: 48 students, grade 4: 21 students) were identified with a math test focusing on basic numerical abilities (ZAREKI-R; von Aster et al., 2006; in the following: ZAREKI-R sample). This subsample was recruited based on newspaper articles addressing families with (suspected) CwD. Between fall 2012 and fall 2013, these participants were invited to university, where testing took place in individual settings on two different days. A second sample of 71 children (age: $M = 9.28$ years, $SD = 0.94$; 46 girls, 25 boys; grade 2: 17 students, grade 3: 35 students, grade 4: 19 students) were classified with a math test mainly focusing on arithmetic skills (HRT 1–4; Haffner et al., 2005; in the following: HRT sample), which was administered in group settings taking 3 school hours in spring to fall 2013. The study was approved by the local ethics committee. To identify children with reading disorder (PR < 10), reading fluency was measured using the *Salzburger Lese-Screening* (SLS 1–4; Mayringer and Wimmer, 2003). The ZAREKI-R sample included 26 CwD with comorbid reading disorder, the HRT sample included 41 CwD with comorbid reading disorder.

Tests

Diagnostic Tests: HRT 1–4 and ZAREKI-R

ZAREKI-R

The Neuropsychological Test Battery for Number Processing and Calculation in Children (*Neuropsychologische Testbatterie für Zahlenverarbeitung, und Rechnen bei Kindern*, ZAREKI-R; internal consistency between $\alpha = 0.93$ and $\alpha = 0.97$; von Aster et al., 2006) is a neuropsychological test battery that taps basic mathematical abilities ranging from counting, transcoding, magnitude and number line estimation to simple arithmetic and word problems. Theoretically, it is based on the Triple Code Model (Dehaene, 1992) and is often used for dyscalculia assessment in practice. Administration takes approximately 40 minutes. Compared to HRT 1–4, response modes are more versatile: Depending on the subtest, children either have to write down an answer, show something on a stimulus display or respond orally. In this study, the test was administered in a one-to-one setting in the facilities of Department of Psychology, University of Münster.

Heidelberg Calculation Test (HRT 1–4)

The Heidelberg calculation test (*Heidelberger Rechentest*; retest reliability: 0.93; Haffner et al., 2005) is a paper-pencil speed test of basic mathematical knowledge. HRT 1–4 consists of the two scales that are combined to a total score: (1) "arithmetic operations" (6 subtests: addition, subtraction, multiplication, division, fill-the-gap tasks, greater/less comparisons; retest reliability: 0.93) and (2) "numerical-logical and visual-spatial skills" (5 subtests: numerical series, lengths estimation, counting cubes, counting magnitudes, connecting numbers; retest reliability: 0.87; Haffner et al., 2005). T-score norms (i.e., a standardization resulting in a mean of 50 and standard deviation of 10) are available for every quarter of the school year. In this study, the test was administered in group setting, either in the facilities of Department of Psychology, University of Münster, or in classroom.

Intelligence

Different tests were used to assess intelligence. In the ZAREKI-R sample, the perceptual reasoning index (retest-reliability: 0.93) of the WISC-IV (Wechsler, 2011) was used to assess intelligence. In the HRT sample, intelligence was measured using the language-free group test CFT 1-R with a retest-reliability of 0.95 (Weiß and Osterland, 2013). Both tests focus on fluid intelligence and do not require any language skills.

Reading Fluency

To measure reading fluency, the *Salzburger Lese-Screening* (SLS 1–4) with a parallel test reliability of at least 0.90 was used (Mayringer and Wimmer, 2003): Children had to read as many simple and unambiguous sentences (e.g., Bananas are blue) as possible within 3 minutes; By ticking a box at the end of each sentence, children had to specify if the sentences were correct or incorrect, and the more correct answers a child gave, the higher the reading fluency (Mayringer and Wimmer, 2003).

Working Memory

The task *matrix span* included in the CODY-M 2–4 battery with a retest reliability of 0.61 (Kuhn et al., 2017) was used in both samples to test the visual-spatial working memory. During this test, children had to memorize a pattern of dots and they had to solve a distracting task; afterward, they had to reproduce the dot pattern (Raddatz et al., 2017). In addition, the *verbal span* test (reported reliability: $\alpha = 0.78$) of the working memory scales by Vock and Holling (2008) was used in the ZAREKI-R sample: First, participants had to remember a list of words; next, a distracting classification task was presented, after which the initially learned word had to be retrieved. Raw scores of the verbal span task were transformed to standardized T-scores based on the total sample. In the ZAREKI-R sample, mean working memory performance was calculated based on both working memory tasks.

Mathematical Abilities

Mathematical abilities were assessed using the CODY-M 2–4 battery (Kuhn et al., 2017). According to the CODY-M 2–4 manual, subscale scores for (1) BNP (retest reliability: 0.72), (2) CNP (retest reliability: 0.76), and (3) Calculation skills (retest reliability: 0.85) were computed to measure different components of mathematical skills (Kuhn et al., 2017). All following descriptions of the mathematical tests are based on Raddatz et al. (2017).

Basic Numerical Processing (BNP)

Efficiency in counting was tested by *dot enumeration*: 1–9 black dots had to be counted as quickly and correctly as possible. Across all correct responses, the median of the children's reaction times was computed. In addition, BNP was tested by two comparison tasks (c.f. Defever et al., 2013): Two different Arabic numerals (*symbolic magnitude comparison*) or a numerosity of dots on one side and an Arabic numeral on the other side (*mixed magnitude comparison*) were displayed on a screen, and children had to decide which of the shown entities was larger (right or left). These tasks have in common that they all assess core number competencies and incorporate very simple and basic tasks as enumeration tasks and the comparison of magnitudes (Reeve et al., 2012; Kuhn et al., 2017).

Complex Number Processing (CNP)

One task tests the precision of the mental *number line* (based on Siegler and Booth, 2004): A number was shown on a screen and the children had to locate this number with a computer mouse on an unscaled number line (only the endpoints were labeled with *0* and *100*). The *number sets* task (based on Geary et al., 2009) was used to assess the efficiency of number processing across presentation formats: Again, an Arabic numeral was shown at the top of the screen. In addition, numbers and/or geometric figures (= a number set) were shown at the bottom of the screen. Children had to compare the sum of the elements represented as a number set with the number above and they had to decide whether the sum of the number set was equal to the shown number above. Two target numbers were used (5 and 9) in this speed test. For example, on the top of the screen a 5 (as an Arabic numeral) was shown as the target number. At the bottom of the screen, three geometric figures and a 1 (as an Arabic numeral) were shown. In this example, the child had to calculate *3 (geometric figures) + 1 (as an Arabic numeral) = 4*, and compare the 4 (the sum of the number set) to the 5 (the target number) and check whether the number set is equal or unequal to the target number. *Transcoding* tasks assessed the ability to translate heard numbers (presented by headphones) into written Arabic numerals. These different tasks have in common that they assess mathematical precursor skills that require more *complex number processing* (CNP; Nuerk et al., 2006; Kuhn et al., 2017).

Calculation (CALC)

The participants had to solve tasks focusing on (1) *addition*, (2) *subtraction,* and (3) *multiplication mixed with place holder tasks*. The addition and subtraction tasks ranged from fact retrieval (e.g., 1 + 8) to more difficult tasks (e g., 183–18). Place holder tasks are arithmetic tasks that are not to be solved linearly from left to right, but an element of the equation has to be determined (e.g., 4 + × = 7; what is ×?). These tasks have in common that they all require the skill to perform arithmetic.

Attention

In the ZAREKI-R sample, three subtests of the KITAP were used to measure different aspects of attention (Zimmermann et al., 2005): (1) The subtest *alertness* (split-half reliability of the reaction time's median: 0.96) tests the intensity of attention. Children had to react as quickly as possible to a witch appearing on a screen. (2) In the subtest *sustained attention* (split-half reliability of the reaction time's median: 0.93), a sequence of ghosts briefly appeared in the windows of a castle and disappeared. Children had to check whether the ghost they saw was identical to the one seen just before. (3) The subtest *flexibility* (split-half reliability of the reaction time's median: 0.93) was used to measure selective attention, i.e., the ability to adapt the focus of attention. The screen was split in two and on each side an identically shaped stimulus (dragon) that varied in color appeared (one stimulus was blue, one was green). The target (= the color of the stimulus) changed alternately and children had to react to where the target color appeared (on the left/right side) as quickly and correctly as possible by pushing a button. The standardized mean of these three attention tests was calculated in order to obtain a score for attention. All descriptions of the used tests to measure attention are based on the KITAP manual (Zimmermann et al., 2005). In the sample measured at school (HRT 1–4 as dyscalculia criterion), no attention data could be captured as the testing procedure requires individual settings.

Statistical Analyses

All calculations were carried out with version 4.0.0 of the statistical software R (R Core Team, 2020). The values of all variables were T-standardized resulting in T-scores; i.e., the standardization sample had a mean of 50 and a standard deviation of 10. Necessary data transformations were carried out using the R-package dplyr (Singh and Soman, 2019).

To identify subtypes of dyscalculia, model-based clustering (parameterized finite Gaussian mixture models) based on the R-package mclust (Fraley et al., 2020) was performed. Each participant of a sample was assigned to a single cluster by calculating the probability of a person belonging to a specific cluster based on the individual cognitive profile (Vanbinst et al., 2015). All participants assigned to the same cluster can be interpreted as a subgroup, and the number of clusters corresponds to the number of subgroups (Bouveyron et al., 2019).

The number of clusters was determined based on the Bayesian Information Criterion (BIC; Bouveyron et al., 2019). Different (preset) competing models that can plausibly describe cluster structures were used to determine the number of clusters that fits the data best: These models vary in their assumptions regarding the geometric characteristics of the clusters as their spatial orientation or their volume (equal vs. varying volume), for example (Makhabel et al., 2017; Bouveyron et al., 2019; Fraley et al., 2020). For each possible model, the BIC is calculated for different numbers of clusters, and the lowest absolute BIC of a model-cluster-combination suggests that this solution fits the data best (Vanbinst et al., 2015; Bouveyron et al., 2019). Each of the possible model-cluster-combinations was compared to other possible model-cluster-combinations in order to find the model-cluster-combination with the strongest evidence. Each model has a specific identifier (e.g., "EEI") and the clustering procedure automatically chooses the most appropriate out of different models. The identifier can be used to look up the characteristics of this model in the manual of the mclust-package: For example, the identifier EEI means that there are diagonal clusters with equal volume and equal shape (Fraley et al., 2020). So, if a specific model-cluster-combination of the EEI model, for example, has the lowest absolute BIC, this means that this model-cluster-combination is the best solution with regard to the data. As in other studies with similar approaches (e.g., Vanbinst et al., 2015), the results of the model-cluster-combination with the lowest absolute BIC are presented. It makes sense to only describe and interpret this model-cluster-combination, since all other model-cluster-combinations fit the empirical data less well and therefore there is no convincing evidence for these other solutions.

To check whether the subgroup-solution of the clustering process is robust, two different ways of clustering were used. First, a clustering was carried out at the *construct level* as described before [intelligence, reading fluency, working memory, Basic numerical processing (BNP), Complex number processing (CNP), Calculation (CALC), and Attention]. Further, another model-based clustering used data at the *subtest level* (variables: intelligence, reading fluency, matrix span, verbal span, enumeration, symbolic magnitude comparison, mixed magnitude comparison, number line, number sets, transcoding, addition, subtraction, multiplication mixed with place holder tasks, attention). If both clustering approaches lead to similar or identical solutions, this is an indication for the validity of the superordinate constructs and for the robustness of the results across levels of measurement.

The resulting subgroups of the best-fitting model were then compared with regard to each construct/subtest used to cluster these subgroups. These comparisons were based on using frequentist and Bayesian t-tests to check the differences and similarities of the subgroups in detail. The significance level for the frequentist t-tests was adjusted by the *sequentially rejective Bonferroni test* to prevent the alpha error from accumulating (Holm, 1979), and Cohen's d as an effect size for between-group differences was computed with the R-package lsr (Navarro, 2015). Bayesian t-tests were carried out to check the robustness of the frequentist results: Both approaches can lead to different conclusions, but if the results of frequentist analyses and the results of Bayesian analyses point to the same direction, they can be rated as robust (Lindley, 1957; Sprenger, 2013; Wagenmakers et al., 2018). In contrast to frequentist statistics, Bayesian methods (e.g., Bayesian t-tests) cannot only unravel whether there is evidence for a difference between groups, but also verify that there is evidence for equality of the analyzed groups (Rouder et al., 2012; Wagenmakers et al., 2018). Bayesian analyses were conducted with the R-package BayesFactor (Morey et al., 2018). An important difference between frequentist and Bayesian statistics is that Bayesian statistics do not provide p-values, but Bayes Factors (BF). A BF lower than 0.33 suggests moderate evidence for the null hypothesis, a BF lower than 0.10 suggests strong evidence for the null hypothesis and a BF lower than 0.033 suggests very strong evidence for the null hypothesis; the other way round, a BF above three suggests moderate evidence for the alternative hypothesis, a BF above 10 suggests strong evidence for the alternative hypothesis and a BF above 30 suggests very strong evidence for the alternative hypothesis (Wagenmakers et al., 2018).

In addition, repeated-measures ANOVAs were calculated to check whether there was a main effect of subgroup (between-group factor), i.e., a mean difference across constructs/subtests between the assumed subtypes (Bulut and Desjardins, 2018; Bulut and Desjardins, 2020). Further, we also checked whether there was a main effect of test (within-group factor), i.e., whether mean performance across constructs/subtests varied independently of subgroups (within groups: intelligence, reading fluency, working memory, BNP, CNP, calculation, and attention). Most importantly, we investigated interaction effects to check whether the identified subgroups differed disproportionately with regard to each different construct/subtest. If subgroups differ disproportionately, profile lines of the subgroups do not run in parallel. Parallelism was additionally tested using profile analysis based on the R package profileR (Bulut and Desjardins, 2018, 2020). Necessary data set modifications were done by using the R-package reshape2 (Wickham, 2020) and ANOVAs as well as effect sizes for ANOVAs – generalized eta squared (η^2_G; Bakeman, 2005) – were computed with the R-package ez (Lawrence, 2016).

As already indicated, it was checked whether relative frequency of children with dyscalculia and a comorbid reading disorder differed across subtypes. To test this, χ^2-tests were conducted with the categorical variables (1) reading disorder (yes/no) and (2) subtype. If the prerequisites for χ^2-tests (i.e., sufficient cell sample sizes) were not met, Fisher's exact test for count data was conducted.

Missing data can significantly influence and distort the results of statistical analyses. Therefore, a two-step approach was used here. In a first step, only complete data sets (data of children with no missing data) were analyzed. In this case, the ZAREKI-R sample consisted of 93 children (26 children with a comorbid reading disorder) and the HRT sample consisted of 67 children (38 children with a comorbid reading disorder). In a second step, the function imputeData from the R-package mclust (Fraley et al., 2020) was used to impute missing data, and the most important calculations were repeated to check the robustness of the results. Because added data vary as a function of random start points, it is strongly recommended to compute multiple imputations (Fraley et al., 2012). To check if the results were robust across imputations, central calculations were rerun with imputed data sets generated with three random seeds (3; 3,000; 3,000,000) (Fraley et al., 2012). If all results point into the same direction, the results can be interpreted as robust.

RESULTS

In all cases (ZAREKI-R sample and HRT sample; analyses on construct level and on subtest level; with and without imputation), mixture model analyses consistently suggested that there were two subgroups of CwD. The EEI-model (cluster characteristics: two diagonal clusters with equal volume and equal shape; Fraley et al., 2020, p. 105) was the model that described the data best in both samples (ZAREKI-R and HRT; each without imputations and clustered by constructs). The absolute BIC of the ZAREKI-R sample (without imputation and with analyses on construct level) was 4,390 and the absolute BIC of the HRT sample (without imputation and with analyses on construct level) was 2,851. The results described in the following are based on complete data sets at the construct level. If deviations occurred in alternative calculations (with imputed data or at the subtest level), these deviations are reported.

For both resulting subgroups of the ZAREKI-R sample, the results of descriptive analyses (mean, standard deviation, skewness, kurtosis, minimum, and maximum) for complete data sets (construct level) are shown in **Table 1**. The results of descriptive analyses of the HRT sample for complete data sets (construct level) are shown in **Table 2**. To check the robustness of the results, the clustering processes were carried out again at the level of subtests: The results of the descriptive analyses for the resulting subgroups are shown in **Table 3** (ZAREKI-R sample, complete data sets) and **Table 4** (HRT sample, complete data sets).

Mean comparisons of the two identified subgroups for complete data sets are shown in **Table 5** (construct level) and **Table 6** (subtest level). In each sample, there was one subgroup (named: subgroup 2) that almost always reached lower test scores (means) in comparison to the other subgroup (named: subgroup 1). Differences between the two subgroups were very small for some measures (e.g., for BNP in the HRT sample or for working memory in both samples), and significantly large for others (e.g., CNP and CALC in both samples). The descriptive analyses therefore suggest that the profiles of the subgroups differed, and that the distinctiveness of subgroups' profiles varied between cognitive measures.

This was tested by ANOVA, showing for the HRT sample that (a) there was a significant main effect of the factor subgroup, $F_{(1,65)} = 37.84$, $p < 0.001$, $\eta^2_G = 0.10$; (b) there was a significant main effect for the different constructs, $F_{(5,325)} = 15.92$, $p < 0.001$, $\eta^2_G = 0.16$; (c) there was a significant interaction effect for subgroups and constructs, $F_{(5,325)} = 5.08$, $p < 0.001$, $\eta^2_G = 0.06$. The profile analysis confirmed these results, providing evidence against parallelism of the subgroups' profiles, $F_{(5,61)} = 8.54$, $p < 0.001$.

In line with these findings, an ANOVA for the ZAREKI-R sample also showed (a) a significant main effect for subgroups, $F_{(1,91)} = 77.03$, $p < 0.001$, $\eta^2_G = 0.13$; (b) a significant main effect for the different constructs, $F_{(6,546)} = 6.04$, $p < 0.001$, $\eta^2_G = 0.05$; (c) a significant interaction effect for subgroups and constructs, $F_{(6,546)} = 3.96$, $p < 0.001$, $\eta^2_G = 0.03$. Again, profile analysis indicated that there was no parallelism of the subgroups' profiles, $F_{(6,86)} = 7.12$, $p < 0.001$. The next paragraphs describe these profile differences in more detail.

Intelligence

Means for intelligence in subgroup 1 were higher than means for intelligence in subgroup 2 across samples and for all ways of clustering. This difference was significant in the main analyses if the subgroups were clustered at the construct level (**Table 5**), but not robust in all *t*-tests with imputations. In some cases, the results of Bayesian analyses did not confirm the significant results

TABLE 1 | Descriptive statistics of the ZAREKI-R sample—clustered by constructs.

	Subgroup 1 (*n* = 27)						Subgroup 2 (*n* = 66)					
	M	***SD***	**Skewness**	**Kurtosis**	**Min.**	**Max.**	***M***	***SD***	**Skewness**	**Kurtosis**	**Min.**	**Max.**
Intelligence	48.24	6.09	0.32	1.76	39.17	58.33	45.34	6.01	0.02	2.41	30.83	58.33
Reading fluency	45.80	11.08	0.15	2.25	24.67	68.00	41.51	9.59	0.54	4.01	21.33	72.00
Working Memory	47.30	5.77	0.32	2.48	37.50	60.50	45.87	4.92	0.20	3.61	33.00	59.50
Basic numerical processing	50.89	7.73	0.40	2.94	36.00	67.00	43.38	6.76	0.31	2.92	29.00	60.00
Complex number processing	47.41	5.06	−0.11	1.73	38.00	55.00	40.64	4.83	−0.24	2.56	30.00	51.00
Calculation	47.48	4.11	0.02	3.91	37.00	58.00	37.30	3.95	0.11	2.30	30.00	46.00
Attention	47.53	7.22	−0.15	1.74	34.67	57.67	41.55	7.48	−0.06	2.45	22.33	58.00

All variables are T-standardized (mean = 50, SD = 10).

TABLE 2 | Descriptive statistics of the HRT sample—clustered by constructs.

	Subgroup 1 (*n* = 39)						Subgroup 2 (*n* = 28)					
	M	***SD***	**Skewness**	**Kurtosis**	**Min.**	**Max.**	***M***	***SD***	**Skewness**	**Kurtosis**	**Min.**	**Max.**
Intelligence	47.35	9.32	0.32	2.48	31.33	67.00	42.17	6.68	−0.05	2.61	30.00	55.33
Reading fluency	38.17	9.97	0.15	2.32	20.00	60.00	33.79	10.24	0.67	2.76	18.67	58.00
Working Memory	45.28	9.12	0.21	2.13	32.00	65.00	43.82	8.33	0.14	2.74	26.00	60.00
Basic numerical processing	46.33	8.37	0.64	3.64	31.00	72.00	46.11	9.08	−0.03	2.55	28.00	65.00
Complex number processing	48.03	4.05	0.11	2.79	39.00	58.00	36.79	4.23	−0.29	2.66	28.00	44.00
Calculation	44.77	4.42	0.04	2.06	37.00	53.00	35.82	4.23	−0.13	3.62	26.00	46.00

All variables are T-standardized (mean = 50, SD = 10).

TABLE 3 | Descriptive statistics of the ZAREKI-R sample–clustered by subtests.

	Subgroup 1 (*n* = 26)						Subgroup 2 (*n* = 60)					
	M	***SD***	**Skewness**	**Kurtosis**	**Mix.**	**Max.**	***M***	***SD***	**Skewness**	**Kurtosis**	**Min.**	**Max.**
Intelligence	46.99	6.36	0.47	2.00	38.33	58.33	45.72	5.88	0.08	2.58	30.83	58.33
Reading fluency	45.49	10.32	0.51	2.37	28.67	68.00	40.88	9.37	0.36	4.03	21.33	72.00
Matrix span	46.23	8.82	0.14	2.38	33.00	65.00	45.87	7.13	0.02	2.77	30.00	61.00
Verbal span	48.54	5.43	0.50	2.71	41.00	61.00	45.98	6.32	0.97	3.97	36.00	67.00
Dot enumeration	51.35	10.83	0.52	2.70	33.00	75.00	42.22	8.53	−0.20	3.12	22.00	65.00
Symbolic magnitude comparison	50.15	9.56	0.10	2.11	35.00	68.00	43.77	11.96	0.31	2.40	22.00	69.00
Mixed magnitude comparison	51.77	13.14	0.12	2.15	31.00	75.00	44.02	10.95	0.16	2.56	22.00	71.00
Transcoding	46.73	8.30	−0.38	1.65	32.00	58.00	41.03	9.14	−0.04	1.84	22.00	54.00
Number sets	47.35	8.67	0.49	2.99	32.00	68.00	41.02	6.30	0.18	2.68	28.00	57.00
Number line	48.00	5.58	−0.36	2.06	37.00	57.00	40.30	7.63	0.41	3.48	23.00	63.00
Addition	48.35	6.39	0.42	2.31	39.00	61.00	36.47	4.73	−0.27	2.86	24.00	46.00
Subtraction	44.96	4.89	0.31	2.91	37.00	57.00	37.27	6.20	0.52	2.28	26.00	49.00
Multiplication mixed with place holder tasks	48.62	7.51	−0.10	2.96	33.00	65.00	38.35	7.04	0.13	2.35	25.00	53.00
Attention	47.24	7.53	−0.29	2.00	32.00	57.67	41.68	7.76	−0.04	2.42	22.33	58.00

All variables are T-standardized (mean = 50, SD = 10).

TABLE 4 | Descriptive statistics of the HRT 1-4 sample—clustered by subtests.

	Subgroup 1 (*n* = 43)						Subgroup 2 (*n* = 24)					
	M	***SD***	**Skewness**	**Kurtosis**	**Min.**	**Max.**	***M***	***SD***	**Skewness**	**Kurtosis**	**Min.**	**Max.**
Intelligence	46.40	9.45	0.39	2.53	30.00	67.00	43.01	6.63	−0.16	2.61	30.00	55.33
Reading fluency	38.03	10.20	0.05	2.16	20.00	60.00	33.31	9.80	0.92	3.60	18.67	58.00
Matrix span	45.07	9.08	0.24	2.10	32.00	65.00	43.96	8.30	0.08	2.93	26.00	60.00
Dot enumeration	46.70	11.31	0.65	3.18	22.00	74.00	42.25	9.66	−0.03	1.88	27.00	58.00
Symbolic magnitude comparison	47.58	11.90	0.74	2.79	29.00	75.00	44.63	12.46	−0.02	2.12	22.00	65.00
Mixed magnitude comparison	46.88	12.44	0.40	2.86	22.00	75.00	47.42	11.50	0.03	2.11	26.00	69.00
Transcoding	49.91	5.72	−0.58	2.16	40.00	58.00	34.63	6.21	−0.11	2.13	22.00	44.00
Number sets	44.56	7.18	0.11	2.74	29.00	60.00	37.96	6.08	−0.13	2.11	26.00	49.00
Number line	48.00	8.12	0.57	2.85	36.00	69.00	35.75	4.61	0.96	4.19	29.00	49.00
Addition	44.70	6.70	0.58	2.90	34.00	60.00	35.04	6.54	0.30	2.97	24.00	51.00
Subtraction	43.07	6.39	0.79	4.62	30.00	65.00	34.67	5.35	−0.33	2.17	26.00	43.00
Multiplication mixed with place holder tasks	45.28	7.78	0.29	2.85	30.00	64.00	35.46	5.64	−0.52	2.81	24.00	45.00

All variables are T-standardized (mean = 50, SD = 10).

TABLE 5 | Subgroup mean comparison—clustered by constructs.

	ZAREKI-R			HRT 1–4		
	***t*-test**	**Cohen's *d***	**BF**	***t*-test**	**Cohen's *d***	**BF**
Intelligence	2.10*	0.48	1.57	2.65*	0.62	3.48
Reading fluency	1.87	0.43	1.07	1.76	0.43	0.93
Working memory	1.20	0.28	0.44	0.67	0.17	0.31
Basic numerical processing	4.66***	1.07	1589.59	0.11	0.03	0.25
Complex number processing	6.06***	1.38	3.28×10^{5}	11.00***	2.73	2.15×10^{13}
Calculation	11.16***	2.55	3.19×10^{15}	8.32***	2.06	7.63×10^{8}
Attention	3.54***	0.81	43.98	–	–	–

Interpretation of p-values: p < 0.05, p < 0.01**, p < 0.001*** the significance level was adjusted by the sequentially rejective Bonferroni test to prevent the alpha error from accumulating (Holm, 1979); interpretation of BFs (Wagenmakers et al., 2018): BF < 0.33 (moderate evidence for the null hypothesis), BF < .10 (strong evidence for the null hypothesis), BF < 0.033 (very strong evidence for the null hypothesis), BF > 3 (moderate evidence for the alternative hypothesis), BF > 10 (strong evidence for the alternative hypothesis), BF > 30 (very strong evidence for the alternative hypothesis).*

of the frequentist analyses, e.g., ZAREKI-R without imputations (**Table 5**): $t(91) = 2.10$, $p < 0.05$, but BF = 1.57. Differences in intelligence were not significant if the subgroups were clustered at the subtest level (**Table 6**). Overall, the data suggest a very small difference between subgroups in terms of their language-free intelligence (subgroup 1 > subgroup 2).

Reading Fluency

Although means in subgroup 1 were generally higher than means in subgroup 2, there was no clear statistical evidence for differences between subgroups. In the ZAREKI-R sample, there was a significant difference between the two subgroups if imputations were used [seed = 3,000,000; $t(101) = 2.53$, $p < 0.05$, BF = 3.52], but this difference was not robust. Overall, subgroup differences seemed to be very small and mostly insignificant, but there was also no clear Bayesian evidence for the groups being equal.

Working Memory

Working memory differences between subgroups were very small—both at construct level and at the subtest level: The *t*-tests were not significant and the BFs were below 1. So, there was no evidence for a difference between these two groups with regard to working memory and there was even moderate evidence for the null hypothesis, i.e., equality of subgroups (HRT sample without imputations: BF = 0.31). In the HRT sample, only the matrix span task was used to assess working memory and these results were identical if the subgroups were clustered by subtests (**Table 6**): In many cases, there was even moderate evidence for the subgroups being equal because BFs were below 0.33. It should be kept in mind here that in the ZAREKI-R sample, two different tests for assessing working memory were used: matrix span and verbal span (cf. section "Working Memory"). If the subgroups were clustered by subtests, there were significant differences (based on imputed data), but these differences were not robust.

Mathematical Skills

The two subgroups in both samples differed very strongly in their mathematical skills; especially for CALC and CNP, very strong and robust evidence for a difference was found. In addition, a significant difference between the two subgroups occurred in the ZAREKI-R sample for BNP, $t(91) = 4.66$, $p < 0.001$, BF = 1589.59.

TABLE 6 | Subgroup mean comparison—clustered by subtests.

	ZAREKI-R			HRT 1–4		
	t-test	Cohen's *d*	BF	*t*-test	Cohen's *d*	BF
Intelligence	0.89	0.21	0.34	1.55	0.39	0.71
Reading fluency	2.03*	0.48	1.40	1.84	0.47	1.07
Matrix span	0.20	0.05	0.25	0.49	0.13	0.29
Verbal span	1.79	0.42	0.95	–	–	–
Dot enumeration	4.19***	0.98	306.95	1.62	0.41	0.78
Symbolic magnitude comparison	2.41	0.57	2.81	0.96	0.24	0.38
Mixed magnitude comparison	2.84*	0.67	7.09	−0.17	0.04	0.26
Transcoding	2.73*	0.64	5.53	10.17***	2.59	9.11×10^{11}
Number sets	3.80**	0.89	92.25	3.80**	0.97	81.06
Number line	4.63***	1.09	1307.06	7.88***	1.73	2.12×10^{6}
Addition	9.58***	2.25	1.05×10^{12}	5.71***	1.45	3.86×10^{4}
Subtraction	5.61***	1.32	4.69×10^{4}	5.46***	1.39	1.62×10^{4}
Multiplication mixed with place holder tasks	6.09***	1.43	3.07×10^{5}	5.43***	1.38	1.45×10^{4}
Attention	3.08*	0.72	12.77	–	–	–

Interpretation of p-values: p < 0.05, p < 0.01**, p < 0.001***; the significance level was adjusted by the sequentially rejective Bonferroni test to prevent the alpha error from accumulating (Holm, 1979); interpretation of BFs (Wagenmakers et al., 2018): BF < 0.33 (moderate evidence for the null hypothesis), BF < 0.10 (strong evidence for the null hypothesis), BF < 0.033 (very strong evidence for the null hypothesis), BF > 3 (moderate evidence for the alternative hypothesis), BF > 10 (strong evidence for the alternative hypothesis), BF > 30 (very strong evidence for the alternative hypothesis).*

However, there was no such difference in the HRT sample, $t(65) = 0.11$, $p = 0.92$, BF = 0.25. The results were robust. Of all constructs or subtests, subgroups differed most strongly in terms of their mathematical skills.

Attention

Attention was only assessed in the ZAREKI-R sample, and the scores for attention were higher in subgroup 1 than in subgroup 2. There was a significant difference between the two subgroups in this sample if clustered by constructs, $t(91) = 3.54$, $p < 0.001$, BF = 43.98. If clustered by subtests, this difference was significant as well, $t(84) = 3.08$, $p < 0.05$, BF = 12.77. These results were robust if imputations were used. There was clear evidence for a difference between the subgroups, but this difference was not as pronounced as for the mathematical skills (CALC and CNP).

Comorbid Reading Disorder

χ^2-tests (for complete data sets at the construct level) showed no significant associations between reading disorder (PR < 10) and the identified subtypes (HRT: $\chi^2 = 0.66$, $p = 0.42$; ZAREKI-R: $\chi^2 < 0.01$, $p = 0.98$). For alternative calculations (e.g., analyses at the subtest level), the results were almost identical and therefore robust.

Comorbid Low Intelligence

Overall, the model-based clustering revealed a slightly impaired subgroup on the one side (subgroup 1) and a severely impaired subgroup on the other side (subgroup 2) in CwD (mathematical abilities: PR < 10). The fact that subgroup 2 showed lower performance in nearly all areas might lead to the assumption that this might be due to a substantial proportion of children with low intelligence (PR < 10) in this subgroup. However, in the ZAREKI-R sample, Fisher's exact test for count data did not suggest a systematic dependency between low intelligence and subgroup affiliation, $p = 0.32$. In the HRT sample, there again was no systematic dependency between low intelligence and subgroup affiliation, $\chi^2 = 0.36$, $p = 0.55$. Results appeared robust across alternative calculations.

Comorbid Attention Deficits

There was a significant difference in attention between the two subgroups in the ZAREKI-R sample (subgroup 1 > subgroup 2). In fact, 22 of 66 children of subgroup 2 and only 3 of 27 children of subgroup 1 displayed deficits in attention (PR < 10). Fisher's exact test for count data suggested a systematic dependency between attention deficits and subgroup affiliation ($p = 0.038$). Again, alternative calculations provided similar results and were therefore robust.

DISCUSSION

In contrast to many other studies with data-driven designs (e.g., Bartelet et al., 2014; Chan and Wong, 2020), no large number of subtypes in CwD was identified in this methodically advanced study. Two subgroups of children with dyscalculia were consistently found, and this result was robust regardless of whether (a) only complete data sets or imputed data sets were used, (b) the clustering was carried out at the level of subtests (e.g., dot enumeration, magnitude comparison) or aggregated constructs (e.g., basic numerical processing) or (c) different dyscalculia assessments were used (HRT 1–4 or ZAREKI-R). In addition, the number of subgroups was not affected by taking the construct of attention into account (only assessed in the ZAREKI-R sample). Although not a complete multiverse analysis (Steegen et al., 2016), the results suggest very convincingly that there are two subtypes of CwD: a slightly impaired subtype (subgroup 1) and a severely impaired group (subgroup 2).

The results of this study underline that different study designs and clustering methods can come to different results. However, this does not necessarily imply that other ways to cluster CwD are misguided: Of course, the formation of subtypes is always a generalization and therefore just a heuristic to facilitate practical decision-making. It must always be weighed to which extent individualization or generalization serves a specific purpose. Furthermore, subtypes from data-based studies depend on the sample, assessments, and constructs under investigation. Hence, results of the present study may differ from other studies (e.g., Bartelet et al., 2014; Chan and Wong, 2020) because only children with very poor mathematical performance (PR $<$ 10) were examined here, and children at risk of dyscalculia (PR between 10 and 25) were excluded. However, children at risk of dyscalculia may display very heterogeneous deficits, and hence, excluding this group may explain the comparably small number of subgroups in our study. Further, the relatively small sample size for a mixture model analysis may be regarded as a key limitation—more subgroups might have emerged in the case of larger sample sizes of CwD, which, however, are resource-intensive to obtain.

Results of the ZAREKI-R sample differed from the HRT sample in one aspect: There was a large difference in basic numerical processing between the two subgroups in the ZAREKI-R sample, but there was no such difference in the HRT sample. This could be a bias due to the different focus of these diagnostic tests: The HRT 1–4 mainly tests the ability to calculate and arithmetic skills, but the HRT 1–4 does not strongly focus on BNP, whereas the ZAREKI-R does. Nevertheless, the two subgroups – regardless of the diagnostic test – showed large differences in calculation and complex number processing. All in all, subgroups differed in particular in the extent to which their mathematical skills were impaired. The fact that CwD can be divided into subgroups based on the severity of impairments is in line with other studies that have also distinguished children with mathematical deficits into subgroups based on their mathematical skills (e.g., Skagerlund and Träff, 2016).

The results of this study suggest that working memory (in particular if measured with a matrix span task that is combined with a distracting task) and reading fluency do not appear to be helpful to characterize different subtypes. The result that reading ability seems to be of no importance for the characterization of subgroups contradicts some prior findings of subtyping CwD (e.g., Ozols and Rourke, 1988; Rourke, 1993). This result also seems to contradict the fact that dyscalculic children with comorbid reading disorders are usually more impaired than children with isolated dyscalculia (e.g., Kißler et al., 2021). Hence, finding a more impaired subtype of CwD with comorbid reading disorders would have been plausible. However, our analysis strategy did not provide results that support the view that reading difficulties co-occur with more severe mathematical difficulties, possibly due to the relatively strict criterion for identifying children with dyscalculia in this study (PR $<$ 10), which results in lower comorbidity rates between dyscalculia and reading disorders (Moll et al., 2014). Even though our analyzes could not find a subtype that is characterized by comorbid reading disorders, remedial teaching should nevertheless be individually tailored to the respective child and the child's needs.

In this study, intelligence seems barely relevant to subtype CwD–in contrast to the findings of Bartelet et al. (2014), for example. Overall, we found a slightly impaired subtype (subgroup 1) as well as a severely impaired subtype (subgroup 2) in CwD, and the intelligence of subtype 2 tends to be slightly lower. Even if there seems to be a small difference in terms of intelligence between the subtypes, no significant accumulation of children with an IQ below 80 (PR $<$ 10) in subtype 2 could be found. Nevertheless, the fact that the children in subtype 2 showed a generally lower cognitive profile could be partly linked to a lower intelligence. Overall, in this study, intelligence seemed to be less relevant in the formation of subgroups compared to attention and math skills themselves—this supports the assumption that the intelligence discrepancy criterion should be of secondary importance (e.g., Ehlert et al., 2012; Kuhn et al., 2013).

In the ZAREKI-R sample, there was strong evidence that attention matters: Subgroup 2 was severely impaired in attention. Due to the study design, it is unclear whether this finding depends on the selected test method (ZAREKI-R) and setting (individual administration at university) or whether this is a general characteristic. However, comorbidity in terms of attention deficits appears to be relevant in the characterization of subtypes in CwD: There seems to be one subtype of CwD that does not only display major difficulties in mathematics but is also characterized by considerable deficits in attention. Because this result was only obtained in one of the two subsamples analyzed here, more research is needed to replicate this result.

The fact that the subtypes differ most strongly in terms of their mathematical skills means that among CwD (PR $<$ 10), there is one group of children that is even more strongly impaired. There is no subtype that is characterized in particular by comorbid deficits in single non-mathematical abilities (e.g., working memory or reading skills). Rather, the subtypes tend to differ in more than one area (but in particular in different mathematical abilities and in attention at once), meaning that comorbidity is still a relevant issue when talking about subtypes in dyscalculia. Overall, the existence of subtype 2 allows the conclusion that attention problems are present in children with severe impairments in their mathematical abilities.

The results of this data-driven study suggest that the existence of two subtypes is robust and plausible. From a practical point of view, a two-subtype-solution can be useful for educational decision-making: Even though each child with dyscalculia needs specific intervention approaches and materials tailored to its individual needs, this two-subtype solution could be the basis for the development of different educational materials taking into account the two broad subtypes that were found in this study. Specifically, when planning interventions to foster CwD, it is important to have in mind that some of these children have substantial attention problems. In further studies, it should be examined whether interventions to improve attention, or taking attention deficits systematically into account during intervention, could lead to an improvement in mathematical skills in this subtype. In the research field of training programs, there are first approaches that try to take the comorbidity of reading disorders and attention disorders into account (Koenigs et al., 2019). Similar approaches for CwD would make sense in light of the results of this study. For educational practice, this means that math teachers should be made aware that children with the biggest problems in mathematics tend to have problems in attention too—and these children may have to be separately addressed. However, recent research (von Wirth et al., 2021) suggests that attention deficits in children with ADHD do not substantially affect basic numerical processing, and that ADHD in children with dyscalculia does not substantially deteriorate mathematical deficits. Therefore, further research is needed to illuminate the role of attention and attention deficits in children with dyscalculia.

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 Ethikkommission des Fachbereichs 7, Psychologie und Sportwissenschaft, Westfälische Wilhelms-Universität Münster (ethics committee of Faculty 7 - Psychology & Sports Sciences, University of Münster). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

J-TK: idea for writing this manuscript. J-TK and CS: data collection. CK: creating the basic structure of the draft and writing the draft of the manuscript. CK, J-TK, and CS: revisions to the text. CK and J-TK: search for articles. Note on the writing process of the method section: (a) CK: writing the draft of the chapter. (b) J-TK and CS: check and ensure that the methodological procedure is reported correctly. Note on the writing process of the results section: CK and J-TK: writing the R-script. CK and J-TK: creating the tables. All authors contributed to the article and approved the submitted version.

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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.2021.589506/full#supplementary-material

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