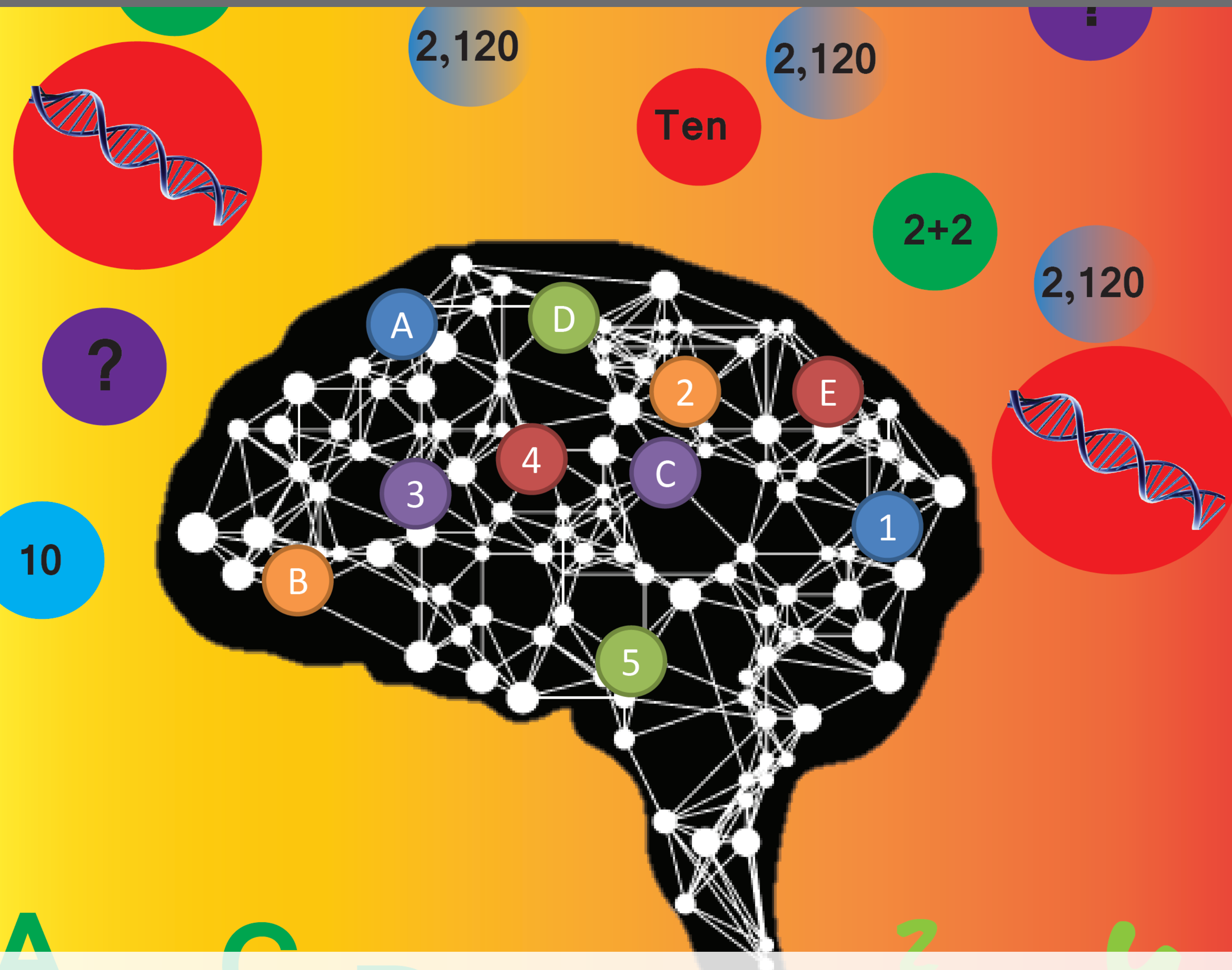
ASSOCIATIONS BETWEEN READING AND MATHEMATICS: GENETIC, BRAIN IMAGING, COGNITIVE AND EDUCATIONAL PERSPECTIVES

EDITED BY: Sarit Ashkenazi, Orly Rubinsten and Bert De Smedt
PUBLISHED IN: Frontiers in Psychology



frontiers Research Topics

ISSN 1664-8714
ISBN 978-2-88945-265-1
DOI 10.3389/978-2-88945-265-1

About Frontiers

Frontiers is more than just an open-access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers Journal Series

The Frontiers Journal Series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the Frontiers Journal Series operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to Quality

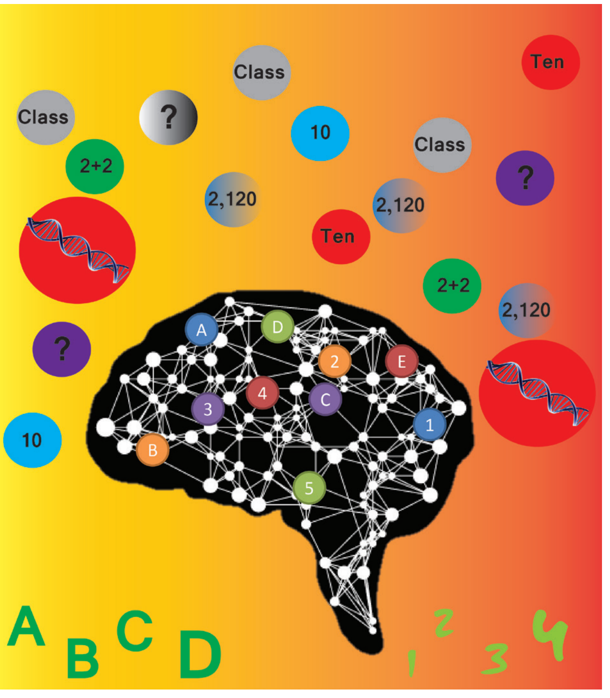
Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews.
Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view.
By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the Frontiers Journals Series: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area! Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers Editorial Office: **researchtopics@frontiersin.org**

ASSOCIATIONS BETWEEN READING AND MATHEMATICS: GENETIC, BRAIN IMAGING, COGNITIVE AND EDUCATIONAL PERSPECTIVES

Topic Editors:
Sarit Ashkenazi, Hebrew University of Jerusalem, Israel
Orly Rubinsten, KU Leuven, Belgium
Bert De Smedt, University of Haifa, Israel



Associations between reading and mathematics: genetic, brain imaging, cognitive and educational perspectives
Cover image by Sarit Ashkenazi, Orly Rubinsten and Bert De Smedt

Converging evidence demonstrates a strong link between reading and mathematics: multiple cognitive processes are shared between reading and mathematics, including the representation and retrieval of symbolic information, attention, working memory, and cognitive control. Additionally, multiple brain networks are involved in both math and reading, and last, common genetic factors might influence both reading and math.

Hence, it comes as no surprise that there are meaningful associations between (aspects of) math and reading abilities. Moreover, comorbidity rates between math learning disabilities (MD) and reading disabilities (RD) are high (up to 66%) and prevalence rate of the comorbid condition is reported to be more common than the prevalence rate of isolated math learning disabilities.

Accordingly, the goal of the research topic is to explore the underline mechanisms of this overlap between reading and math. The research topic aims to include the following topics:

- Genetics - it has been found that both RD and MD are based on genetic factors and run in families. Moreover, math problem solving shares significant genetic overlap with general cognitive ability and reading decoding, whereas math fluency shares significant genetic overlap with reading fluency and general cognitive ability.

Hence, this topic will explore the shared and unique genetic risk factors to RD and MD, In addition to shared and unique genetic influence on reading and math.

- Neural perspective - converging evidence from both structural and multiple functional imaging studies, involving a wide range of numerical tasks, points to the intraparietal sulcus (IPS) as a core region that involve in quantity manipulation. However, several additional brain areas, such as frontoparietal and temporoparietal areas were found to be involved in numerical tasks. Individuals with MD show deficits in a distributed, set of brain regions that include the IPS, fusiform gyrus in posterior brain regions and pre frontal cortex regions. Similarly, converging evidence indicate that the left hemisphere regions centered in the fusiform gyrus, temporoparietal cortex, and pre frontal cortex regions are strongly involve in typical reading and present lower activity, connectivity or abnormal structure in RD. Thus, there is a meaningful neural overlap between reading and math. Hence, the authors can submit empirical studies on the role of several of brain regions that are involved in math and reading (commonality and diversity) both in the typical and a-typical development.

- Cognitive factors that play role in mathematics and reading, and comorbidity between RD and MD - There is a long lasting debate whether MD and RD originate from unique cognitive mechanisms or not. Multiple cognitive processes are shared between reading and mathematics. Therefore, impairments in any one of domain-general skills could conceivably play an important role in both pure and comorbid conditions. Moreover, it has been suggested that phonological processing has a significant role in some aspects of numerical processing such as retrieval of arithmetical facts.

- Education - it will be interesting to look at the effect of interventions that aim to improve reading (such as phonological awareness) and there transfer effect on improving mathematical processing. Alternatively, it will be good to test whether math interventions will improve reading.

Citation: Ashkenazi, S., Rubinsten, O., De Smedt ,B., eds. (2017). Associations between Reading and Mathematics: Genetic, Brain Imaging, Cognitive and Educational Perspectives. Lausanne: Frontiers Media. doi: 10.3389/978-2-88945-265-1

Table of Contents

05 ***Editorial: Associations between Reading and Mathematics: Genetic, Brain Imaging, Cognitive and Educational Perspectives***
Sarit Ashkenazi, Orly Rubinsten and Bert De Smedt

Education

07 ***Factors That Influence Improvement in Numeracy, Reading, and Comprehension in the Context of a Numeracy Intervention***
Ann Dowker

17 ***A Review about Functional Illiteracy: Definition, Cognitive, Linguistic, and Numerical Aspects***
Réka Vágvölgyi, Andra Coldea, Thomas Dresler, Josef Schrader and Hans-Christoph Nuerk

30 ***Teachers' Beliefs and Practices Regarding the Role of Executive Functions in Reading and Arithmetic***
Shirley Rapoport, Orly Rubinsten and Tami Katzir

44 ***Predicting Children's Reading and Mathematics Achievement from Early Quantitative Knowledge and Domain-General Cognitive Abilities***
Felicia W. Chu, Kristy vanMarle and David C. Geary

Cognitive determinants of reading and mathematics

58 ***Early Literacy and Numeracy Skills in Bilingual Minority Children: Toward a Relative Independence of Linguistic and Numerical Processing***
Paola Bonifacci, Valentina Tobia, Luca Bernabini and Gian Marco Marzocchi

72 ***Spatial Ability Explains the Male Advantage in Approximate Arithmetic***
Wei Wei, Chuansheng Chen and Xinlin Zhou

Neurological perspective

81 ***Neural Correlates of Math Gains Vary Depending on Parental Socioeconomic Status (SES)***
Özlem Ece Demir-Lira, Jérôme Prado and James R. Booth

Causal models of comorbid disorders of mathematics and reading

93 ***An Extension of the Procedural Deficit Hypothesis from Developmental Language Disorders to Mathematical Disability***
Tanya M. Evans and Michael T. Ullman

102 ***Shared and Unique Risk Factors Underlying Mathematical Disability and Reading and Spelling Disability***
Esther M. Slot, Sietske van Viersen, Elise H. de Bree and Evelyn H. Kroesbergen

frontiers in Psychology

EDITORIAL
published: 21 April 2017
doi: 10.3389/fpsyg.2017.00600

Editorial: Associations between Reading and Mathematics: Genetic, Brain Imaging, Cognitive and Educational Perspectives

Sarit Ashkenazi[1], Orly Rubinsten[2] and Bert De Smedt[3]*

[1] The Seymour Fox School of Education, The Hebrew University of Jerusalem, Jerusalem, Israel, [2] Edmond J. Safra Brain Research Center for the Study of Learning Disabilities, Department of Learning Disabilities, University of Haifa, Haifa, Israel, [3] Faculty of Psychology and Educational Sciences, University of Leuven, Leuven, Belgium

Keywords: reading, mathematics, cognitive, education, neurobiological

Editorial on the Research Topic

Associations between Reading and Mathematics: Genetic, Brain Imaging, Cognitive and Educational Perspectives

Converging evidence demonstrates a strong link between reading and mathematics (LeFevre et al., 2010; Purpura and Ganley, 2014). This research topic aimed to explore the underlying mechanisms of this overlap between reading and mathematics. The empirical studies in this special issue cover three important, although not independent, perspectives including the neurobiological, cognitive, and educational perspectives.

Different aspects of numerical processing are represented in different brain regions. Specifically, the bilateral intraparietal sulcus is assumed to host preverbal innate representations of numerical quantity, whereas the left angular gyrus, in connection with other left-hemispheric perisylvian areas, supports the manipulation of numbers lexically. The first representations are based on spatial processes, and are independent from reading, but, the latter shares similar brain networks and cognitive processes with reading (Dehaene, 1992).

In accordance, mathematics represents heterogeneous cognitive abilities and involves the use of different strategies, which rely differentially on these nonverbal and verbal representations (LeFevre et al., 2010). There are also individual differences in the tendency to use these representations and these may also depend on environmental factors, such as socioeconomic status (SES). For example, Demir-Lira et al. tested neural predictors of math gains (up to 3 years) by examining activations in brain regions related to verbal numerical representations and spatial numerical representations. This association was moderated by SES: Activity in verbal brain regions (left inferior frontal gyrus) predicted math in children with high SES, while activity in spatial brain regions (superior parietal lobe) predicted math in children with low SES.

Atypical development of mathematics and reading tends to co-occur (comorbidity) of mathematics learning disabilities (MD) and reading disabilities (RD) is more common than the prevalence of MD without RD (Von Aster and Shalev, 2007) It has been suggested that these two conditions represent distinct subtypes of MD, i.e., MD-only vs. MD/RD, of which the latter may depend on weaknesses in the verbal code shared with reading (Ashkenazi et al., 2013; Szűcs, 2016). In line with this hypothesis, Slot et al. reported that phonological awareness influenced both math and literacy, and was a shared risk factor for MD, RD and spelling disabilities. On the other hand, Evans and Ullman, suggest that this common mechanism is related to procedural memory and its underlying brain systems.

OPEN ACCESS

Edited and reviewed by:
Bernhard Hommel,
Leiden University, Netherlands

Correspondence:
Sarit Ashkenazi
sarit.ashkenazi@mail.huji.ac.il

Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *22 March 2017*
Accepted: *31 March 2017*
Published: *21 April 2017*

Citation:
Ashkenazi S, Rubinsten O and De Smedt B (2017) Editorial: Associations between Reading and Mathematics: Genetic, Brain Imaging, Cognitive and Educational Perspectives. Front. Psychol. 8:600. doi: 10.3389/fpsyg.2017.00600

Multiple cognitive processes are shared between reading and mathematics, including the representation and retrieval of symbolic information, attention, working memory, and cognitive control. This is nicely illustrated by Chu et al. who showed in a 3-year longitudinal study that cognitive skills that are relevant to reading (e.g., phonological awareness) as well as cognitive skills that are specific to mathematics (e.g., sensitivity to relative quantity) predicted preschoolers' mathematics achievement.

To further explore the role of reading in mathematics, Bonifacci et al. compared the abilities of bilingual and monolingual children in numerical and arithmetical tasks with or without verbal components. Interestingly, bilingual children, who had better verbal skills, outperformed monolingual children in numerical tasks with a verbal (e.g., knowledge of digits) but not with nonverbal (e.g., quantity comparison) tasks.

Wei et al. approached this issue of interaction between reading and mathematics by analyzing sex differences. Assuming that males outperform females in spatial ability while females outperform males in verbal abilities, it can be predicted that males should be better in nonverbal mathematical tasks but not in verbal tasks. Wei et al. observed indeed that males outperform females in approximate arithmetic, which require spatial processing, and this difference was explained by gender differences in spatial ability.

Turning to the educational perspective with focus on reading and mathematics in the classroom, Rapoport et al. examined teachers' beliefs and practices about the link between reading and mathematics, by focusing on the role of executive functions. Dowker examined the effect of an individualized numeracy intervention, aiming to further determine whether children with MD-only and children with MD/RD require different interventions. Numeracy, reading comprehension and nonverbal IQ were measured before and after the intervention. Although literacy measures correlated with numeracy, they did not influence children's mathematical progress, or the effectiveness of intervention.

In adults, academic skills are crucial to make decisions in daily life Against this background, Vágvölgyi et al. examined functional illiteracy, defined by the inability to use reading, writing, and calculation skills or his/her own and the community's development. They proposed a new definition and add numerical aspects, in addition to the linguistic aspects, to a definition of functional illiteracy.

To sum, the current research topic adds to unraveling the communalities and differences between reading and mathematics learning and its atypical development. The studies in this research topic point to shared mechanisms (e.g., phonological awareness, procedural learning) as well as mechanisms that are clearly distinct between reading and math (e.g., spatial-numerical processes). Future studies should investigate these mechanisms in more detail at the neural level, by focusing on the overlap in networks between reading and different mathematical tasks. It could also be that these shared and independent mechanisms, and consequently the overlap between reading and mathematics, changes across development (De Smedt et al., 2009). Developmental studies are needed in order to determine how the overlap evolves over developmental time. Finally, there is a need for examining the effects of interventions that focus on factors that are either common or specific to reading and math. If a particular skill is causally related to both reading and mathematics, then interventions focused at this skill should have effects on both reading and mathematics. These studies are also needed from an educational point of view, as effective interventions will help to improve children's mathematics and reading skills.

AUTHOR CONTRIBUTIONS

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

REFERENCES

Ashkenazi, S., Black, J. M., Abrams, D. A., Hoeft, F., and Menon, V. (2013). Neurobiological underpinnings of math and reading learning disabilities. *J. Learn. Disabil.* 46, 549–569. doi: 10.1177/0022219413483174

De Smedt, B., Janssen, R., Bouwens, K., Verschaffel, L., Boets, B., and Ghesquiere, P. (2009). Working memory and individual differences in mathematics achievement: a longitudinal study from first grade to second grade. *J. Exp. Child Psychol.* 103, 186–201. doi: 10.1016/j.jecp.2009.01.004

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition* 44, 1–42. doi: 10.1016/0010-0277(92)90049-N

LeFevre, J. A., Fast, L., Skwarchuk, S. L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., et al. (2010). Pathways to mathematics: longitudinal predictors of performance. *Child Dev.* 81, 1753–1767. doi: 10.1111/j.1467-8624.2010.01508.x

Purpura, D. J., and Ganley, C. M. (2014). Working memory and language: skill-specific or domain-general relations to mathematics? *J. Exp. Child Psychol.* 122, 104–121. doi: 10.1016/j.jecp.2013.12.009

Szűcs, D. (2016). Subtypes and comorbidity in mathematical learning disabilities: multidimensional study of verbal and visual memory processes is key to understanding. *Prog. Brain Res*, 227, 277–304. doi: 10.1016/bs.pbr.2016.04.027

Von Aster, M. G., and Shalev, R. S. (2007). Number development and developmental dyscalculia. *Dev. Med. Child Neurol.* 49, 868–873. doi: 10.1111/j.1469-8749.2007.00868.x

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

frontiers in Psychology

ORIGINAL RESEARCH
published: 20 December 2016
doi: 10.3389/fpsyg.2016.01929

Factors That Influence Improvement in Numeracy, Reading, and Comprehension in the Context of a Numeracy Intervention

Ann Dowker *

Experimental Psychology, University of Oxford, Oxford, UK

In a randomized controlled trial 104 primary school children, who received an individualized numeracy intervention, Catch Up Numeracy, were compared with 100 children, who received matched-time teaching, and 107, who received business-as-usual teaching. They were assessed before and after intervention, on the Number Screening Test and on both the reading and comprehension components of the Salford Sentence Reading Test. Those who received the intervention improved significantly more than the controls in numeracy but not in reading or comprehension. Numeracy, reading, and comprehension scores were significantly correlated. Both reading and numeracy predicted improvement in comprehension, but only comprehension predicted improvement in reading, and neither literacy measure predicted improvement in numeracy. Children eligible for free school meals scored lower than others on all pre-tests and post-tests, but did not differ in their levels of improvement. Age negatively predicted improvement in reading and comprehension, but not numeracy. Gender affected comprehension but not reading or numeracy.

Keywords: intervention studies, randomized controlled trial, numeracy, reading, reading comprehension, primary school children, influences on academic improvement, gender

OPEN ACCESS

Edited by:
Bert De Smedt,
KU Leuven, Belgium

Reviewed by:
Luis J. Fuentes,
University of Murcia, Spain
Evelyn Kroesbergen,
Utrecht University, Netherlands

***Correspondence:**
Ann Dowker
ann.dowker@psy.ox.ac.uk

Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *20 April 2016*
Accepted: *24 November 2016*
Published: *20 December 2016*

Citation:
Dowker A (2016) Factors That Influence Improvement in Numeracy, Reading, and Comprehension in the Context of a Numeracy Intervention. Front. Psychol. 7:1929. doi: 10.3389/fpsyg.2016.01929

INTRODUCTION

This study deals with an investigation of certain factors that influence children's levels of improvement in response to a mathematics intervention. We will discuss both the general levels of response to the mathematics intervention, and the question of whether the extent of progress is influenced by children's performance in measures of literacy.

Evidence shows that reading and mathematical abilities are correlated, and in particular that reading and mathematical disabilities often show comorbidity (Miles et al., 2001; Fuchs et al., 2004; Dirks et al., 2008; Rubinsten, 2008; Slot et al., 2016). Moreover, children with comorbid mathematics and reading disabilities tend to do less well on mathematical tasks than children with mathematical disabilities without reading disabilities (Jordan and Montani, 1997; Jordan and Hanich, 2000; Jordan et al., 2003). This association is far from invariable and discrepancies between reading and arithmetic are common (Jordan et al., 2003; Landerl et al., 2009). Some studies suggest that there are common factors underlying mathematical and reading disabilities, e.g., phonological abilities (Slot et al., 2016). Other studies suggest that this may be only true of those who do have comorbid reading and mathematical difficulties. Moll et al. (2015) found that children with mathematical difficulties alone tend to have deficits in processing numerosities, while those with combined reading and mathematical difficulties tend to have deficits in phonological awareness.

It is important to understand more about the relationships between reading and arithmetic, in order to increase our understanding of both arithmetical development and reading development in their own right, and possibly of the factors that may influence the nature, treatment and outcomes of reading difficulties and arithmetical difficulties.

There are several issues that limit the conclusions that can be drawn with regard to existing studies of the influences of reading ability on the nature and outcomes of children's mathematical difficulties. One is that most studies have compared children who have mathematical difficulties with and without comorbid reading difficulties, but have not investigated the effects of continuous variations in reading ability on mathematical difficulties. Another is that neither arithmetic nor reading is a unitary ability.

Arithmetical ability is not a single entity but is made up of many components (Dowker, 2005, 2015) and different components appear to be differentially related to reading ability. It is usually found that reading difficulties are more associated with difficulties in retrieval of arithmetical facts than with other aspects of arithmetic (Miles et al., 2001; Simmons and Singleton, 2006, 2009; Goebel and Snowling, 2010).

Reading also has different components: most notably decoding ability and comprehension. Most studies of the relationships between reading and mathematics have not separated the effects of decoding (usually treated as synonymous with reading) and comprehension. Those studies, that have separated the two, have tended to suggest that decoding is more associated with arithmetical fluency, possibly because phonological awareness contributes to both (De Smedt et al., 2010; Jordan et al., 2010) while comprehension is more associated with mathematical reasoning and word problem solving (Pimperton and Nation, 2010; Vukovic et al., 2010; Bjork and Bowyer-Crane, 2013; Bjorn et al., 2016).

Most studies of the relationships between reading and arithmetic have been cross-sectional and have not involved longitudinal studies. In particular, few have looked at the influence of either reading or arithmetic on response to intervention in the other subject. An exception is a study by Fuchs et al. (2004). They gave a 16-week mathematical problem-solving intervention to children who were assessed to be at risk of reading disability, mathematics disability, both or neither. All at-risk groups showed less improvement than the no-risk group in computation and labeling; and those at risk of both showed less improvement in conceptual underpinnings. However, mathematics-related abilities were better predictors of improvement than reading-related abilities. Thus, it seems that reading-related limitations are a negative predictor of improvement in mathematics, but not as much as mathematical limitations.

Although mathematics-related limitations have in some studies (Fuchs et al., 2004) proved a negative predictor of improvement as well as current performance, we predicted that initial mathematics score would be a negative predictor of improvement, since parallel forms of the same test were being used, and there is more room for improvement if scores are lower to start with.

The present study was carried out in the context of an evaluation, funded by the Education Endowment Fund of a numeracy intervention. The evaluation included pre-tests and post-tests not only in numeracy but in reading (decoding) and comprehension, making it possible to investigate both the specificity of effects of the intervention on numeracy, and more generally, whether numeracy influenced performance and improvement in reading or comprehension, and vice versa. There was also some information about the children's socio-economic status, which made it possible to investigate its effects on performance and improvement in all the domains studied.

The intervention studied was Catch Up™ Numeracy, developed by the author in collaboration with Graham Sigley and the Catch Up™ Trust (Dowker and Sigley, 2010; Holmes and Dowker, 2013; Dowker and Morris, 2014). The target pupils for this intervention are primary school pupils, who have numeracy difficulties (not necessarily amounting to dyscalculia), and its key focus is assessing and targeting specific strengths and weaknesses. The intervention begins by assessing the children on 10 components of early numeracy. Each child is assessed individually by a trained teacher/teaching assistant. This assessment is used to construct a "Catch Up Numeracy" learner profile, which determines the entry level for each of the 10 Catch Up Numeracy components and the appropriate focus for numeracy teaching. Children are provided with mathematical games and activities targeted to their specific levels in specific activities.

The children receive two 15-min sessions per week for ∼30 weeks, focusing on the components with which they have difficulty.

The 10 components include: (1) Counting orally; (2) Counting objects; (3) Reading and writing numbers; (4) Comparing, adding and subtracting tens and units; (5) Ordinal numbers; (6) Word problems; (7) Translation between different formats (numerals, number words and sets of objects; (8) Derived fact strategies (the use of known facts, combined with arithmetical principles such as commutativity, to derive new facts; e.g., if $8 + 6 = 14$, then $6 + 8$ must also be 14); (9) Estimation of quantities and of answers to arithmetic problems and (10) Remembered number facts.

For a detailed account of the intervention programme, see Holmes and Dowker (2013). The focus of the present study is more on the characteristics in children that may influence improvement in general, and response to intervention in particular.

The present investigation involved a randomized controlled study, which compared children, who underwent the intervention, with controls, who received business-as-usual teaching. There was an additional control group, who received equivalent time for individualized numeracy intervention not using Catch Up. However, this part of the study proved problematic, as the randomization of the groups was within schools, and there was evidence that there was often communication between the staff involved, so that the staff supposedly administering the equivalent-time measure were often adopting Catch Up techniques from other staff (this issue is being addressed in an ongoing follow-up study). Several predictions were made.

(1) On the basis of earlier findings (Dowker and Sigley, 2010; Holmes and Dowker, 2013), it was predicted that children who underwent Catch Up Numeracy would show more improvement than controls.
(2) It was predicted that girls might perform better at reading and comprehension, given that studies often show better literacy performance by girls (e.g., OECD, 2015).
(3) No gender difference was expected for improvement in any of the domains.
(4) It was predicted that pupils eligible for free school meals would perform less well in all domains, given that most studies show a strong effect of SES on academic performance (e.g., Melhuish et al., 2008; Dickerson and Popli, 2016).
(5) It was also expected at pupils eligible for free school meals might also show less improvement and, in the case of mathematics, less response to intervention, on the basis of somewhat parallel findings with regard to literacy (Torgesen et al., 1999).
(6) It was predicted that chronological age might negatively predict improvement in all domains, as any weaknesses might become harder to correct, whether by external intervention or by standard teaching, as children become older.
(7) As most studies show that academic skills correlate with one another and with IQ (e.g., see Mellanby and Theobald, 2014), it was expected that scores in reading, comprehension and numeracy would all correlate significantly with one another; and that all would correlate with an IQ measure.
(8) As regards influences on improvement, it was tentatively predicted that reading would predict levels of improvement in comprehension and vice versa, but that numeracy would not influence improvement in either.
(9) It was, however, expected that reading would influence improvement in, and possibly response to, intervention in numeracy, but that comprehension would not. This was because the numeracy task predominantly involved computation and number understanding, and contained only a small element of word problem solving; and previous findings had suggested the former are more strongly related to decoding and the latter to comprehension (e.g., Fuchs et al., 2004).

METHODS

Ethics

The NFER has a well-developed Code of Practice that contains detailed ethical protocols. These protocols govern all research undertaken by NFER and the trial lies within them.

Parents gave active written consent for all eligible pupils put forward for the intervention and testing, and the Catch Up team confirmed that consent had been received before continuation of the trial.

Parental consent was obtained (see above). Interventions were carried out by teachers or teaching assistants already employed by the schools. All researchers involved in testing had undergone enhanced Criminal Records Bureau/ Disclosure and Barring Services checks.

Design and Participants

The larger-scale study originally included 336 participants. All had been selected by their schools as low attainers in numeracy, who might benefit from intervention. Six pupils from each of 53 primary schools were randomly assigned to one of three groups: a control group that received business-as-usual teaching, a Catch Up Numeracy intervention group that received the intervention as described above, and an "matched time" group that received two 15 min sessions a week without Catch Up Numeracy, to replicate the one to one nature of the intervention. One hundred and twelve pupils were assigned to each group. Due to 25 children moving from their schools, or being consistently absent for tests, the number of participants was reduced to 311: 104 in the Catch Up Numeracy group, 100 in the Matched Time group, and 107 in the Business as Usual group.

The 311 children included 146 boys (49 in the Catch Up group, 39 in the Matched Time group and 58 in the Business as Usual group) and 165 girls. The overall mean age of the participants was 97.51 months with a standard deviation of 14.85. The ages of the different groups are given in **Table 1**. An ANOVA showed no significant group difference in ages.

Tests

Before the start of intervention, the children were given the Non-Reading Intelligence Test (Young and McCarty, 2012); the Numeracy Screening Test (Gillham et al., 2012) and the New Salford Sentence Reading Test (Bookbinder et al., 2012). The latter includes tests of both Reading and Comprehension. They were given parallel forms of the same tests, ∼8 months later, after the intervention; except for the Non-Reading Intelligence Test, which was not repeated.

RESULTS

Table 1 gives the mean starting ages of the children in the Catch Up, Matched Time, and Business as Usual groups and their initial standard scores, for all the tests. A multivariate analysis of variance was carried out with Assignment (Catch Up vs. Matched Time vs. Business as Usual) as the grouping factor, and Age, Non-Reading Intelligence Test standard score, and initial standard scores in Numeracy, Reading, and Comprehension as the dependent variables. The table gives the resulting *F*-values, *p*-values, and effect sizes (partial eta squared). The multivariate $F_{(5, 306)} = 1.34$; $p = 0.25$; partial eta squared = 0.021.

As can be seen, there were no significant differences between the groups in age or in any of the initial test scores.

Table 2 gives the post-test scores. A multivariate analysis of variance was carried out with Assignment (Catch Up vs. Matched Time vs. Business as Usual) as the grouping factor, and post-test standard scores in Numeracy, Reading, and Comprehension as the dependent variables. The table gives the resulting *F*-values, *p*-values, and effect sizes (partial eta squared). The multivariate $F_{(3, 308)} = 2.03$; $p = 0.11$; partial eta squared = 0.019.

Again, none of the comparisons were significant.

TABLE 1 | Starting ages and initial test scores in all groups and results of ANOVAs comparing the groups.

Group	Catch up	Matched time	Business as usual	Total	Degrees of freedom	*F*	*p*	Partial eta squared
N	104	100	107	311	–	–	–	–
Age in months	96.56 (14.69)	97.39 (14.89)	98.03 (15.16)	97.51 (14.9)	2, 309	0.317	0.728	0.002
NRIT standard score	90.91 (14.46)	94.89 (16.6)	93.33 (13.27)	93.02 (14.85)	2, 309	1.855	0.158	0.012
Numeracy pre-test standard score	80.3 (12.19)	82.74 (12.7)	82.75 (10.91)	81.89 (11.96)	2, 309	1.549	0.214	0.01
Reading pre-test standard score	96.54 (18.99)	100.02 (19.65)	96.02 (18.43)	97.48 (19.04)	2, 309	1.32	0.268	0.009
Comprehension pre-test standard score	98.96 (16.6)	101.35 (17.0)	97.03 (15.95)	99.06 (16.55)	2, 309	1.76	0.174	0.011

TABLE 2 | Post-test scores in all groups and results of ANOVAs comparing groups.

Group	Catch up	Matched time	Business as usual	Total	Degrees of freedom	*F*	*p*	Partial eta squared
N	104	100	107	311	–	–	–	–
Numeracy post-test standard score	89.02 (14.36)	90.97 (14.65)	87.65 (11.53)	89.68 (13.58)	2, 309	1.961	0.142	0.013
Reading post-test standard score	99.49 (20.42)	102.51 (17.33)	97.95 (17.58)	99.97 (18.5)	2, 309	1.365	0.257	0.009
comprehension post-test standard score	100.87 (16.54)	103.68 (14.67)	99.75 (15.55)	101.48 (15.64)	2, 309	1.521	0.22	0.01

Table 3 gives the standard score gains in Numeracy, Reading, and Comprehension. A multivariate analysis of variance was carried out with Assignment (Catch Up vs. Matched Time vs. Business as Usual) as the grouping factor, and standard score gains in Numeracy, Reading, and Comprehension as the dependent variables. The table gives the resulting *F*-values, *p*-values, and effect sizes (partial eta squared). The multivariate $F_{(3, 308)} = 2.295$; $p = 0.078$; partial eta squared = 0.022.

As can be seen, there was a significant effect of Assignment on Numeracy Standard Score Gain, but not on gains in Reading or Comprehension. Tamhane 2 *post-hoc* tests showed that the Catch Up group made significantly more gains in Numeracy than the Business as Usual group, but neither the Catch Up group nor the Business as Usual group differed significantly from the Matched Time group.

A univariate analysis of covariance was carried out to investigate whether there were group differences in Numeracy standard score gain *after* controlling for Numeracy pre-test Standard score, Age, and Non-reading Intelligence standard score. Numeracy pre-test Standard score was a highly significant covariate [$F_{(1, 306)} = 50.7$; $p < 0.001$; partial eta squared = 0.42] and Age was also independently significant [$F_{(1, 306)} = 5.09$; $p = 0.025$; partial eta squared = 0.0.016]. Non-reading Intelligence was not a significant covariate [$F_{(1, 306)} = 2.234$; $p = 0.136$; partial eta squared = 0.007]. The main effect of Assignment (Catch Up vs. Matched Time vs. Business as Usual) remained significant [$F_{(2, 306)} = 3.667$; $p = 0.027$; partial eta squared = 0.023].

Other measures of numeracy gain were examined, and gave similar results. The mean gain in months in Number Age over the intervention period was 17.56 months (*s.d.* 13.07) for the Catch Up group, 16.89 (*s.d.* 14.99) for the Matched Time group, and 12.68 months (*s.d.* 12.19) for the Business as Usual group. Gain in Number Age was divided by gain in chronological age to give the Ratio Gain (so that if a child gained exactly as many months in Number Age as they had in chronological age, the Ratio Gain would be 1). The mean Ratio Gain was 2.14 (*s.d.* 1.58) for the Catch Up group. 2.11 (*s.d.* 1.81) for the Matched Time group, and 1.54 (*s.d.* 1.47) for the Business as Usual Group.

A further multivariate of variance were performed with Assignment (Catch Up vs. Matched Time vs. Business as Usual) as the grouping factor; and Number Age Gain and Ratio Gain as the dependent variables. The multivariate $F_{(2, 309)} = 4.914$; $p = 0.008$; partial eta squared = 0.03. There were significant group differences for Number Age Gain [$F_{(2, 309)} = 4.39$; $p = 0.013$; partial eta squared = 0.027] and for Ratio Gain [$F_{(1, 209)} = 4.71$; $p = 0.01$; partial eta squared = 0.029]. Tamhane 2 *post-hoc* tests showed that for Number Age Gain, the Catch Up Numeracy group differed significantly from the Business as Usual Group, but the Matched Time group did not differ significantly from either; and that for Ratio Gain, the Catch Up Numeracy and Matched Time groups differed significantly from the Business as Usual group, but not from one another.

Gender Effects

Table 4 gives boys' and girls' pre-test standard scores, for all the tests. A multivariate analysis of variance was carried out with Gender (Boys vs. Girls) as the grouping factor, and Non-Reading Intelligence Test standard score, and pre-test standard scores in Numeracy, Reading, and Comprehension as the dependent variables. The table gives the resulting *F*-values, *p*-values, and effect sizes (partial eta squared). The multivariate $F_{(4, 307)} = 5.48$; $p < 0.001$; partial eta squared = 0.063.

As can be seen, girls scored higher in both the intelligence test and the comprehension test, but there were no significant gender differences in numeracy or in reading.

Table 5 gives boys' and girls' post-test standard scores, for all the tests. A multivariate analysis of variance was carried out

TABLE 3 | Gains in standard scores in all groups and results of ANOVAs comparing groups.

Group	Catch up	Matched time	Business as usual	Total	Degrees of freedom	*F*	*p*	Partial eta squared
N	104	100	107	311	–	–	–	–
Numeracy standard score gain	8.73 (11.77)	8.22 (13.56)	4.79 (1.79)	7.19 (12.14)	2, 309	3.276	0.039	0.021
Reading standard score gain	2.59 (11.05)	2.97 (14.19)	1.93 (11.73)	2.49 (12.37)	2, 309	0.185	0.831	0.001
Comprehension standard score gain	1.91 (14.87)	2.28 (13.93)	2.42 (14.26)	2.2 (14.32)	2, 309	0.034	0.967	0.000

TABLE 4 | Pre-test scores of boys and girls and results of ANOVAs comparing genders.

	Boys	Girls	Total	Degrees of freedom	*F*	*p*	Partial eta squared
N	146	165	311	–	–	–	–
Non-reading intelligence test standard score	90.79 (14.41)	95.01 (14.99)	93.02 (14.85)	1, 310	6.325	0.012	0.02
Numeracy pre-test standard score	82.37 (13.61)	81.44 (13.39)	81.89 (11.96)	1, 310	0.478	0.49	0.001
Reading pre-test standard score	97.29 (20.68)	97.56 (17.44)	97.48 (19.04)	1, 310	0.017	0.896	0
Comprehension pre-test standard score	97.08 (16.75)	101.1 (15.76)	99.06 (16.55)	1, 310	4.81	0.029	0.015

TABLE 5 | Post-test scores of boys and girls and results of ANOVAs comparing genders.

	Boys	Girls	Total	Degrees of freedom	*F*	*p*	Partial eta squared
N	146	165	311	–	–	–	–
Numeracy standard score post-test	89.48 (13.61)	88.78 (13.39)	89.68 (13.57)	1, 310	0.213	0.644	0.001
Reading standard score post-test	100.28 (20.37)	99.8 (16.68)	99.97 (18.5)	1, 310	0.053	0.819	0
Comprehension standard score post-test	101.54 (16.41)	101.46 (14.98)	101.48 (15.64)	1, 310	0.002	0.967	0

with Gender (Boys vs. Girls) as the grouping factor, and pre-test standard scores in Numeracy, Reading, and Comprehension as the dependent variables. The table gives the resulting *F*-values, *p*-values, and effect sizes (partial eta squared). The multivariate $F_{(3, 308)} = 0.066$; $p < 0.978$; partial eta squared $= 0.001$.

As can be seen, there were no significant gender differences in any of the post-test scores.

Table 6 gives boys' and girls' standard store gains. A multivariate analysis of variance was carried out with Gender (Boys vs. Girls as the grouping factor, and standard score gains in Numeracy, Reading, and Comprehension as the dependent variables. The table gives the resulting *F*-values, *p*-values, and effect sizes (partial eta squared). The multivariate $F_{(4, 307)} = 2.107$; $p < 0.099$; partial eta squared $= 0.099$.

The only significant group difference was for Comprehension Standard Score Gain, where boys made greater gains.

Effects of Free School Meal Status

Table 7 gives the initial standard scores on all tests for the children in the Free School Meals and No Free School Meals groups. A multivariate analysis of variance was carried out with Free School Meal status (Free School Meals vs. No Free School Meals) as the grouping factor, and Non-Reading Intelligence Test standard score, and initial standard scores in Numeracy, Reading, and Comprehension as the dependent variables. The table gives the resulting *F*-values, *p*-values, and effect sizes (partial eta squared). The multivariate $F_{(4, 307)} = 9.91$; $p < 0.001$; partial eta squared $= 0.11$.

Table 8 gives the post-test standard scores on all tests for the children in the Free School Meals and No Free School Meals groups. A multivariate analysis of variance was carried out with Free School Meal status (Free School Meals vs. No Free School Meals) as the grouping factor, and post-test standard scores in Numeracy, Reading, and Comprehension as the dependent variables. The table gives the resulting *F*-values, *p*-values, and effect sizes (partial eta squared). The multivariate $F_{(3, 306)} = 12.12$; $p < 0.001$; partial eta squared $= 0.103$.

Table 9 gives the standard gains on all tests for the children in the Free School Meals and No Free School Meals groups. A multivariate analysis of variance was carried out with Free School Meal status (Free School Meals vs. No Free School Meals) as the grouping factor, standard score gains in Numeracy, Reading, and Comprehension as the dependent variables. The table gives the resulting *F*-values, *p*-values, and effect sizes (partial eta squared). The multivariate $F_{(3, 306)} = 1.55$; $p = 0.202$; partial eta squared $= 0.015$.

Thus, children eligible for free school meals performed significantly less well on all pre-tests and post-tests than children, who were not eligible for free school meals, despite the fact that *all* of the children were selected for their low attainment in numeracy. Socio-economic status clearly has a strong effect on primary school children's performance in literacy and numeracy. However, free school meal status had no effect on children's gains.

Similar ANOVAs were carried out with both Assignment and Free School Meals Status as grouping factors, to investigate the

TABLE 6 | Standard score gains of boys and girls and results of ANOVAs comparing genders.

	Boys	Girls	Total	Degrees of freedom	*F*	*P*	Partial eta squared
N	146	165	311	–	–	–	–
Numeracy standard score gain	7.11 (10.74)	7.34 (13.14)	7.19 (12.14)	1, 310	0.028	0.866	0
Reading standard score gain	2.99 (12.89)	2.23 (11.64)	2.49 (12.37)	1, 310	0.299	0.585	0.001
Comprehension standard score gain	4.46 (14.36)	0.37 (13.96)	2.2 (14.32)	1, 310	6.57	0.011	0.021

TABLE 7 | Mean starting ages and pre-test standard scores of children with and without free school meals and results of ANOVAs comparing groups.

	Free school meals	No free school meals	Total	Degrees of freedom	*F*	*p*	Partial eta squared
N	110	211	311	–	–	–	–
Non-reading intelligence standard score	87.69 (13.19)	95.22 (14.89)	92.69 (14.76)	1, 310	20.110	<0.001	0.058
Numeracy pre-test standard score	76.94 (10.47)	84.12 (11.77)	81.71 (11.83)	1, 310	29.287	<0.001	0.083
Reading pre-test standard score	91.12 (17.75)	100.12 (18.58)	97.09 7(18.77)	1, 310	17.67	<0.001	0.052
Comprehension pre-test standard score	94.09 (16.61)	101.09 (15.85)	98.73 (16.42)	1, 310	13.769	<0.001	0.041

TABLE 8 | Mean post-test standard scores of children with and without free school meals and ANOVAs comparing groups.

	Free school meals	No free school meals	Total	Degrees of freedom	*F*	*p*	Partial eta squared
N	110	201	311	–	–	–	–
Numeracy post-test standard score	85.37 (12.41)	91.11 (13.48)	89.68 (13.42)	1, 310	14.888	<0.001	0.045
Reading post-test standard score	93.13 (19.23)	103.04 (17.25)	99.97 (18.51)	1, 310	19.416	<0.001	0.058
Comprehension post-test standard score	94.18 (15.56)	104.23 (14.67)	101.48 (15.64)	1, 310	30.234	<0.001	0.087

TABLE 9 | Mean standard score gains by children with and without free school meals.

	Free school meals	No free school meals	Total	Degrees of freedom	*F*	*p*	Partial eta squared
N	110	201	311	–	–	–	–
Numeracy standard score gain	8.43 (12.46)	6.66 (11.79)	7.26 (12.03)	1, 310	1.504	0.221	0.004
Reading standard score gain	2.01 (13.31)	2.92 (11.87)	2.61 (12.36)	1, 310	0.375	0.541	0.001
Comprehension standard score gain	0.09 (13.72)	3.23 (14.49)	2.17 (14.29)	1, 310	3.362	0.068	0.11

possibility of interactions. No significant interactions were found for any of the dependent variables, so the results will not be reported further.

Correlations

Pearson correlation coefficients were computed between the initial standard scores in all three domains and the Non-Reading Intelligence standard score, and between these scores and chronological age in months. All correlations were significant. With 311 participants, Numeracy correlated highly with Reading ($r = 0.449$; $p < 0.001$) and Comprehension ($r = 0.42$: $p < 0.001$) as well as with Non-Reading Intelligence ($r = 0.279$; $p < 0.001$). Reading correlated highly with both Comprehension ($r = 0.844$; $p < 0.001$) and Non-Reading Intelligence ($r = 0.314$; $p < 0.001$). Comprehension also correlated highly with Non-Reading Intelligence ($r = 0.397$; $p < 0.001$). Age correlated significantly with standard scores in Numeracy ($r = 0.274$; $p < 0.001$), Reading ($r = 0.347$; $p < 0.001$), and Comprehension ($r = 0.339$; $p < 0.001$); but not with Non-Reading Intelligence ($r = 0.016$; $p = 0.77$).

Pearson correlation coefficients were also computed between the post-test standard scores in all three domains, and between these scores and chronological age. All correlations between scores continued to be significant. Reading correlated highly with both Comprehension ($r = 0.8$; $p < 0.001$) and Numeracy ($r = 0.376$; $p < 0.001$). Comprehension also correlated highly with Numeracy ($r = 0.358$; $p < 0.001$). Age continued to show a significant correlation with Numeracy ($r = 0.273$; $p < 0.001$) but ceased to correlate significantly with Reading ($r = 0.108$; $p = 0.113$) or Comprehension ($r = 0.046$; $p = 0.502$).

Multiple Regressions

An entry level multiple regression was carried out with Reading Standard Score Gain as the dependent variable and Initial Reading Standard Score, Age, Initial Comprehension Standard

Score, Initial Numeracy Standard Score, and Non-Reading Intelligence Standard Score as the predictors. $R^2 = 0.212$; $F_{(5, 306)} = 15.958$, $p < 0.001$. Initial Reading Standard Score was a significant negative predictor [$\beta = -0.478$, $t_{(306)} = -4.704$, $p < 0.001$] as was Age [$\beta = -0.27$, $t_{(306)} = -4.759$, $p < 0.001$]. Initial Comprehension Standard Score was an independent positive predictor [$\beta = 0.204$; $t_{(306)} = 1.978$; $p = 0.049$], but Initial Numeracy Standard Score was not a significant predictor [$\beta = 0.053$, $t_{(306)} = 0.862$; $p = 0.389$] and nor was Non-Reading Intelligence Standard Score [$\beta = 0.063$, $t_{(306)} = 1.042$; $p = 0.298$].

Another entry level multiple regression was carried out with Comprehension Standard Score Gain as the dependent variable and Initial Comprehension Standard Score, Age, Initial Reading Standard Score, Initial Numeracy Standard Score, and Non-Reading Intelligence Standard Score as the predictors. $R^2 = 0.461$; $F_{(5, 306)} = 29.46$, $p < 0.001$. Initial Comprehension Standard Score was a significant negative predictor [$\beta = -0.841$, $t_{(306)} = -8.86$, $p < 0.001$] as was Age [$\beta = -0.219$, $t_{(306)} = -4.174$, $p < 0.001$]. Initial Reading Standard Score was an independent positive predictor [$\beta = 0.405$, $t_{(306)} = 4.346$; $p < 0.001$]. There were trends toward Initial Numeracy Standard Score [$\beta = -0.106$, $t_{(306)} = 1.855$, $p = 0.065$] and Non-Reading Intelligence Standard Score [$\beta = -0.106$, $t_{(306)} = 1.896$, $p = 0.059$] being independent positive predictors, but neither reached significance.

An entry level multiple regression was carried out with Numeracy Standard Score Gain as the dependent variable and Initial Reading Standard Score, Age, Initial Comprehension Standard Score, and Initial Numeracy Standard Score as the predictors. $R^2 = 0.196$; $F_{(5, 306)} = 14.487$; $p < 0.001$). The significant independent predictors were Initial Numeracy Standard Score, which was a strong negative predictor [$\beta = -0.485$, $t_{(5, 306)} = -7.77$; $p < 0.001$] and Initial Comprehension Standard Score, which was a positive predictor [$\beta = 0.301$, $t_{(5, 306)} = 2.896$; $p = 0.004$]. There was no significant effect of Age [$\beta = -0.046$, $t_{(5, 306)} = 0.801$, $p = 0.424$], Initial Reading Standard Score [$\beta = -0.068$, $t_{(5, 306)} = -0.66$, $p = 0.51$] or Non-Reading Intelligence Standard Score [$\beta = -0.009$, $t_{(5, 306)} = 0.155$, $p = 0.877$] Similar results were obtained when the same multiple regressions were carried out separately for the Catch Up group, the Matched Time group, and Business as Usual group. Initial Numeracy Standard Score was a strong negative predictor of Numeracy Standard Score Gain in the Catch Up group [$\beta = -0.351$, $t_{(5, 99)} = -2.92$; $p = 0.004$], the Matched Time group [$\beta = -0.546$, $t_{(5, 95)} = -5.100$; $p < 0.004$], and the Business as Usual group [$\beta = -0.506$, $t_{(5, 102)} = -4.976$; $p < 0.001$]; but none of the other predictors was significant in either group.

DISCUSSION

Firstly, the results show that, as predicted (Prediction 1), those who underwent the interventions significantly more improvement in numeracy than those who did not. They showed an average of nearly 5 months greater gain in number age and over four points greater gain in standard score than those who underwent "business as usual." Analysis of ratio gains showed that children who underwent intervention also showed more than twice the level of improvement that would be expected from the passage of time alone, Thus, the results support earlier findings that the Catch Up Numeracy intervention leads to a significant improvement in mathematics performance (Dowker and Sigley, 2010; Holmes and Dowker, 2013). There was no significant effect of the numeracy intervention on improvement in reading or comprehension, indicating that the effect was specific to numeracy.

There was, however, no significant difference in improvement between children who underwent the Catch Up Numeracy intervention and the Matched Time intervention; though it was found that the Catch Up Numeracy intervention differed significantly from the Business as Usual intervention, while the Matched Time intervention did not. In previous studies, the Catch Up Numeracy intervention had resulted in significantly more improvement than Matched Time intervention (Dowker and Sigley, 2010; Holmes and Dowker, 2013). It is possible that the current results are due to a contamination effect, as the teaching assistants delivering the Catch Up Numeracy and Matched Time interventions were in the same schools, and interview evidence suggests that some of the teaching assistants delivering Matched Time interventions were influenced by input from those delivering Catch Up Numeracy interventions. An ongoing randomized controlled study is currently being conducted to compare Matched Time with Catch Up Numeracy.

It is notable that the children in general showed improvement in all tests between pre-test and post-test. This may be due to regression to the mean; to "Hawthorn effects" of being in schools that were part of a study programme even in the case of controls; or to increased familiarity with test expectations, even though they were given parallel forms rather than repetitions of the same test.

There were a few factors that appeared to affect initial performance, level of improvement or both. Gender had very little effect. Prediction (2) that girls would do better on reading and comprehension tests was only partially confirmed. They did do better on the comprehension pre-test, but not the post-test; and they did not differ in reading. The group somewhat atypical, as the children had been selected for being low attainers in arithmetic; though their scores on literacy measures were much higher than those on arithmetic. Prediction (3) that gender would not influence improvement was broadly supported, Gender had virtually no influence on performance, with one exception: boys made significantly more gains in Comprehension than did girls. This seems to be due to the fact that they started at a lower point, but ended at the same point. This result is a little hard to interpret, and would need further replication to ensure that the findings are not due to chance. If replicated, it may reflect some differences between boys and girls as regards the timing of developmental changes in language comprehension.

In accordance with Prediction 4, one factor that strongly influenced performance was SES, as indicated by free school meal status. Children, who were eligible for free school meals, performed much less well than other children in all domains, both at pre-test and post-test. However, contrary to Prediction 5, free school meal status did not influence level of improvement in any of the domains, nor did it show any interaction with intervention group assignment with regard to improvement in numeracy. Thus, while there is a striking effect of socio-economic status on academic performance, even within a group already selected for low achievement in arithmetic, it does not appear to influence the chances of improvement, or the response to intervention.

Unexpectedly, chronological age was positively correlated with initial standard scores in all the tested domains, despite the fact that the scaling is carried out to control for age. One possible explanation may be that older children did not have to be as markedly delayed as younger children for teachers to note that they were having difficulties and recommend them for intervention. In accordance with Prediction 6, age was a negative predictor of improvement in Reading and Comprehension, even after controlling for initial scores. However, age did not predict improvement in numeracy, either overall or in any of the Assignment groups. Thus, the prediction that age might be negatively associated with improvement was supported for the literacy measures, but not for numeracy. This is not due to intervention nullifying this relationship, since age was not associated with numeracy improvement in the Business as Usual group any more than in the intervention groups. Presumably as a result of this negative association between age and improvement, the correlations between age and the literacy measures disappeared between pre-test and post-test, while the correlations between age and Numeracy persisted.

In accordance with Prediction 7, standard scores in all domains correlated with one another, with the highest correlation being between Reading and Comprehension; and IQ correlated with all the pre-test standard scores. Gains in Reading and Comprehension correlated significantly with one another, but not with gains in Numeracy. Multiple regressions showed that in all domains, initial scores were negative predictors of gains in the same domain, presumably because the lower the initial score, the more room there is for improvement.

In accordance with Prediction 8, initial score in Reading predicted progress in Comprehension, and vice versa, indicating that these are indeed two closely related abilities, longitudinally as well as concurrently.

Contrary to Prediction 9, neither initial Reading score nor initial Comprehension score predicted improvement in Numeracy, whether for the Catch Up group, the Matched Time group the Business as Usual group, or the sample as a whole. Thus, it seems that, while literacy measures do correlate with numeracy, they do not influence children's mathematical progress, or the effectiveness of intervention, and the factors that influence progress in literacy seem to be different from those that influence gains in Numeracy. Intriguingly, initial score in Numeracy predicted progress in Comprehension but not in Reading. This had not been expected, either in terms of the direction of the association, or in terms of the greater association between mathematics and comprehension than between mathematics and reading. The latter was especially unexpected, in view of the fact that the mathematics test was one of numeracy, rather than mainly involving the word problem solving and mathematical reasoning abilities, previously found to be more associated with comprehension. However, it is noteworthy that Haarlar et al. (2012) carried out a twin study involving 12-year-olds, there and found higher genetic and phenotypic correlations between mathematics and reading comprehension than between mathematics and word decoding.

There are some limitations to this study that should be addressed in future studies. As mentioned above, one is the need for an equivalent time group, which avoids the problem of cross-contamination by using between-school rather than within-school randomization. Also, it would be desirable if possible to match children more precisely on their test scores at the start. Although the initial differences between groups were non-significant, the Catch Up group showed a somewhat lower initial Numeracy score than the Business as Usual group (see **Table 1**), seemingly resulting in the fact that although they showed significantly greater gains, they did not differ significantly in the post-test Numeracy score when not controlling for initial Numeracy score.

It would also be of considerable interest to carry out studies that include interventions in Reading and Comprehension as well as Numeracy, in order to be able to assess influences on response to intervention in these literacy measures as well as in numeracy.

Finally, it would be desirable to look at the factors influencing improvement in these domains over a wider range of ability in these domains. Would the same factors influence or fail to influence improvement in Numeracy children who were initially performing at average and above-average levels, as in these children, who were selected for weaknesses in arithmetic? Would the finding that, for example, initial Numeracy score predicted improvement in Comprehension but not vice versa be replicated in a group who were better at Comprehension than Numeracy to start with? Would such predictive relationships differentiate between children with specific difficulties in literacy or numeracy and those who are performing poorly in all academic domains?

In any case, the results indicate that relationships between different abilities, and between these abilities and other factors such as age, are not simple or static. Future studies should focus more on how such relationships change over time, and how initial factors may predict changes over time in general, and response to interventions in particular.

There are several implications for education. One is that a structured individualized system of one-to-one teaching can lead to quite significant improvement in children with numeracy difficulties, and it does not need to be highly intensive to be effective. Another is that, at least among primary school children, such interventions can be effectively delivered at any age: age did not affect the level of improvement that children showed. Children's socio-economic status, as shown by free school meal status, also does not seem to affect response to intervention, though it does affect the overall level of performance. The results suggest that there are strong concurrent correlations between numeracy and literacy measures. However, they do not suggest a strong *longitudinal* relationship between numeracy and literacy. Numeracy improvement, whether within or outside the context of intervention, was not predicted by either reading or comprehension. However, it appears that numeracy, at least in a group selected as low attainers in numeracy, can to some extent predict children's progress in reading comprehension (but not decoding), at least in the short term. Since there was no such relationship in the reverse direction, it is unlikely to indicate a strong intrinsic relationship between numeracy and comprehension. It is possible, however, that numeracy is a prerequisite for, but not a consequence of, improvement in comprehension; though there appear to be no previous studies indicating such a relationship. More likely, some domain-general ability may be influencing both. Such an ability is unlikely general logical reasoning, as the intelligence measure used in this study did not predict improvement in comprehension, and the relationship between initial numeracy level and comprehension remained significant even after controlling for this measure.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

FUNDING

The Education Endowment Foundation provided funding for the intervention study, on which this article is based.

ACKNOWLEDGMENTS

I am grateful to Graham Sigley and the Catch Up™ Trust for their collaboration. The Education Endowment Fund provided financial support. The National Foundation for Educational Research acted as external evaluator for the intervention project. Charli Coyte, Lauren Edison, Lucy Elliott, Stephanie Gedge, Alix Hibble, Kalaiyashni Puvanendran, Natalie Rowe, and Dr. Peter Morris assisted in collecting data.

REFERENCES

Bjork, I. M., and Bowyer-Crane, C. (2013). Cognitive skills used to solve mathematical word problems and numerical operations: a study of 6-to 7-year-old children. *Eur. J. Psychol. Educ.* 28, 1345–1360. doi: 10.1007/s10212-012-0169-7

Bjorn, P. M., Aunola, K., and Nurmi, J. E. (2016). Primary school text comprehension predicts mathematical word problem skills in secondary school. *Educ. Psychol.* 36, 362–377. doi: 10.1080/01443410.2014.992392

Bookbinder, G. E., McCarty, C., and Lallaway, M. (2012). *New Salford Sentence Reading Test*. London: Hodder.

De Smedt, B., Taylor, J., Archibald, L., and Ansari, D. (2010). How is phonological processing related to individual differences in children's arithmetic skills? *Dev. Sci.* 13, 508–520. doi: 10.1111/j.1467-7687.2009.00897.x

Dickerson, A., and Popli, G. K. (2016). Persistent poverty and children's cognitive development: evidence from the UK Millennium Cohort Study. *J. R. Stat. Soc. A* 179, 535–558. doi: 10.1111/rssa.12128

Dirks, E., Spyer, G., Van Lieshout, E., and De Sonneville, L. (2008). Prevalence of combined reading and arithmetical disabilities. *J. Learn. Disabil.* 41, 460–473. doi: 10.1177/0022219408321128

Dowker, A. (2005). *Individual Differences in Arithmetic: Implications for Psychology, Neuroscience and Education.* Hove: Psychology Press.

Dowker, A. (2015). "Individual differences in arithmetical abilities: the componential nature of arithmetic," in *Oxford Handbook of Mathematical Cognition*, eds R. Cohen Kadosh and A. Dowker (Oxford: Oxford University Press), 878–894.

Dowker, A., and Morris, P. (2014). "Interventions for children with difficulties in learning mathematics," in *The Routledge International Handbook of Dyscalculia and Mathematical Learning Difficulties*, ed S. Chinn (London: Routledge), 256–264.

Dowker, A., and Sigley, G. (2010). Targeted interventions for children with arithmetical difficulties. *Br. J. Educ. Psychol. Monogr.* 11, 65–81. doi: 10.1348/97818543370009X12583699332492

Fuchs, L. S., Fuchs, D., and Prentice, K. (2004). Responsiveness to mathematical problem-solving instruction: comparing students at risk of mathematics disability with and without risk of reading disability. *J. Learn. Disabil.* 37, 293–306. doi: 10.1177/00222194040370040201

Gillham, B., Hesse, K., and McCarty, C. (2012). *Basic Number Screening Test, 4th Edn*. London: Hodder.

Goebel, S. M., and Snowling, M. J. (2010). Number processing skills in adults with dyslexia. *Q. J. Exp. Psychol.* 63, 1361–1373. doi: 10.1080/17470210903359206

Haarlar, N., Kovas, Y., Dale, P. S., Petrill, S. A., and Plomin, R. (2012). Mathematics is differentially related to reading comprehension and word decoding: evidence from a genetically sensitive design. *J. Educ. Psychol.* 104, 622–635. doi: 10.1037/a0027646

Holmes, W., and Dowker, A. (2013). Catch Up Numeracy: a targeted intervention for children who are low-attaining in mathematic. *Res. Math. Educ.* 15, 249–265. doi: 10.1080/14794802.2013.803779

Jordan, J. A., Wylie, J., and Mulhern, G. (2010). Phonological awareness and mathematical difficulties: a longitudinal perspective. *Br. J. Dev. Psychol.* 28, 89–97. doi: 10.1348/026151010X485197

Jordan, N. C., and Hanich, L. B. (2000). Mathematical thinking in second-grade children with different forms of LD. *J. Learn. Disabil.* 33, 567–578. doi: 10.1177/002221940003300605

Jordan, N. C., Hanich, L. B., and Kaplan, D. (2003). A longitudinal study of mathematical competencies in children with spedific mathematical difficulties versus children with comorbid mathematics and reading difficulties. *Child Dev.* 74, 834–850. doi: 10.1111/1467-8624.00571

Jordan, N. C., and Montani, T. O. (1997). Cognitive arithmetic and problem solving: a comparison of children with specific and general mathematics difficulties. *J. Learn. Disabil.* 30, 624–634. doi: 10.1177/002221949703000606

Landerl, K., Fussenegger, B., Moll, K., and Wilburger, E. (2009). Dyslexia and dyscalculia: two learning disorders with different cognitive profiles. *J. Exp. Child Psychol.* 103, 309–324. doi: 10.1016/j.jecp.2009.03.006

Melhuish, E. C., Phan, M. B., Sylva, K., Sammons, P., Siraj-Blatchford, I., and Taggart, B. (2008). Effects of the home learning environment and preschool center experience upon literacy and numeracy development in early primary school. *J. Soc. Issues* 64, 95–114. doi: 10.1111/j.1540-4560.2008.00550.x

Mellanby, J., and Theobald, K. (2014). *Education and Learning: An Evidence-Based Approach*. Oxford: Wiley-Blackwell.

Miles, T. R., Haslum, M. M., and Wheeler, T. J. (2001). The mathematical abilities of dyslexic 10-year-olds. *Ann. Dyslexia* 51, 299–321. doi: 10.1007/s11881-001-0015-0

Moll, K., Göebel, S., and Snowling, M. J. (2015). Basic number processing in children with specific learning disorders: comorbidity of reading and mathematics disorders. *Child Neuropsychol.* 21, 399–417. doi: 10.1080/09297049.2014.899570

OECD (2015). *The ABC of Gender Equality in Education: Aptitude, Behaviour, Confidence.* PISA, OECD Publishing.

Pimperton, H., and Nation, K. (2010). Understanding words, understanding numbers: an exploration of the mathematical profiles of poor comprehenders. *Br. J. Educ. Psychol.* 80, 255–268. doi: 10.1348/000709909X477251

Rubinsten, O. (2008). Co-occurrence of developmental disorders: The case of developmental dyscalculia. *Cogn. Dev.* 2008, 363–370. doi: 10.1016/j.cogdev.2009.09.008

Simmons, F. M., and Singleton, C. (2006). The arithmetical difficulties of adults with dyslexia. *Dyslexia* 12, 96–114. doi: 10.1002/dys.312

Simmons, F. M., and Singleton, C. (2009). The mathematical strengths and weaknesses of children with dyslexia. *J. Res. Spec. Educ. Needs* 9, 154–163. doi: 10.1111/j.1471-3802.2009.01128.x

Slot, E. M., Van Viersen, S., De Bree, E., and Kroesbergen, E. H. (2016). Shared and unique risk factors underlying mathematical disability and reading and spelling disability. *Front. Psychol.* 7:803. doi: 10.3389/fpsyg.2016.00803

Torgesen, J. K., Wagner, R. K., Rashotte, C. A., Rose, E., Lindamood, P., Conway, T., et al. (1999). Preventing reading failure in young children with phonological processing disabilities: group and individual responses to instruction. *J. Educ. Psychol.* 91, 579–595. doi: 10.1037/0022-0663.91.4.579

Vukovic, R. K., Leseaux, N. K., and Siegel, L. S. (2010). The mathematics skills of children with reading difficulties. *Learn. Individ. Differ.* 20, 639–643. doi: 10.1016/j.lindif.2010.08.004

Young, D., and McCarty, C. (2012). *New Non-Reading Intelligence Tests 1-3.* London: Hodder

Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

REVIEW
published: 10 November 2016
doi: 10.3389/fpsyg.2016.01617

A Review about Functional Illiteracy: Definition, Cognitive, Linguistic, and Numerical Aspects

Réka Vágvölgyi[1], Andra Coldea[2], Thomas Dresler[1,3], Josef Schrader[1,4] and Hans-Christoph Nuerk[1,5,6]**

[1] LEAD Graduate School & Research Network, University of Tuebingen, Tuebingen, Germany, [2] School of Psychology, University of Glasgow, Glasgow, Scotland, [3] Department of Psychiatry and Psychotherapy, University of Tuebingen, Tuebingen, Germany, [4] German Institute for Adult Education – Leibniz Centre for Lifelong Learning, Bonn, Germany, [5] Department of Psychology, University of Tuebingen, Tuebingen, Germany, [6] Knowledge Media Research Center – Leibniz Institut für Wissensmedien, Tuebingen, Germany

OPEN ACCESS

Edited by:
Bert De Smedt, KU Leuven, Belgium

Reviewed by:
Jascha Ruesseler, University of Bamberg, Germany
Sarit Ashkenazi, Hebrew University of Jerusalem, Israel

***Correspondence:**
Réka Vágvölgyi
reka.vagvoelgyi@lead.uni-tuebingen.de
Hans-Christoph Nuerk
hc.nuerk@uni-tuebingen.de

Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

***Received:** 29 January 2016*
***Accepted:** 03 October 2016*
***Published:** 10 November 2016*

Citation:
Vágvölgyi R, Coldea A, Dresler T, Schrader J and Nuerk H-C (2016) A Review about Functional Illiteracy: Definition, Cognitive, Linguistic, and Numerical Aspects. Front. Psychol. 7:1617. doi: 10.3389/fpsyg.2016.01617

Formally, availability of education for children has increased around the world over the last decades. However, despite having a successful formal education career, adults can become functional illiterates. Functional illiteracy means that a person cannot use reading, writing, and calculation skills for his/her own and the community's development. Functional illiteracy has considerable negative effects not only on personal development, but also in economic and social terms. Although functional illiteracy has been highly publicized in mass media in the recent years, there is limited scientific knowledge about the people termed functional illiterates; definition, assessment, and differential diagnoses with respect to related numerical and linguistic impairments are rarely studied and controversial. The first goal of our review is to give a comprehensive overview of the research on functional illiteracy by describing gaps in knowledge within the field and to outline and address the basic questions concerning who can be considered as functional illiterates: (1) Do they possess basic skills? (2) In which abilities do they have the largest deficits? (3) Are numerical and linguistic deficits related? (4) What is the fundamental reason for their difficulties? (5) Are there main differences between functional illiterates, illiterates, and dyslexics? We will see that despite partial evidence, there is still much research needed to answer these questions. Secondly, we emphasize the timeliness for a new and more precise definition that results in uniform sampling, better diagnosis, conclusion, and intervention. We propose the following working definition as the result of the review: functional illiteracy is the incapability to understand complex texts despite adequate schooling, age, language skills, elementary reading skills, and IQ. These inabilities must also not be fully explained by sensory, domain-general cognitive, neurological or mental disorders. In sum, we suggest that functional illiteracy must be more thoroughly understood and assessed from a theoretical, empirical, and diagnostic perspective.

Keywords: functional illiteracy, literacy, illiteracy, dyslexia, adults

ON THE IMPORTANCE OF LITERACY

About Literacy

According to the recent literacy rate, 85% of the adult population in the world is literate, and therefore worldwide about 757 million people are illiterate (UNESCO, 2015). Large-scale assessments measuring literacy skills indicate that in developing countries, illiteracy is more prevalent, while in developed countries, functional illiteracy is more prevalent (Bhola, 1995, p. 18). According to the Organization for Economic Co-operation and Development (OECD), literacy is defined as follows:

> "*Literacy is defined as the ability to understand, evaluate, use, and engage with written texts to participate in society, achieve one's goals, and develop one's knowledge and potential* (OECD, 2013, p. 59)." More detailed, find other institutions, e.g., UNESCO.

Literacy and basic knowledge cannot be clearly separated from each other. Even though the term "literacy" is a part of basic knowledge, it is a precondition as well as an outcome of basic knowledge. Literacy may refer to the ability to read and write, but also to application-oriented basic knowledge that develops during the whole lifetime, not only during school years (Nickel, 2007).

Formal literacy has increased over the last decades. For instance, while in sub-Saharan Africa there are still 29.8 million children who do not have access to education, this number represents a one-quarter decrease from 2000. In contrast, in Europe "only" 0.7 million of children had never attended school in 2011 (UNESCO, 2013). However, despite improvements in formal literacy, many people still have problems understanding formal texts. On the one hand, this is a problem because in today's society, functioning literacy plays a significant role. It appears in every aspect of daily life, e.g., opening bank accounts, reading ingredients of food products, understanding medication or technical instructions, signing contracts, etc. (Cree et al., 2012). On the other hand, this leads to fewer educational and employment opportunities and hinders living a successful life.

Possessing literacy has many benefits for individuals, families, communities, and nations. The improvement in literacy levels has beneficial effects on individual (e.g., self-esteem), political (e.g., democratic values), cultural (e.g., cultural openness), social (e.g., children's health), and economic (e.g., individual income) levels (UNESCO, 2006). On the other hand, functioning in a society without literacy becomes more difficult: those who cannot acquire basic literacy skills have fewer opportunities in every area of life (Cree et al., 2012).

About (Functional) Illiteracy

So far, we have talked about literacy. However, many people do not achieve literacy because of inadequate schooling or even despite adequate schooling. On 1949, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) set the generalized functionality of literacy. The acquisition of reading and writing was regarded as basic rights: people should be enabled to become functionally literate in their own culture (Bhola, 1995). A need for a standard and a workable definition materialized to differentiate between literates and non-literates (illiterates) and also to distinguish various levels in between. The result of the demand was realized at the General Conference of the UNESCO in 1978:

> *"A person is literate who can with understanding both read and write a short simple statement on his everyday life.*
> *A person is illiterate who cannot with understanding both read and write a short simple statement on his everyday life.*
> *A person is functionally literate who can engage in all those activities in which literacy is required for effective functioning of his group and community and also for enabling him to continue to use reading, writing, and calculation for his own and the community's development.*
> *A person is functionally illiterate who cannot engage in all those activities in which literacy is required for effective functioning of his group and community and also for enabling him to continue to use reading, writing, and calculation for his own and the community's development (UNESCO, 1978, p.183)."*

The difference between literate and illiterate people is explicit here: illiterates had never attended school and are unable to read or write even single words while literates can (Reis and Castro-Caldas, 1997).

In contrast with literacy and illiteracy, the difference between functional illiteracy, literacy and illiteracy is not obvious enough. Functionality, which is the essence of the difference between these terms, was never operationally defined. Recently, the number of functional illiterates in Europe was estimated to be about 80 million, their proportion is lowest in Sweden with 8% and highest in Portugal with 40% (e.g., in Eme, 2011; Grotlüschen and Riekmann, 2011a). However, the frequently referred original International Adult Literacy Survey (IALS) report does not imply functional illiteracy (OECD and Statistics Canada, 2000). Different definitions and different diagnostic assessment standards can lead to fundamentally different epidemiological estimations, so any estimations of functional illiteracy rates may be unreliable.

DIAGNOSTICS OF FUNCTIONAL ILLITERACY: DIFFERENT APPROACHES

As there is no explicit assessment for functional illiteracy, researchers had to find other techniques to assess the number of functional illiterates or to identify functional illiterates for experimental studies.

The UNESCO, the OECD and the IEA (International Association for the Evaluation of Educational Achievement) measure literacy and other key knowledge skills of children, young adults, and adults a large-scale, international assessment about strengths and weaknesses in different countries. Research such as the IALS and the Adult Literacy and Life Skills Survey (ALL) build on each other (Thorn, 2009; UNESCO, 2009). These kinds of international tests generally measure literacy and numeracy skills in various ways, including mapping the whole literacy spectrum and grouping the performance and the abilities into discrete levels. The international, supranational and national political actors are first interested in large-scale assessments, not in individual diagnostics. Against this background, it is understandable (but nevertheless at least unfortunate) that the diagnostic materials lack test criteria (reliability, construct validity, criterion validity), which are demanded in standard individual diagnostic tests.

The IALS, the ALL, and the PIAAC (Survey of Adult Skills) all contain *prose and document literacy tasks* that purport to understand and use information from different text formats. The *quantitative literacy* and *numeracy tasks* measure arithmetic abilities in all three assessments, but *problem solving tasks* are only included in the ALL and in the PIAAC study (**Table 1**). However, these studies usually analyze literacy in a theoretical way and give no practical diagnostic advice regarding the assessment of *functional* illiteracy. It can be only a conclusion from the result of the lowest achievement level.

A common way of diagnosing functional illiterates is based on the *years of schooling*. However, the standard seems to vary among cultures. In the USA, 12 years of schooling marks the limit of functional literacy (Bhola, 1995), while in Latin America, only 7 years of effective schooling is sufficient to exceed the level of functional illiteracy (Infante, 2000 In. Martinez and Fernandez, 2010). In the European Union, the compulsory education is between 9 and 13 years, so children can leave school between age 14 and 18 (European Commission, 2014/2015). Therefore, we cannot consider compulsory education as the only diagnostic attribute of functional illiteracy.

Another common diagnostic practice is using *grade-equivalent scores* and *reading-level match designs*. This concept is concrete, easy to understand, and it does not require a new specific test because the researchers use general standardized assessments. This method is mostly used when low literate adults are assessed and compared with primary school children (Greenberg et al., 1997; Thompkins and Binder, 2003; Greenberg, 2007; Rüsseler et al., 2011; Grosche, 2012; Eme et al., 2014). Comparing children who have already acquired basic reading, writing, and mathematical skills with low literate (functional illiterate) adults could answer a few questions. The developmental differences between children and adults can cause problems in interpreting the results of such studies.

The German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung) organized a national strategy to reduce the number of people who do not acquire basic literacy skills. To explore the problem, Grotlüschen and Riekmann constructed a representative household survey, the Level One Study (leo.). They specified five alpha-levels a priori in the lea. (Literalitätsentwicklung von Arbeitskräften; Grotlüschen et al., 2011), however, the validity of these five alpha-levels (even their eventual borders) has not yet been – to the best of our knowledge – never systematically evaluated in a diagnostic manner. Nevertheless, these five levels were applied to the leo. The lea. was constructed to measure employees' different competence domains, including literacy and aimed to support individual teaching and development instead of comparing a person to a social norm (Grotlüschen et al., 2011). The leo. aimed to assess people on the lower end of the literacy spectrum. The authors identified functional illiterates as those who perform in the first, second, or third level in the leo. According to their results, 14.5% of the working-age population (about 7.5 million people) in Germany is functionally illiterate (Grotlüschen and Riekmann, 2011a). It is important to note that 3.1 million adults (41%) of the estimated functional illiterate population were not native German speakers (Grotlüschen et al., 2014). This is a point which we view as critical, because despite general reading and writing skills, we are all functional illiterates in most foreign languages. In our view (outlined below), language production and comprehension do not need to be that of a native speaker, but should at least be mastered without major problems before a specific deficit in functional illiteracy can be diagnosed. Otherwise, what seems to be a fundamental reading problem is simply a problem of not mastering sufficiently a foreign language. Finally, and unfortunately, the test lacks multivariate analyses of construct validity and only descriptive statistics are available. Consequently, results and conclusions have to be interpreted with caution.

The authors suggest the individual differences resulting from various social roles make it impossible to create a general functional illiteracy test. They argue that different skills are required, for example for a highly qualified IT expert or a motor mechanic (Grotlüschen and Riekmann, 2011b).

For specific professions this is a valid argument, but it also raises the question of whether a general construct of literacy exists. To return to the example, in everyday life, IT experts and motor mechanics have to operate machines (e.g., laundry machine), have to read their bank statements, have to take medicine (and read package inserts), have to compare prices

TABLE 1 | Summary of international assessments.

	Date	Number of countries	Tasks	Proficiency scales
IALS (Thorn, 2009)	1994–1998	23	1. Prose literacy 2. Document literacy 3. Quantitative literacy	Level 1–5
ALL (Statistics Canada and OECD, 2005)	2002–2006	12	1. Prose literacy 2. Document literacy 3. Numeracy 4. Problem solving	1. Level 1–5 2. Level 1–5 3. Level 1–5 4. Level 1–4
PIAAC (OECD, 2013)	2011–2012	24	1. Literacy (prose + document) 2. Numeracy 3. Problem solving in technology rich environments	1. Below level 1–5 2. Below level 1–5 3. Below level 1–3

in the supermarket, etc. Therefore, we assume that some basic functional literacy skills should exist.

While the leo. is not considered a universal instrument for functional illiteracy by its authors, the Tests of Adult Basic Education (TABE) is a universal instrument to assess the mastery of basic skills and skills-growth measurement. The test includes practical, life-skills stimuli in an adult-relevant context (life-skills, work, and education) and contains tasks from the very low literacy level (e.g., recognizing letters, signs) to the advanced level (CTB/McGraw-Hill, 2008). The comprehensibility of the measured skills and the universality of the tasks suggest that it is possible to create an assessment to measure functional illiteracy, despite the fact that the main aim of the assessment is different.

It is important to note that functional illiterates (as low literate adults) would show floor effects in standard adult literacy (AL) and text comprehension tasks. This would make appropriate identification and within-group distinctions impossible. Therefore, it is worth considering the application of standardized tests for children to measure functional illiteracy. On the one hand, Egloff et al. (2011) argue for a *competence-based approach* to identify functional illiterates instead of a *norm-oriented view*. They suggest that it would be better to take different social expectations into account and handle the category of functional illiteracy as a less static phenomena. But on the other hand, they accept to use reading and spelling tasks (with child norms) with well-defined cut-off values to classify functional illiterates (Egloff et al., 2011).

To sum up, many methods have been used to identify functional illiterates, but none of these methods are yet standardized and systematically diagnostically evaluated in a representative sample of functional illiterates and adults. Therefore, they cannot be considered adequate for measuring and identifying functional illiterates on the basis of the current data.

WHO IS DEFINED AS FUNCTIONAL ILLITERATE?

Functional illiteracy is assumed to originate from cognitive or linguistic disorders and/or be associated with a sociocultural disadvantage (Eme, 2011; Boltzmann and Rüsseler, 2013). The diagnostic assessments and therefore the definition of the sample in different studies is not consistent and sometimes not even explicit.

For a rough categorization, we can divide sample definition of functional illiteracy in scientific publications into three groups:

(1) Some studies call their sample "functional illiterates," but do not give any reason/explanation/diagnostic justification (Van Linden and Cremers, 2008; Kosmidis et al., 2011). From an educational-psychological perspective, it is not acceptable to categorize a subgroup without any empirical reason for doing so.

(2a) Some studies conduct experiments on adults taking part in basic courses [AL or adult basic education (ABE) classes] and call them functional illiterates (Thompkins and Binder, 2003). The similarity between functional illiterates and AL or ABE students is appropriate but has its shortcomings. In particular, it is not evident why people take these courses. Did they have sufficient schooling and nevertheless did not learn to read and write? Did they have insufficient schooling for whatever reason without the chance to become literate? Do they have profound reading/writing problems or are they taking these courses for other reasons (e.g., because the job center recommends doing them)? In short, the problem is that we have no assessment of how severe their functional illiteracy problem really is and whether we are encountering functional illiteracy or real illiteracy due to insufficient schooling.

(2b) It should be noted that there is also another group of studies concerning those who conduct experiments on AL or ABE students but do not call them functional illiterates (Greenberg et al., 1997; MacArthur et al., 2010). Despite that, theoretical backgrounds and reviews (e.g., Eme, 2011) frequently use these articles, which point out one main limitation of the field.

(3) Only a German and a French research group made explicit how they determine functional illiteracy in their studies. From the German side, Grosche (2012) used reading-level match design is his dissertation and labeled those ABE students as functional illiterates, who performed in two standardized reading tests in the level of first–fourth grade children (Grosche, 2012). While Rüsseler et al. (2013) used German diagnostic reading and spelling tests and involved only those adults to their intervention study who performed worse than average fourth grade level (Boltzmann and Rüsseler, 2013; Boltzmann et al., 2013; Rüsseler et al., 2013)[1]. The French group measured five components: phonological processing, orthographic processing, sentence comprehension, reading speed, and reading comprehension. Those ABE students who performed below the third grade level were then classified as functional illiterates (Eme et al., 2010). Three problems stick:

(i) The deficits of adult groups are defined as (severe) developmental delays. This cannot be taken for granted; for many adult deficits, and even for dyslexia, different patterns of deficits and developmental delays have been observed.

(ii) Even if one accepts that functional illiteracy is merely developmental delay, there is an inconsistency as regards the severity of the delay. While Rüsseler et al. (2013) suggest lower performance than (average) fourth grade level, Eme et al. (2010) suggest a more severe performance deficit even below third grade level.

(iii) The components for defining functional illiteracy differ between studies: while Rüsseler and colleagues use reading and spelling tests (Boltzmann and Rüsseler, 2013; Boltzmann et al., 2013; Rüsseler et al., 2013), Eme et al. (2010) use a much broader range of test components. It

[1]The authors explicitly wrote this criteria only in Rüsseler et al. (2013, p. 242) but as they speak about the evaluation of the same training program in Boltzmann and Rüsseler (2013) and in Boltzmann et al. (2013), we suppose that they used the same inclusion criteria.

is still unknown which approach is more valid. In most definitions, functional illiteracy is mainly about impaired understanding of texts. We suggest that diagnostic tests should operationalize this definition and focus on impaired understanding of texts, until other test components prove important for diagnostic assessment of functional illiteracy.

In sum, there is inconsistency in definition and assessment of functional illiterates in the scientific literature. There are only a few studies that include well-established methods in the fundamental sampling question. As the literature lacks a clear definition and clear assessment criteria, we use the term "functional illiterate" to refer to all the participants from the three groups of scientific papers.

Factors Contributing to Functional Illiteracy – The Scientific Aspect[2]

Unfortunately, few studies[2] investigated differential diagnostic properties of functional illiteracy. Although there are related deficits that may or may not be part of functional illiteracy depending on the definition and the assessment tool. Here, we focus on three of these related deficits: language-related deficits, general cognitive deficits, and deficits related to numerical abilities (Supplementary Tables S1–S3).

Language-Related Deficits

The few articles that assess the basic skills of their specific sample separately have shown that functional illiterates have phonological processing deficits. Their profile is more similar to children with developmental dyslexia than to typical elementary school children. Adults performed much worse in phonological tasks than children matched for reading-level (Greenberg et al., 1997; Thompkins and Binder, 2003; Grosche, 2012; Eme et al., 2014).

Functional illiterates' spelling skills are also weak (Greenberg et al., 1997; Thompkins and Binder, 2003; Eme et al., 2014): They rely more on orthographic processes (Greenberg et al., 1997), although they may also have orthographic processing difficulties (Greenberg et al., 1997; Thompkins and Binder, 2003; Eme, 2006). A comparison with reading-level matched children showed that their vocabulary size is also smaller (Greenberg et al., 1997; Eme et al., 2014) and they are slower in naming tasks (Grosche, 2012). Although functional illiterates seem to be a heterogeneous group, on the whole they performed poorer in phonology than in morphosyntax and semantics, with their low performance in oral language tasks being reflected in their written abilities (Eme et al., 2014).

This issue is further complicated by the fact that functional illiterates may not be a homogeneous sample. Eme et al. (2010) suggested that functional illiterates can be divided into five subtypes according to their oral narrative abilities (Eme et al., 2010). However, when the same research group examined the relationship between reading, spelling, and oral language abilities in a later study, the cluster analysis showed four profiles (Eme et al., 2014). So, the subtyping problem is not resolved yet.

Other papers (Eme, 2006; Grotlüschen and Riekmann, 2011a; Rüsseler et al., 2011; Eme et al., 2014) mention that functional illiterates have problems in text understanding but only one study examined whether more fundamental factors cause this difficulty. The paper that compared matched normal readers with functional illiterates and children with reading and writing disabilities found that the perceptual skills of functional illiterates are weak but have no impact on reading abilities (Rüsseler et al., 2011).

In sum, functional illiterates seem to have linguistic deficits in several domains, including phonological, orthographic and lexical processing, oral and reading comprehension, and verbal fluency. However, these deficits may not be homogeneous. It is important to note that correlated or co-morbid deficits are not necessarily functionally causal. What is more, they do not necessarily add unique variance to the diagnostic assessment. Finally, we do not know whether the linguistic inabilities described above are their main difficulties or whether these are due to or influenced by other more general cognitive factors (Supplementary Table S1).

Cognitive Deficits

Cognitive deficits of functional illiterates have also been reported. Van Linden and Cremers (2008) showed that functional illiterates performed significantly worse than literates not only in language processing, but also in all cognitive tasks such as in copying and recalling the Rey Complex Figure, visual organizational, and visual memory, mental spatial orientation as well sustained or split attention tasks (Van Linden and Cremers, 2008).

Functional illiterates seem to have working memory difficulties: they performed worse than reading-level matched children (Eme, 2006; Grosche, 2012) and than normal adult readers (Grosche, 2012) in the verbal tasks. Comparing functional illiterates with children matched for reading-level, adults performed better on a backward, while they did not differ in a forward digit span task (Thompkins and Binder, 2003). However, the studies only used digit or letter span tasks (Thompkins and Binder, 2003; Eme, 2006; Grosche, 2012).

As regards perceptual skills, functional illiterates perform similar to children with reading and writing disabilities and differ from regular adult readers. This supports a developmental delay view on functional illiteracy (Rüsseler et al., 2011). The authors suggest that perceptual training could develop functional illiterates, as it improved the reading and spelling performance of children with reading and writing disabilities (Rüsseler et al., 2011).

In sum, it is clear that functional illiterates deviate from adults; their performance seems to be more similar to children. However, basic control variables (e.g., intelligence) are often missing, when the cognitive abilities of functional illiterates are assessed. Moreover, again participant selection could drive the results and the subsequent interpretations of deficits. Nevertheless, the available data point to the view that functional illiterates seem

[2]Relevant studies for this review were identified by (1) carrying out a keyword search in EBSCOhost, PsycInfo, and Google Scholar. It was conducted for keywords functional illiteracy, illiteracy, literacy, adult dyslexia, child dyslexia, and several variations of these keywords and the basic abilities that we mention in Supplementary Tables S1–S3. (2) And we were conducting a manual search for references cited in relevant papers.

to show various cognitive deficits. However, the question about whether these deficits are (partially) causal for the functional illiteracy or just co-morbid impairments remains unanswered so far (Supplementary Table S2).

Deficits Related to Numerical Abilities and Dyscalculia

Although numerical abilities are measured as one of the basic skills and are considered as part of functional illiteracy (e.g., in IALS as quantitative literacy, Thorn, 2009; in ALL and in PIAAC as numeracy, Statistics Canada and OECD, 2005; OECD, 2013), research on numerical deficits in functional illiteracy has largely been neglected (Supplementary Table S3). Therefore, further experimental studies are needed to answer the question whether functional illiterates have numerical difficulties or not.

(Functional) Illiteracy Programs – The Practical Aspect

In order to eradicate illiteracy, governments, NGOs (non-governmental organization) and supranational agencies such as UNESCO fund numerous programs worldwide (Abadzi, 2003), but the programs are assessed with great skepticism in the literature (Shi and Tsang, 2008). It is important to note that the ABE programs are rarely targeted explicitly at functional illiterates, as they generally aim to increase the participants' literacy skills[3].

In Western societies, adult literacy programs are often offered to vulnerable or hard-to-reach learners. Some programs rely extensively on the use of technology and distance learning platforms (e.g., AlphaRoute in Canada), others are tailored to each participant's needs, both in workshops and individual help (e.g., Fight Against Illiteracy in France). According to their main interest, we can differentiate from general literacy courses the work- (e.g., El Trabajo En Red Como Proyecto Educativo in Spain) and family-oriented (e.g., Family Literacy Project in Germany) programs (Aker et al., 2010). Former supports the (re)integration to labor market (Bhola, 1995), while latter's key-strategy called the "Teach the parents – reach the children" approach in which parents and their children are working both separately and together. It aims at a long-term effect in the education of next generation (Nickel, 2007). Furthermore, supplementing literacy and numeracy classes with technology, even mobile phones, is restricted by its reduced availability (Aker et al., 2010).

Adult basic education classes are still struggling to overcome high drop-out rates, failure to pass literacy tests, and a fast deterioration of literacy skills. High drop-out rates are associated with younger age, worse blending, slower naming, and comprehension skills, as well as increased avoidance of reading difficult materials. Furthermore, current/past enrollment in ABE classes increased the probability of midpoint completion (Greenberg et al., 2012). Therefore, the programs should pay more attention to the participants that fall within these categories. In Germany, Rüsseler et al. (2012) created and investigated the effects of a special training program called Alpha Plus. While the regular literacy courses offer reading and writing classes once a week, the intensive Alpha Plus training does not only improve reading and writing skills. But it builds also on the progress of other basic, daily and work-related abilities (e.g., perceptual and social skills). The program is clearly more effective than the regular classes offered to functional illiterates by the adult education schools in Germany. The efficiency of Alpha Plus was confirmed by behavioral, ERP, and fMRI studies (Rüsseler et al., 2012; Boltzmann and Rüsseler, 2013; Boltzmann et al., 2013; Rüsseler et al., 2013). The success of the program is evident but the authors stress the large variability between the participants. The achievement would be larger if it could better handle individual differences (e.g., with more groups with smaller sizes; Rüsseler et al., 2013) and follow a more personalized adaptive learning approach.

To sum up, solving the problem of illiteracy and functional illiteracy is relevant to governments and various organizations and their efficiency show up in statistics (UNESCO, 2015). But the development of programs based on scientific research (e.g., Alpha Plus: Rüsseler et al., 2012) could improve the efficacy of the programs and the persistence of the students.

[3] http://www.unesco.org/uil/litbase/?menu=7

DISSOCIATING FUNCTIONAL ILLITERACY FROM ILLITERACY AND DYSLEXIA

For establishing a solid picture about the construct of functional illiteracy, it is necessary to distinguish it from related constructs such as illiteracy and developmental dyslexia, and to define non-overlapping characteristics. Without such dissociation, functional illiteracy is just a new name for a deficit that is already part of other constructs.

Functional Illiteracy and Illiteracy: What Does Functionality Mean?

Illiteracy is a well-defined phenomenon and the diagnostic criteria for this group are clear-cut. It has been investigated since the 1970s and researchers have investigated many characteristics of illiteracy (Huettig and Mishra, 2014). According to the original notion, the difference between functional illiterates and illiterates is that illiterates are unable to read, write, and understand short sentences. In contrast functional illiterates are unable to use their acquired literacy skills in daily life (UNESCO, 1978), e.g., to read and understand a medicine label or a bank statement, fill out a job application, compare the cost of two items and choose the item that offers the best value (Cree et al., 2012).

When we outline these studies, we focus on the same three related groups of deficits we distinguished for functional illiterates (Supplementary Tables S1–S3).

Language-Related Deficits in Illiterates

As the illiterates have never attended school and did not acquire basic language skills, they differ in most language-related abilities. It is known that phonemic awareness is not attained spontaneously, since associations of phonemes with graphemes emerge with reading acquisition (Morais et al., 1979).

Indeed, performances on phoneme addition, discrimination, deletion, and pseudoword repetition tasks (e.g., Greenberg et al., 1997; Thompkins and Binder, 2003) clearly demonstrated that illiterates have phonological processing deficits (Morais et al., 1979; Rosselli et al., 1990; Reis and Castro-Caldas, 1997; Castro-Caldas et al., 1998).

Decreased performance was shown also in orthographic (Petersson et al., 2000) and in lexical processing (Kosmidis et al., 2006) when low literate and literate adults were compared.

In addition, researchers observed impairments in naming ability (Rosselli et al., 1990; Ostrosky-Solis et al., 1999; Reis et al., 2006), in oral comprehension (Rosselli et al., 1990; Ostrosky-Solis et al., 1999) and in verbal fluency skills (Rosselli et al., 1990; Reis and Castro-Caldas, 1997; Ostrosky-Solis et al., 1999; Kosmidis et al., 2004) as well. Yet, it is important to mention that when using ecologically more valid categories in the verbal fluency task (e.g., supermarket), the difference can disappear (Reis et al., 2003).

In sum, illiterates can be characterized by impairments in the whole spectrum of language-related skills (Supplementary Table S1), which are less variable than those of functional illiterates.

Cognitive Deficits in Illiterates

As lack of reading and writing acquisition affects language skills, could it be assumed that basic cognitive functions also depend on it? The need for assessing the cognitive abilities of illiterates materialized many years ago.

Illiterates performed significantly worse than the three other assessed educated groups (1–4; 5–9; 10–24 years of education) in abilities as orientation, verbal fluency, attention, perception, and motor functions (Ostrosky-Solis et al., 1999; Dansilio and Charamelo, 2005; Landgraf et al., 2011). The latter was confirmed in visuo-motor integration tasks as well: while literates used a systematic visual scanning strategy, illiterates were less systematic and slower in a computerized visual-motor task (Bramão et al., 2007).

Oral cultures have better long-term memory abilities, as they can preserve their traditional songs by rote learning (Huettig and Mishra, 2014). Conversely, illiterates did not succeed in standardized working memory tasks (Ardila et al., 1989; Reis et al., 2003; Kosmidis et al., 2011; Silva et al., 2012). In addition, Kosmidis et al. (2011) revealed that literacy *per se* and not formal schooling affected working memory skills.

In sum, illiterates perform worse in various cognitive skills than literates. The deficits seem more universal than in studies with functional illiterates. Lack of education and basic skill acquisition have been brought forward as the reason for the weakness of cognitive skills in illiterates (Ardila et al., 1989; Rosselli et al., 1990) (Supplementary Table S2).

Deficits Related to Numerical Abilities in Illiterates

Although illiterates never attended school and never acquired number reading and writing, the majority of the tests that examine mental calculation or basic arithmetical abilities were administered to illiterates in written form. It is not surprising that these studies solidly verified that illiterates have poor mental calculation or basic arithmetical abilities (Ostrosky-Solis et al., 1999; Reis et al., 2003; Landgraf et al., 2011; Silva et al., 2012). Only one experiment gave calculations orally where the illiterates achieved low score as well (Rosselli et al., 1990). However, it is also possible that the deficits extend to basic number sense. Halberda and Feigenson (2008) have shown that early processing of non-symbolic information long before formal schooling influences arithmetic performance at a later age (Halberda and Feigenson, 2008). Whether the so-called approximate number system (ANS) – measured by non-symbolic magnitude comparison – really contributes to symbolic and arithmetic performance when other symbolic factors are controlled is a matter of intense discussion (De Smedt et al., 2013; Lyons et al., 2015). The answer to this question is not easy as performance in ANS tasks and their correlations with arithmetic seem to depend on the particular method involved (Dietrich et al., 2015). Nevertheless, it would be helpful to assess more basic numerical abilities like the ANS or spatial-numerical capabilities (Siegler and Opfer, 2003; Moeller et al., 2009) or indices of multi-digit integration (Moeller et al., 2011; Nuerk et al., 2015 for a review) to identify basic numerical deficits in functional illiterates that might lead to deficits in later more complex arithmetic tasks.

In sum, illiterates performed less accurately not only in language-related tasks, but also in cognitive and mathematical tasks. But it remains unclear whether the lack of reading acquisition, the absence of formal education, or even basic perceptual and cognitive deficits underlying more than one skill drive their functional illiteracy (Supplementary Table S3).

Functional Illiteracy and Dyslexia: Different Constructs for the Same Sample?

Is it possible that functional illiterates are dyslexics with a new name?

We have outlined above that various language deficits are part of functional illiteracy. Some authors even claim that functional illiterates can somehow count as untreated developmental dyslexics (Greenberg et al., 1997; Grosche, 2012, but see diagnostic problematic outlined above). Therefore, it is unclear whether the terms "functional illiterate" and "dyslexic" reflect different terminology used to refer to the same group of people due to preference and history of the field, rather than due to actual differences between the two groups. It is surprising that we have not found any experimental research that has investigated this thesis. Therefore, we will outline developmental dyslexia in more detail, again with the same three subsections, language-related deficits, general cognitive, and numerical deficits (Supplementary Tables S1–S3).

Language-Related Deficits in Dyslexia

Developmental dyslexia is associated with abnormalities in a variety of brain regions, and has a strong genetic basis (Lyon et al., 2003; Fletcher, 2009; Habib and Giraud, 2013). However, it is not clear whether the neurobiological changes are a cause or consequence of reading difficulties.

Dyslexic children have problems in at least three domains: decoding single words, reading fluency, and comprehension

(Fletcher, 2009). Leading theories suggest that the main problem in dyslexia is the phonological processing deficit. It can appear even at a single word level, independently of intelligence and is adequate for a dyslexia diagnosis (Ramus et al., 2003). Such a deficit in phonological awareness was confirmed in children by many studies (Joanisse et al., 2000; Casalis et al., 2004; White et al., 2006; Everatt et al., 2008; Landerl et al., 2009; Varvara et al., 2014; Zoubrinetzky et al., 2014). The most common tasks were phonological fluency (Landerl et al., 2009; Varvara et al., 2014) and manipulation with phonemes as phoneme deletion (Joanisse et al., 2000; Landerl et al., 2009; Chung et al., 2010; Zoubrinetzky et al., 2014) and spoonerism tasks (White et al., 2006; Varvara et al., 2014).

The results suggest that the phonological symptoms associated with dyslexia persist into adulthood (Hatcher et al., 2002; Ramus et al., 2003; Beidas et al., 2013; Bogdanowicz et al., 2014; Law et al., 2015). A study that compared adults with and without learning difficulties demonstrated that even high-achieving dyslexic adults are slower in phonological, semantic, and syntactic judgment tasks (Rüsseler et al., 2007).

In spelling, the tendency remains similar: both dyslexic children (White et al., 2006; Everatt et al., 2008; Chung et al., 2010) and adults (Hatcher et al., 2002; Beidas et al., 2013; Law et al., 2015) showed difficulties in their performance. In contrast, dyslexic adults performed well in the semantic fluency task (Hatcher et al., 2002) and vocabulary tasks (e.g., Cavalli et al., 2016) but the success of children were mixed (Joanisse et al., 2000; White et al., 2006; Everatt et al., 2008; Landerl et al., 2009; Varvara et al., 2014).

Nevertheless, their reading and naming speed were also significantly slower than in children and adults without learning difficulties (De Luca et al., 2002; Hatcher et al., 2002; Ramus et al., 2003; White et al., 2006; Everatt et al., 2008; Willburger et al., 2008; Boets and De Smedt, 2010; De Smedt and Boets, 2011; Beidas et al., 2013; Bogdanowicz et al., 2014; Suarez-Coalla et al., 2014; Law et al., 2015).

Basic language-related skills are necessary for accurate text comprehension (Martens and de Jong, 2006). Therefore, it is not surprising that dyslexic children and adults systematically perform below-average on reading comprehension tasks (Casalis et al., 2004; Fletcher, 2009; Rimrodt et al., 2009; Wiseheart et al., 2009; Rello et al., 2013). If texts are optimized according to word-frequency and word-length, thus using more common and shorter words, dyslexic adolescents and adults understand better and read faster written materials (Rello et al., 2013).

Dyslexia is not only categorized by phonological deficit, reading fluency, and text comprehension; it is also considered to be a heterogeneous learning disorder (Zoubrinetzky et al., 2014). Co-morbid language deficits and other cognitive difficulties are common. A regression study that aimed to examine the contribution of linguistic and cognitive factors to oral reading fluency in dyslexic adolescents found that word decoding, working memory, and vocabulary are the key predictors. The factors together explain 56% of the variance in connected-text oral reading fluency (Rose and Rougani, 2012). Despite the regression analysis, one must keep in mind that these are still correlations. Whether co-morbid cognitive difficulties causally influence reading fluency or whether linguistic deficits cause associated cognitive problems over the course of learning and development is not entirely clear yet (Beidas et al., 2013) (Supplementary Table S1).

In sum, we can conclude that dyslexic children have problems in phonological tasks, reading fluency, reading comprehension and associated linguistic and cognitive factors. Most such deficits observed in dyslexic children are preserved in adulthood. However, dyslexic adults may be able to compensate some of their deficits (e.g., in reading comprehension) and function better in language-related tasks than functional illiterates. Whether this summary of the literature holds, must be examined, with direct investigation of dyslexics and functional illiterates.

Cognitive Deficits in Dyslexia

In the last decades, auditory, visual processing, or attention deficits were suggested as being potential sources of dyslexia. Valdois et al. (2004) argue that phonological and attention deficits in dyslexic patients can present independently from each other (Valdois et al., 2004). Accordingly, dyslexics struggle with attentional and perceptual difficulties (Ramus et al., 2003; Ziegler et al., 2010; Leong et al., 2011; Beidas et al., 2013; Bogdanowicz et al., 2014; Varvara et al., 2014; Zoubrinetzky et al., 2014).

As regards cognitive abilities, most articles are examining working memory. It was shown that dyslexic children have poor working memory (Beneventi et al., 2010; Varvara et al., 2014), which remains weak during adulthood (Ramus et al., 2003; Abd Ghani and Gathercole, 2013; Beidas et al., 2013; Bogdanowicz et al., 2014). This deficit seems stable, considering that weak performance appears both in verbal (e.g., digit span, e.g., Everatt et al., 2008), in spatial (e.g., Corsi blocks, Landerl et al., 2009), and in visual (e.g., n-back, Beneventi et al., 2010) working memory tests. Exploring the four regions of executive functions (inhibition, planning, sequencing, and organizing abilities), researchers found that compensated dyslexic university students did not differ from the non-dyslexic control group in any of the functions (Brosnan et al., 2002). A more recent study showed that in a set shifting task, dyslexic adults were slower than age and IQ matched controls. In contrast, in an inhibition task the reaction time did not differ, although the accuracy depended on the task (Smith-Spark et al., 2016).

Experiments showed that dyslexic children have no problems in tasks requiring fine manual skills (White et al., 2006; Everatt et al., 2008) but they have difficulties in balancing tasks (White et al., 2006; Brookes et al., 2010). Conversely, adults did not show any problems in balance and motor coordination tasks (Ramus et al., 2003).

In sum, diverse types of cognitive difficulties are inseparable from the symptoms of dyslexia both in childhood and adulthood. Over time, dyslexics can improve some of their skills but most of their problems are remained. Nevertheless, their deficits seem less universal than in functional illiteracy (Supplementary Table S2).

Deficits Related to Numerical Abilities and Dyscalculia in Dyslexia

Research examining mathematical abilities has shown that dyslexic children and adults generally solved basic arithmetical problems slower and less accurately than children and adults without dyslexia (Hatcher et al., 2002; Simmons and Singleton, 2006; Boets and De Smedt, 2010; De Smedt and Boets, 2011).

A study examining children with reading disability and/or math disability found that all three groups showed difficulties in the examined neuropsychological measures. However, the impairments of reading and math disability group were the largest (Willcutt et al., 2013). Studies confirmed that reading and mathematical learning disabilities have independent domain-specific deficits: in the case of dyslexia in phonological processing and numerosity in the case of dyscalculia. Nevertheless, there are some common domain-general "bridge symptoms" as rapid naming (Wilson et al., 2015), working memory, processing speed, and verbal comprehension (Willcutt et al., 2013). In contrast, another experiment described that the cognitive deficits of children with dyslexia and dyscalculia were only additive (Landerl et al., 2009) (Supplementary Table S3).

The Triple-Code Model (Dehaene and Cohen, 1995) supposes three distinguished mental representations of numbers within different brain areas. According to the model, we can distinguish visual representation (established in the left and right inferior ventral occipito-temporal areas), magnitude representations (established in the left and right inferior parietal areas), and verbal representation (established in the left-hemispheric perisylvian language areas). Thus, the numerical and linguistic representations work separately. Therefore, those who have poor numerical or poor reading skills might be differentiated clearly according to their anatomical and functional brain processes (Dehaene and Cohen, 1995, 1998).

In sum, we can state that reading disabilities do not go obviously hand in hand with mathematical weaknesses, therefore, not just dyslexics and dyscalculics but also functional illiterates and functional innumerates may represent separate groups (Supplementary Tables S1–S3).

SUMMARY, NEW DEFINITION, AND FURTHER CHALLENGES

From the outline of the review, it is clear that the field of functional illiteracy has been under-represented in research despite its worldwide effects on social and economic levels (UNESCO, 2006) and although millions of dollars are invested in remediation programs of (functional) literacy.

In this review, we clarified our knowledge about functional illiterates, especially how different approaches try to diagnose them, and in what areas they differ from illiterates and dyslexics.

We summarized the challenges of empirical research that hinder the researchers of the field as the lack of an adequate assessment and resources for programs and researches.

A comprehensive, exploratory examination is needed to guarantee the success of the literacy programs. This examination should assess in detail the basic foundations and the variables that play a crucial role in functional illiteracy, emphasizing not only the language, but the mathematical-related and cognitive skills which are essential in everyday life.

The first step in that direction is to establish a new, up-to-date definition that is adequate for experimental research:

Functional illiteracy is the incapability to understand complex texts[4] despite adequate schooling, age, language skills, elementary reading skills, and IQ. These inabilities must also not be fully explained by sensory, domain-general cognitive, neurological or psychiatric deficits.

Here we suppose the main criteria and justification that a working definition should contain:

Inclusion criteria:

- very poor performance in a functional illiteracy assessment: despite the fact that there is no consensus about an operationalized definition of functional illiteracy, many self-claimed assessments tried to measure it, but there is no standardized and validated tool for this aim[5],
- age: older than 16 years old. We suppose that children cannot be categorized as functional illiterates,
- schooling: minimum 6–8 finished years, in agreement with the duration of compulsory education for single countries (in Germany it means 9 years),
- proper (German) language use: fluent, native-like oral language skills without major difficulties (natives, bilinguals). We should take with great care people with migration background because we cannot be sure whether a person shows weakness because he/she is a functional illiterate or because he/she has difficulties in second language acquisition. Nevertheless, being a native speaker is in our view not a necessary criterion if the second language is sufficiently well mastered in oral language,
- IQ: level of 70 or above.

Exclusion criteria:

- neurological or mental disorder,
- uncorrected speech, hearing, or vision problem.

Exclusion criteria for pure functional illiteracy:[6]

- dyslexia,
- dyscalculia,
- hyperactivity.

[4]Beyond this scope of review but we define complex text as comprising at least of two sentences with some conjunctions or subjunctions and propositional relations between these sentences. Questions concerning such tests should be impossible to answer on the basis of understanding one single sentence alone. For a more precise definition we suppose computer linguistically quantifiable measures about the readability and complexity of a text (e.g., after the methods of Vajjala and Meurers, 2014).

[5]According to our opinion, functional illiterates in general have fundamental problems in text comprehension. Therefore, we suggest using tasks based on text comprehension, enhanced with an interview about their educational background. We agree with Boltzmann and Rüsseler (2013) that children's tasks are well suited for assessing the functional illiterate sample, e.g., because of their complexity that admit of the differentiation and their short length that is not frustrating. However, these tasks have not yet been normed to low literate adults.

[6]We would like to stress that we do not want to exclude functional illiterates with dyslexia, but we would like to raise awareness that further research should pay more attention to the related linguistic and numerical impairments. It is likely that functional illiterates meet the criteria for dyslexia and because of the dissociation between dyslexia and functional illiteracy merits further investigations.

Further characteristics that describe functional illiterates:

- impaired oral language comprehension,
- impaired writing skills,
- impaired arithmetic skills,
- difficulties in functioning in society: problems with active, independent functioning in daily life.

Due to lack of empirical studies the underlying cause of functional illiteracy is still unclear. Rüsseler et al. (2011) suggested a combined model, where the unfavorable familiar background and school experiences could be identified as risk factors and together with biological and cognitive determinants could cause functional illiteracy (Rüsseler et al., 2011).

As regards our five research questions in the beginning, they can be answered as follows. We propose four different social and cognitive aspects that can lead to functional illiteracy in itself or together:

(1) Cognitive aspect: weak cognitive skills cause the inability to acquire proper basic literacy skills;
(2) Educational aspect: primary and secondary school teachers have no opportunity to take care the individual level of each student, therefore the children with feeble abilities or low motivation fall behind in long-term;
(3) Social aspect: the lack of an encouraging and motivating model in a child's family for acquiring new skills, having new experiences, can lead to an unmotivated learning style in school;
(4) Competency loss aspect: loss of competencies in adulthood caused by a decrease of cognitive demands (Q4).

The focus on cognitive and social aspects does not preclude that some of them (e.g., the cognitive aspects) are neurobiologically routed.

The review shows that despite formal education, functional illiterates do not possess basic skills (Q1). This general deficit can be theoretically distinguished from the deficits associated with illiteracy and dyslexia; illiterates lack formal education, while functional illiterates have had some schooling and therefore may have advantages from this education. Additionally, dyslexia has genetic underpinnings while social factors seems to have stronger impact on the development of functional illiteracy (Q5), therefore their diagnostic and remediation processes may differ as well.

From the summary we cannot conclude in which abilities functional illiterates have the largest deficit, because we did not find any research that aimed at measuring their mathematical abilities (Q2). We suppose that functional illiterates have both numerical and linguistic deficits. According to the Triple-Code Model, the underlying representations work separately (Dehaene and Cohen, 1995, 1998) but we do not know any research that has tried to confirm this in a functional illiterate sample (Q3).

Summarizing our presumptions about functional illiteracy in details, we define as functional illiterates those adults who attended the compulsory years in education but could not acquire basic reading, writing, and calculation skills. Their impairments negatively affect their effective functioning in everyday life. In particular, functional illiterates have poor language skills (writing, reading, oral communication) (e.g., difficulty understanding a medicine label) as well as poor arithmetic abilities (e.g., inability to compare the price of two products) that generally influence everyday life situations (e.g., get the information from a timetable). People belonging to this group have average or below-average IQ levels and their difficulties cannot result from any other kind of neurological or psychiatric disorder, organic problem, non-verbal learning problem, general learning difficulty or hyperactivity. Of course, these criteria do not exclude co-morbidities with such other impairments.

CONCLUSION

We would stress the need for methodologically more substantiated research, comparing basic linguistic, numerical and cognitive functions in normal readers, functional illiterates, dyslexic adults, and reading-level matched dyslexic children.

AUTHOR CONTRIBUTIONS

RV, TD, JS, and H-CN made the review design, RV and AC did the literature search, and RV, AC, TD, JS, and H-CN wrote the paper.

ACKNOWLEDGMENTS

This research ("Basic foundations of functional illiteracy") is funded by the LEAD Graduate School & Research Network [GSC1028], a project of the Excellence Initiative of the German federal and state governments. RV is a doctoral student of the LEAD Graduate School & Research Network. We acknowledge support by the Deutsche Forschungsgemeinschaft and the Open Access Publishing Fund of the University of Tuebingen.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2016.01617/full#supplementary-material

REFERENCES

Abadzi, H. (2003). *Adult Literacy: A Review of Implementation Experience*. Washington, DC: The World Bank Operations Evaluations Department.

Abd Ghani, K., and Gathercole, S. E. (2013). Working memory and study skills: a comparison between dyslexic and non-dyslexic adult learners. *Procedia Soc. Behav. Sci.* 97, 271–277. doi: 10.1016/j.sbspro.2013.10.233

Aker, C., Ksoll, C., and Lybbert, T. J. (2010). *ABC, 123: The Impact of a Mobile Phone Literacy Program on Educational Outcomes*. Washington, DC: Center for Global Development.

Ardila, A., Rosselli, M., and Rosas, P. (1989). Neuropsychological assessment in illiterates: visuospatial and memory abilities. *Brain Cogn.* 11, 147–166. doi: 10.1016/0278-2626(89)90015-8

Beidas, H., Khateb, A., and Breznitz, Z. (2013). The cognitive profile of adult dyslexics and its relation to their reading abilities. *Read. Writ.* 26, 1487–1515. doi: 10.1007/s11145-013-9428-5

Beneventi, H., Tonnessen, F. E., Ersland, L., and Hughdahl, K. (2010). Working memory deficit in dyslexia: behavioral and fMRI evidence. *Int. J. Neurosci.* 120, 51–59. doi: 10.3109/00207450903275129

Bhola, H. S. (1995). *Functional Literacy, Workplace Literacy and Technical and Vocational Education: Interfaces and Policy Perspectives*. Paris: UNESCO, Section for Technical and Vocational Education.

Boets, B., and De Smedt, B. (2010). Single-digit arithmetic in children with dyslexia. *Dyslexia* 16, 183–191.

Bogdanowicz, K. M., Łockiewicz, M., Bogdanowicz, M., and Pąchalska, M. (2014). Characteristics of cognitive deficits and writing skills of Polish adults with developmental dyslexia. *Int. J. Psychophysiol.* 93, 78–83. doi: 10.1016/j.ijpsycho.2013.03.005

Boltzmann, M., and Rüsseler, J. (2013). Training-related changes in early visual processing of functionally illiterate adults: evidence from event-related brain potentials. *BMC Neurosci.* 14:154. doi: 10.1186/1471-2202-14-154

Boltzmann, M., Rüsseler, J., Ye, Z., and Münte, T. F. (2013). Learning to read in adulthood: an evaluation of a literacy program for functionally illiterate adults in Germany. *Probl. Educ. 21 Century* 51, 33–46.

Bramão, I., Mendonça, A., Faísca, L., Ingvar, M., Petersson, K. M., and Reis, A. (2007). The impact of reading and writing skills on a visuo-motor integration task: a comparison between illiterate and literate subjects. *J. Int. Neuropsychol. Soc.* 13, 359–364. doi: 10.1017/S1355617707070440

Brookes, R. L., Tinkler, S., Nicolson, R. I., and Fawcett, A. J. (2010). Striking the right balance: motor difficulties in children and adults with dyslexia. *Dyslexia* 16, 358–373.

Brosnan, M., Demetre, J., Hamill, S., Robson, K., Shepherd, H., and Cody, G. (2002). Executive functioning in adults and children with developmental dyslexia. *Neuropsychologia* 40, 2144–2155. doi: 10.1016/S0028-3932(02)00046-5

Casalis, S., Colé, P., and Sopo, D. (2004). Morphological awareness in developmental dyslexia. *Ann. Dyslexia* 54, 114–138. doi: 10.1007/s11881-004-0006-z

Castro-Caldas, A., Petersson, K. M., Reis, A., Stone-Elander, S., and Ingvar, M. (1998). The illiterate brain: learning to read and write during childhood influences the functional organization of the adult brain. *Brain* 121, 1053–1063. doi: 10.1093/brain/121.6.1053

Cavalli, E., Casalis, S., El Ahmadi, A., Zira, M., Poracchia-George, F., and Colé, P. (2016). Vocabulary skills are well developed in university students with dyslexia: evidence from multiple case studies. *Res. Dev. Disabil.* 5, 89–102. doi: 10.1016/j.ridd.2016.01.006

Chung, K. K. H., Ho, C. S.-H., Chan, D. W., Tsang, S.-M., and Lee, S.-H. (2010). Cognitive profiles of chinese adolescents with dyslexia. *Dyslexia* 16, 2–23. doi: 10.1002/dys.392

Cree, A., Kay, A., and Steward, J. (2012). *The Economic & Social Cost of Illiteracy: a Snapshot of Illiteracy in a Global Context*. Melbourne: The World Literacy Foundation.

CTB/McGraw-Hill (2008). *Discover TABE 9&10*. Monterey, CA: CTB/McGraw-Hill.

Dansilio, S., and Charamelo, A. (2005). Constructional functions and figure copying in illiterates or low-schooled Hispanics. *Arch. Clin. Neuropsychol.* 20, 1105–1112. doi: 10.1016/j.acn.2005.06.011

De Luca, M., Borrelli, M., Judica, A., Spinelli, D., and Zoccolotti, P. (2002). Reading words and pseudowords: an eye movement study of developmental dyslexia. *Brain Lang.* 80, 617–626. doi: 10.1006/brln.2001.2637

De Smedt, B., and Boets, B. (2011). Phonological processing and arithmetic fact retrieval: evidence from developmental dyslexia. *Neuropsychologia* 48, 3973–3981. doi: 10.1016/j.neuropsychologia.2010.10.018

De Smedt, B., Noël, M. P., Gilmore, C., and Ansari, D. (2013). How do symbolic and non-symbolic numerical magnitude processing skills relate to individual differences in children's mathematical skills? A review of evidence from brain and behavior. *Trends Neurosci. Educ.* 2, 48–55.

Dehaene, S., and Cohen, L. (1995). Towards an anatomical and functional model of number processing. *Math. Cogn.* 1, 83–120.

Dehaene, S., and Cohen, L. (1998). "Levels of representation in number processing," in *Handbook of Neurolinguistics*, eds B. Stemmer and H. A. Whitaker (Amsterdam: Elsevier), 331–341.

Dietrich, J. F., Huber, S., and Nuerk, H.-C. (2015). Methodological aspects to be considered when measuring the approximate number system (ANS) – a research review. *Front. Psychol.* 6:295. doi: 10.3389/fpsyg.2015.00295

Egloff, B., Grosche, M., Hubertus, P., and Rüsseler, J. (2011). "Funktionaler Analphabetismus: eine aktuelle Definition," in *Zielgruppen in Alphabetisierung und Grundbildung Erwachsener. Bestimmung, Verortung, Ansprache*, ed. Projektträger im DLR e.V (Bielefeld: WBV-Verlag), 11–31. .

Eme, E. (2006). L′examen psycholinguistique et neuropsychologique de personnes en situation d′illettrisme. *Rev. Neuropsychol.* 16, 3–40.

Eme, E. (2011). Cognitive and psycholinguistic skills of adults who are functionally illiterate: current state of research and implications for adult education. *Appl. Cogn. Psychol.* 25, 753–762. doi: 10.1002/acp.1746

Eme, E., Lacroix, A., and Almecija, Y. (2010). Oral narrative skills in french adults who are functionally illiterate: linguistic features and discourse organization. *J. Speech Lang. Hear. Res.* 53, 1349–1371. doi: 10.1044/1092-4388(2010/08-0092)

Eme, E., Lambert, E., and Alamargot, D. (2014). Word reading and word spelling in French adult literacy students: the relationship with oral language skills. *J. Res. Read.* 37, 268–296. doi: 10.1111/j.1467-9817.2011.01508.x

European Commission (2014/2015). *Compulsory Education in Europe 2014/15. Eurydice – Facts and Figures*. Brussels: European Commission.

Everatt, J., Weeks, S., and Brooks, P. (2008). Profiles of strengths and weaknesses in dyslexia and other learning difficulties. *Dyslexia* 14, 16–41. doi: 10.1002/dys.342

Fletcher, J. M. (2009). Dyslexia: the evolution of a scientific concept. *J. Int. Neuropsychol. Soc.* 15, 501–508. doi: 10.1017/S1355617709090900

Greenberg, D. (2007). "Tales from the field: the struggles and challenges of conducting ethical and quality research in the field of adult literacy," in *Toward Defining and Improving Quality in Adult Basic Education*, eds A. Belzer and H. Beder (Hillside, NJ: Lawrence Erlbaum Associates), 124–140.

Greenberg, D., Ehri, L. C., and Perin, D. (1997). Are word-reading processes the same or different in adult literacy students and third-fifth graders matched for reading level? *J. Educ. Psychol.* 89, 262–275. doi: 10.1037/0022-0663.89.2.262

Greenberg, D., Wise, J. C., Frijters, J. C., Morris, R., Fredrick, L. D., Rodrigo, V., et al. (2012). Persisters and nonpersisters: identifying the characteristics of who stays and who leaves from adult literacy interventions. *Read. Writ.* 26, 495–514. doi: 10.1007/s11145-012-9401-8

Grosche, M. (2012). *Analphabetismus und Lese-Rechtschreib-Schwächen*. Münster: Waxmann.

Grotlüschen, A., Kretschmann, R., Quante-Brandt, E., and Wolf, K. D. (eds) (2011). *Literalitätsentwicklung von Arbeitskräften*. Münster: Waxmann Verlag.

Grotlüschen, A., and Riekmann, W. (2011a). *leo. – Level One Study.* Hamburg: Universität Hamburg.

Grotlüschen, A., and Riekmann, W. (2011b). *leo. – Level-One Studie. Literalität von Erwachsenen auf den Unteren Kompetenzniveaus In Presseheft*. Hamburg: Universität Hamburg.

Grotlüschen, A., Riekmann, W., and Buddeberg, K. (2014). "Functional illiteracy in Germany," in *Lifelong Learning and Governance. From Programming to Action – Selected Experiences from Asia and Europe*, eds H. Hintzen and J. H. Knoll (Paris: UNESCO Insitute for Lifelong Learning), 55–67.

Habib, M., and Giraud, K. (2013). "Dyslexia," in *Handbook of Clinical Neurology, Pediatric Neurology*, Part I, eds O. Dulac, M. Lassonde, and H. B. Sarnat (Amsterdam: Elsevier), 229–235.

Halberda, J., and Feigenson, L. (2008). Developmental change in the acuity of the "Number Sense": the approximate number system in 3-, 4-, 5-, and 6-year-olds and adults. *Dev. Psychol.* 44, 1457–1465. doi: 10.1037/a0012682

Hatcher, J., Snowling, M. J., and Griffiths, Y. M. (2002). Cognitive assessment of dyslexic students in higher education. *Br. J. Educ. Psychol.* 72, 119–133. doi: 10.1348/000709902158801

Huettig, F., and Mishra, R. K. (2014). How literacy acquisition affects the illiterate mind – a critical examination of theories and evidence. *Lang. Linguist. Compass* 8, 401–427. doi: 10.1111/lnc3.12092

Infante, I. (2000). *Functional Literacy in Seven Latin American Countries*. Santiago: UNESCO.

Joanisse, M. F., Manis, F. R., Keating, P., and Seidenberg, M. S. (2000). Language deficits in dyslexic children: speech perception, phonology, and morphology. *J. Exp. Child Psychol.* 77, 30–60. doi: 10.1006/jecp.1999.2553

Kosmidis, M. H., Tsapkini, K., and Folia, V. (2006). Lexical processing in illiteracy: effect of literacy or education? *Cortex* 42, 1021–1027. doi: 10.1016/S0010-9452(08)70208-9

Kosmidis, M. H., Tsapkini, K., Folia, V., Vlahou, C. H., and Kiosseoglou, G. (2004). Semantic and phonological processing in illiteracy. *J. Int. Neuropsychol. Soc.* 10, 818–827. doi: 10.1017/S1355617704106036

Kosmidis, M. H., Zafiri, M., and Politimou, N. (2011). Literacy versus formal schooling: influence on working memory. *Arch. Clin. Neuropsychol.* 26, 575–582. doi: 10.1093/arclin/acr063

Landerl, K., Fussenegger, B., Moll, K., and Willburger, E. (2009). Dyslexia and dyscalculia: two learning disorders with different cognitive profiles. *J. Exp. Child Psychol.* 103, 309–324. doi: 10.1016/j.jecp.2009.03.006

Landgraf, S., Beyer, R., Pannekamp, A., Schaadt, G., Koch, D., Foth, M., et al. (2011). Dissociating improvement of attention and intelligence during written language acquisition in adults. *Int. J. Intell. Sci.* 1, 17–24. doi: 10.4236/ijis.2011.12003

Law, J. M., Wouters, J., and Ghesquière, P. (2015). Morphological awareness and its role in compensation in adults with dyslexia. *Dyslexia* 21, 254–272. doi: 10.1002/dys.1495

Leong, V., Hämäläinen, J., Soltész, F., and Goswani, U. (2011). Rise time perception and detection of syllable stress in adults with developmental dyslexia. *J. Mem. Lang.* 64, 59–73. doi: 10.1016/j.jml.2010.09.003

Lyon, G. R., Shaywitz, S. E., and Shaywitz, B. A. (2003). A definition of dyslexia. *Ann. Dyslexia* 53, 1–14. doi: 10.1007/s11881-003-0001-9

Lyons, I. M., Nuerk, H.-C., and Ansari, D. (2015). Rethinking the implications of numerical ratio effects for understanding the development of representational precision and numerical processing across formats. *J. Exp. Psychol. Gen.* 144, 1021–1035. doi: 10.1037/xge0000094

MacArthur, C. A., Konold, T. R., Glutting, J. J., and Alamprese, J. A. (2010). Reading component skills of learners in adult basic education. *J. Learn. Disabil.* 43, 108–121. doi: 10.1177/0022219409359342

Martens, V. E. G., and de Jong, P. F. (2006). The effect of word length on lexical decision in dyslexic and normal reading children. *Brain Lang.* 98, 140–149. doi: 10.1016/j.bandl.2006.04.003

Martinez, R., and Fernandez, A. (2010). *The Social and Economic Impact of Illiteracy. Analytical Model and Pilot Study*. Santiago: OREALC/UNESCO.

Moeller, K., Huber, S., Nuerk, H.-C., and Willmes, K. (2011). Two-digit number processing – holistic, decomposed or hybrid? A computational modelling approach. *Psychol. Res.* 75, 290–306. doi: 10.1007/s00426-010-0307-2

Moeller, K., Pixner, S., Kaufmann, L., and Nuerk, H.-C. (2009). Children's early mental number line: logarithmic or rather decomposed linear? *J. Exp. Child Psychol.* 103, 503–515. doi: 10.1016/j.jecp.2009.02.006

Morais, J., Cary, L., Alegria, J., and Bertelsen, P. (1979). Does awareness of speech as a sequence of phones arise spontaneously? *Cognition* 7, 323–331. doi: 10.1016/0010-0277(79)90020-9

Nickel, S. (2007). "Familienorientierte grundbildung im sozialraum als schlüsselstrategie zur breiten teilhabe an literalität," in *Literalität, Grundbildung oder Lesekompetenz? Beiträge zu einer Theorie-Praxis-Diskussion*, eds A. Grotlüschen and A. Linde (Münster: Waxmann), 31–41.

Nuerk, H.-C., Patro, K., Cress, U., Schild, U., Friedrich, C. K., and Goebel, S. M. (2015). How space-number associations may be created in preliterate children: six distinct mechanisms. *Front. Psychol.* 6:215. doi: 10.3389/fpsyg.2015.00215

OECD (2013). *OECD Skills Outlook 2013. First Results from the Survey of Adult Skills*. Paris: OECD.

OECD and Statistics Canada (2000). *Literacy in the Information Age. Final Report of the International Adult Literacy Survey*. Paris: OECD.

Ostrosky-Solis, P., Ardila, A., and Rosselli, M. (1999). NEUROPSI: a brief neuropsychological test battery in Spanish with norms by age and educational level. *J. Int. Neuropsychol. Soc.* 5, 413–433. doi: 10.1017/S1355617799555045

Petersson, K. M., Reis, A., Askelöf, S., Castro-Caldas, A., and Ingvar, M. (2000). Language processing modulated by literacy: a network analysis of verbal repetition in literate and illiterate subjects. *J. Cogn. Neurosci.* 12, 364–382. doi: 10.1162/089892900562147

Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., et al. (2003). Theories of developmental dyslexia: insights from a multiple case study of dyslexic adults. *Brain* 126, 841–865. doi: 10.1093/brain/awg076

Reis, A., and Castro-Caldas, A. (1997). Illiteracy: a cause of biased cognitive development. *J. Int. Neuropsychol. Soc.* 3, 444–450.

Reis, A., Faisca, L., Ingvar, M., and Petersson, K. M. (2006). Color makes a difference: two-dimensional object naming in literate and illiterate subjects. *Brain Cogn.* 60, 49–54. doi: 10.1016/j.bandc.2005.09.012

Reis, A., Guerreiro, M., and Petersson, K. M. (2003). A sociodemographic and neuropsychological characterization of an illiterate population. *Appl. Neuropsychol.* 10, 191–204. doi: 10.1207/s15324826an1004_1

Rello, L., Baeza-Yates, R., Dempere-Marco, L., and Saggion, H. (2013). Frequent words improve readability and short words improve understandability for people with dyslexia. *Lecture Notes Comput. Sci.* 8120, 203–219.

Rimrodt, S. I., Clements-Stephens, A. M., Pugh, K. R., Courtney, S. M., Gaur, P., Pekar, J. J., et al. (2009). Functional MRI of sentence comprehension in children with dyslexia: beyond word recognition. *Cereb. Cortex* 19, 402–413. doi: 10.1093/cercor/bhn092

Rose, L. T., and Rougani, P. (2012). Influence of verbal working memory depends on vocabulary: oral reading fluency in adolescents with dyslexia. *Mind Brain Educ.* 6, 1–9. doi: 10.1111/j.1751-228X.2011.01135.x

Rosselli, M., Ardila, A., and Rosas, P. (1990). Neuropsychological assessment in illiterates II.: language and Praxic Abilities. *Brain Cogn.* 12, 281–296. doi: 10.1016/0278-2626(90)90020-O

Rüsseler, J., Becker, P., Johannes, S., and Münte, T. F. (2007). Semantic, syntactic, and phonological processing of written language in adult developmental dyslexic readers: an event-related brain potential study. *BMC Neurosci.* 8:52. doi: 10.1186/1471-2202-8-52

Rüsseler, J., Boltzmann, M., Menkhaus, K., and Aulbert-Siepelmeyer, A. (2013). Evaluation eines neuen trainingsprogramms zur verbesserung der lese- und rechtschreibfähigkeiten funktionaler analphabeten. *Empirische Sonderpädagogik* 3, 237–249.

Rüsseler, J., Gerth, I., and Boltzmann, M. (2011). "Basale wahrnehmungsfähigkeiten von erwachsenen funktionalen analphabeten und analphabetinnen," in *Lernprozesse in Alphabetisierung und Grundbildung Erwachsener. Diagnostik, Vermittlung, Professionalisierung*, ed. Projektträger im DLR e.V (Bielefeld: WBV-Verlag), 11–28.

Rüsseler, J., Menkhaus, K., Aulbert-Siepelmeyer, A., Gerth, I., and Boltzmann, M. (2012). "Alpha Plus": an innovative training program for reading and writing education of functionally illiterate adults. *Creat. Educ.* 3, 357–361. doi: 10.4236/ce.2012.33056

Shi, Y., and Tsang, M. C. (2008). Evaluation of adult literacy education in the United States: a review of methodological issues. *Educ. Res. Rev.* 3, 187–217. doi: 10.1016/j.edurev.2007.10.004

Siegler, R. S., and Opfer, J. E. (2003). The development of numerical estimation: evidence for multiple representations of numerical quantity. *Psychol. Sci.* 14, 237–243. doi: 10.1111/1467-9280.02438

Silva, C., Faisca, L., Ingvar, M., Petersson, K. M., and Reis, A. (2012). Literacy: exploring working memory system. *J. Clin. Exp. Neuropsychol.* 1, 1–9.

Simmons, F. R., and Singleton, C. (2006). Arithmetic abilities of adults with dyslexia. *Dyslexia* 12, 96–114. doi: 10.1002/dys.312

Smith-Spark, J. H., Henry, L. A., Messer, D. J., Edvardsdottir, E., and Ziecik, A. P. (2016). Executive functions in adults with developmental dyslexia. *Res. Dev. Disabil.* 53, 323–341. doi: 10.1016/j.ridd.2016.03.001

Statistics Canada, and OECD (2005). *Learning a Living. First Results of the Adult Literacy and Life Skills Survey*. Paris: OECD.

Suarez-Coalla, P., Ramos, S., Alvarez-Canizo, M., and Cuetos, F. (2014). Orthographic learning in dyslexic Spanish children. *Ann. Dyslexia* 64, 166–181. doi: 10.1007/s11881-014-0092-5

Thompkins, A. C., and Binder, K. S. (2003). A comparison of the factors affecting reading performance of functional illiterate adults and children matched by reading level. *Read. Res. Q.* 38, 236–258. doi: 10.1598/RRQ.38.2.4

Thorn, W. (2009). *International Adult Literacy and Basic Skills Surveys in the OECD Region. OECD Education Working Papers,* 26. Paris: OECD Publishing.

UNESCO (1978). *Records of the General Conference. 20th Session*, Vol. 1. Paris: UNESCO.

UNESCO (2006). "Why Literacy Matters," in *Education for All. Literacy for Life*, ed. UNESCO (Paris: UNESCO Publishing), 135–145.

UNESCO (2009). *The Next Generation of Literacy Statistics: Implementing the LITERACY ASSESSMENT and Monitoring Programme (LAMP)*. Paris: UNESCO Institute for Statistics Montreal.

UNESCO (2013). *Schooling for Millions of Children Jeopardized by Reductions in Aid. Education for All Global Monitoring Report*. Paris: UNESCO Institute for Statistics.

UNESCO (2015). *Adult and Youth Literacy. UIS Fact Sheet*. Paris: UNESCO Institute for Statistics.

Vajjala, S., and Meurers, D. (2014). Readability assessment for text simplification: from analyzing documents to identifying sentential simplifications. *Int. J. Appl. Linguist.* 165, 194–222.

Valdois, S., Bosse, M.-L., and Tainturier, M.-J. (2004). The cognitive deficits responsible for developmental dyslexia: review of evidence for a selective visual attentional disorder. *Dyslexia* 10, 339–363. doi: 10.1002/dys.284

Van Linden, S., and Cremers, A. H. M. (2008). "Cognitive abilities of functionally illiterate persons relevant to ICT use," in *Computers Helping People with Special Needs*, eds K. Miesenberger, J. Klaus, W. Zagler, and A. Karshmer (Heidelberg: Springer-Verlag), 705–712.

Varvara, P., Varuzza, C., Sorrentino, A. C. P., Vicari, S., and Menghini, D. (2014). Executive functions in developmental dyslexia. *Front. Hum. Neurosci.* 8:120. doi: 10.3389/fnhum.2014.00120

White, S., Milne, E., Rosen, S., Hansen, P., Swettenham, J., Frith, U., et al. (2006). The role of sensorimotor impairments in dyslexia: a multiple case study of dyslexic children. *Dev. Sci.* 9, 237–269. doi: 10.1111/j.1467-7687.2006.00483.x

Willburger, E., Fussenegger, B., Moll, K., Wood, G., and Landerl, K. (2008). Naming speed in dyslexia and dyscalculia. *Learn. Individ. Differ.* 18, 224–236. doi: 10.1016/j.lindif.2008.01.003

Willcutt, E. G., Petrill, S. A., Wu, S., Boada, R., DeFries, J. C., Olson, R. K., et al. (2013). Comorbidity between reading disability and math disability: concurrent psychopathology, Functional Impairment, and Neuropsychological Functioning. *J. Learn. Disabil.* 46, 500–516. doi: 10.1177/0022219413477476

Wilson, A. J., Andrewes, S. G., Struthers, H., Rowe, V. M., Bogdanovic, R., and Waldie, K. E. (2015). Dyscalculia and dyslexia in adults: cognitive bases of comorbidity. *Learn. Individ. Differ.* 37, 118–132. doi: 10.1016/j.lindif.2014.11.017

Wiseheart, R., Altmann, L. J. P., Park, H., and Lombardino, L. J. (2009). Sentence comprehension in young adults with developmental dyslexia. *Ann. Dyslexia* 59, 151–167. doi: 10.1007/s11881-009-0028-7

Ziegler, J. C., Pech-Georgel, C., Dufau, S., and Grainger, J. (2010). Rapid processing of letters, digits and symbols: what purely visual-attentional deficit in developmental dyslexia? *Dev. Sci.* 13, 8–14. doi: 10.1111/j.1467-7687.2010.00983.x

Zoubrinetzky, R., Bielle, F., and Valdois, S. (2014). New insights on developmental dyslexia subtypes: heterogeneity of mixed reading profiles. *PLoS ONE* 9:e99337. doi: 10.1371/journal.pone.0099337

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

frontiers in Psychology

ORIGINAL RESEARCH
published: 17 October 2016
doi: 10.3389/fpsyg.2016.01567

Teachers' Beliefs and Practices Regarding the Role of Executive Functions in Reading and Arithmetic

*Shirley Rapoport, Orly Rubinsten and Tami Katzir**

The Edmond J. Safra Brain Research Centre for the Study of Learning Disabilities, Department of Learning Disabilities and Special Education, University of Haifa, Haifa, Israel

The current study investigated early elementary school teachers' beliefs and practices regarding the role of Executive Functions (EFs) in reading and arithmetic. A new research questionnaire was developed and judged by professionals in the academia and the field. Reponses were obtained from 144 teachers from Israel. Factor analysis divided the questionnaire into three valid and reliable subscales, reflecting (1) beliefs regarding the contribution of EFs to reading and arithmetic, (2) pedagogical practices, and (3) a connection between the cognitive mechanisms of reading and arithmetic. Findings indicate that teachers believe EFs affect students' performance in reading and arithmetic. These beliefs were also correlated with pedagogical practices. Additionally, special education teachers' scored higher on the different subscales compared to general education teachers. These findings shed light on the way teachers perceive the cognitive foundations of reading and arithmetic and indicate to which extent these perceptions guide their teaching practices.

Keywords: pedagogical practices, executive functions, reading, arithmetic

OPEN ACCESS

Edited by:
Bernhard Hommel,
Leiden University, Netherlands

Reviewed by:
Jason F. Reimer,
California State University,
San Bernardino, USA
Lorenza S. Colzato,
Leiden University, Netherlands

****Correspondence:***
Tami Katzir
katzirta@gmail.com

Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *23 February 2016*
Accepted: *26 September 2016*
Published: *17 October 2016*

Citation:
Rapoport S, Rubinsten O and Katzir T (2016) Teachers' Beliefs and Practices Regarding the Role of Executive Functions in Reading and Arithmetic. Front. Psychol. 7:1567. doi: 10.3389/fpsyg.2016.01567

INTRODUCTION

"Executive functions" (EF) are typically defined as "general-purpose control mechanisms that modulate the operation of various cognitive sub-processes and thereby regulate the dynamics of human cognition" (Miyake et al., 2000; Miyake and Friedman, 2012). They allow individuals to be goal-directed and adaptively select their responses, rather than respond in an automatic fashion (Garon et al., 2008) by relying on instinct or intuition (Diamond, 2013). Core EF components, such as inhibition, shifting and working memory begin to develop during infancy (Garon et al., 2008), predicting school readiness in the language and social-emotional domains (Bierman et al., 2008). EF continue to develop into adulthood, forming the foundation for higher cognitive processes (Garon et al., 2008) affecting mental and physical health, job success, intimate relationships and social behavior (Diamond, 2013).

In recent years, there is also accumulated research regarding the contribution of domain-general EF to the development of reading and arithmetic (e.g., Durand et al., 2005; Altemeier et al., 2008; Cartwright, 2012; Compton et al., 2012; Ashkenazi et al., 2013; Georgiou et al., 2013; Miller et al., 2013; Davidse et al., 2015). The domains of reading and arithmetic have been traditionally linked to separable underlying cognitive mechanisms. Reading is considered to be dependent on linguistic processes (Lyon et al., 2003) while arithmetic depends on abstract manipulation of quantities (Price et al., 2007). Yet, first of all, semantic and arithmetical concepts are both communicated through formally acquired symbol systems. Alphabetic writing systems and Arabic numerals even emerged from the same source – counting coins, which are tracked back to 8000BC (Wolf, 2008).

Furthermore, apart from the shared origin of symbol systems, reading and arithmetic depend on shared cognitive mechanisms. Most of these mechanisms, as mentioned, can be conceptualized as domain-general EF (amongst other cognitive mechanisms, such as general verbal ability, e.g., Krajewski and Schneider, 2009; Schroeder, 2011; Bar-Kochva, 2012; Vukovic and Lesaux, 2012). For example, EF in preschool accounted for substantial variability in mathematical and reading achievement 2 years later (Röthlisberger et al., 2013). In another study, neuropsychological tests and teacher reports of EFs accounted for as far as 40% of variance in English scores and 30% of variance in mathematics scores in the 4th grade (Waber et al., 2006).

With all that being said, it is still unclear whether this important link between EF and school achievements has any expression in pedagogical practices. As much as this link is well established in scientific literature, we have yet to understand how it is reflected in teachers' beliefs, as well as in their practices (Pajares, 1992). For example, if a teacher witnesses some students struggle with all schoolwork, is he/she exposed to the possibility that these challenges may stem from an underlying difficulty in executive functioning?

To discover whether recent scientific findings are bridged into pedagogy, the current study will look into elementary school teachers' beliefs regarding the link between EF and achievements in reading and arithmetic. We will focus on teachers' beliefs, due to the crucial influence they may exert on pedagogical practices (Borg, 2001; Baccus, 2004; Cross, 2009), and learning opportunities (Falcón-Huertas, 2006; Kaya, 2014). We will also explore to what extent teachers' beliefs correlate with their reported pedagogical practice in arithmetic and reading instruction, and examine patterns of beliefs and practices in different populations of teachers (differing by level of experience and type of students taught).

Past studies of teachers' beliefs have typically focused on teachers' attitudes toward themselves (Tschannen-Moran and Hoy, 2007; van Uden et al., 2014), their students (Lavigne, 2014) and the nature of teaching and learning (Windschitl and Sahl, 2002; Kim et al., 2013). Other studies examined teachers of specific academic domains, focusing, for example, on attitudes toward literacy (Martin et al., 2007; Jiménez et al., 2015; Ritchey et al., 2015), such as stressing phonics as opposed to a whole-language approach when teaching reading (DeFord, 1979). Other studies explored beliefs regarding mathematics instruction (Lerman, 1990; Stipek et al., 2001; Sweeting, 2011), for example, stressing answer correctness as opposed to focusing on understanding mathematical concepts (Stipek et al., 2001). However, to our knowledge, there is no published study that focuses on teachers' beliefs about the connection between EF and school achievements in reading and arithmetic. Thus, the current study addresses an important gap in the literature, by exploring teachers' beliefs and practices regarding the role of domain-general cognitive mechanisms such as EF on domain-specific subject matters such as reading and arithmetic.

Before describing research questions and methods, scientific literature regarding the contribution of EF to both reading and arithmetic will be reviewed, along with literature about the connection between the two domains. Lastly, the connection between teachers' beliefs and their pedagogical practices will be reviewed.

Conceptualization of Executive Functions in the Current Study

Different researchers included different cognitive mechanisms under the umbrella of EF (e.g., compare Jurado and Rosselli, 2007 with Barkley, 1997). Furthermore, some studies refer to "EFs" as one general construct (e.g., Waber et al., 2006; Best et al., 2011; Röthlisberger et al., 2013), while others study the contribution of the different EFs separately (e.g., Inhibition and working memory, Borella et al., 2010; Planning, updating in working memory and inhibition, Kroesbergen et al., 2009; Inhibition, shifting and updating, Van der Ven et al., 2012). Both approaches have merit, as EFs differ in terms of both cognition and biology (e.g., Miyake et al., 2000; Gunning-Dixon and Raz, 2003; Jurado and Rosselli, 2007), yet share some underlying commonalities (Miyake et al., 2000). In addition, EF sub-processes work in conjunction many times (Alvarez and Emory, 2006) and it might be hard to separate their joint contribution to academic achievements.

Since the incorporation of teaching methods addressing EF in the school curriculum is relatively new and still not widespread (Dias and Seabra, 2015), studies linking specific EF to the acquisition of both reading and arithmetic will be reviewed, but when addressing teachers' beliefs in the current study, the different EFs and EF-related mechanisms reviewed will be later conceptualized as one joint construct.

THE CONTRIBUTION OF DIFFERENT EXECUTIVE FUNCTIONS TO READING AND ARITHMETIC

Some specific EF and EF-related mechanisms that have been shown to predict reading and arithmetic are: Inhibition (e.g., Altemeier et al., 2008; Toll et al., 2011), attentional control (Welsh et al., 2010), cognitive flexibility or shifting (e.g., Altemeier et al., 2008; Yeniad et al., 2013), planning (e.g., Sesma et al., 2009), working memory (e.g., McVay and Kane, 2012; Miller et al., 2013) and fluent retrieval of information from long-term memory (e.g., Ashkenazi et al., 2013; Georgiou et al., 2013).

EF and Reading

Inhibitory control (i.e., the ability to restrain responses; Blair and Razza, 2007), and attention control (the ability to control the focus on particular information; Welsh et al., 2010) were found to have a significant relationship with pre-reading skills in kindergarten. In elementary school, inhibition (Altemeier et al., 2008) and shifting (i.e., changing the mental set that has been learned to a new one; Yeniad et al., 2013) were linked to general reading performance (Yeniad et al., 2013) and particular decoding and word-reading measures (van der Sluis et al., 2007; Altemeier et al., 2008).

Executive function also plays a role in reading comprehension: attention shifting and inhibitory control was uniquely associated with reading comprehension in the 4th grade, controlling for working memory, processing speed and phonological awareness (Kieffer et al., 2013). Along the same lines, poor comprehenders in elementary and middle school were shown to lack inhibition (De Beni and Palladino, 2000) and also planning (deciding which tasks are necessary to complete a goal, and in what order; Sesma et al., 2009) abilities, compared to good comprehenders.

EF and Math

In the field of arithmetic, attention control (Welsh et al., 2010) and planning (Kroesbergen et al., 2009) predicted emergent numeracy skills. More EFs found to predict arithmetical ability are inhibition, underlying factual and procedural knowledge, and shifting, underlying procedural and conceptual arithmetical knowledge (Cragg and Gilmore, 2014). Inhibition predicted early school math achievement (Kroesbergen et al., 2009; Clark et al., 2010; Gilmore et al., 2013; Viterbori et al., 2015) and discriminated children with mathematical difficulties from typically achieving children in 1st and 2nd grade (Toll et al., 2011). Students in 3rd–5th grades with weak inhibition skills mixed conceptual knowledge with an incompatible computational algorithm, suggesting they had the right knowledge but failed to inhibit a previously well-learned algorithm (Robinson and Dubé, 2013).

Shifting ability is also generally thought to predict performance in mathematics (Yeniad et al., 2013). It predicted early school math achievement (Clark et al., 2010) and was correlated with arithmetic abilities in children aged 9–12 (van der Sluis et al., 2007). However, these findings are debatable since some studies did not find inhibition and shifting abilities to predict math achievement in early elementary school (e.g., Van der Ven et al., 2012).

CONTRIBUTION OF EF-RELATED COGNITIVE MECHANISMS TO READING AND ARITHMETIC

Along with cognitive mechanisms defined as EF *per se*, there are additional cognitive mechanisms related to EF, which are significantly related to the development of reading and arithmetic.

Working memory (Baddeley, 1992) has been closely linked to executive functioning. For example, McCabe et al. (2010), have found a correlation of 0.97 between the constructs of WM capacity and EF. WM has been found to contribute greatly to academic performance in reading and arithmetic from preschool to older children (e.g., Alloway et al., 2005; Berg, 2008; Krajewski and Schneider, 2009; Geary, 2011). It has been shown to be a crucial contributor to literacy and numeracy skills in preschool and later on (Alloway and Alloway, 2010; Miller et al., 2013).

WM strongly predicted math achievement in 1st–3rd grade (Toll et al., 2011; Viterbori et al., 2015). In particular, WM is considered to underlie both factual and procedural arithmetical knowledge (Cragg and Gilmore, 2014). One possible explanation for these ties are that calculation seems to rely on WM processes, since it involves storing temporary information while performing a mental operation on it, especially when the problem is presented verbally rather than visually (Berg, 2008). In addition, WM was found to contribute to strategy implementation in solving math problems (Geary et al., 2004; Lemaire, 2010).

In reading, Swanson et al. (2009) claimed that WM deficits contribute to problems in learning to read, supported by Nevo and Breznitz's (2011) findings that measures of verbal WM predict decoding and reading rate. Conversely, other studies of early literacy development show that verbal short-term memory but not WM *per se*, is related to word decoding proficiency, especially in primary grades (Alloway et al., 2005). At later stages of reading development, WM predicted reading comprehension (Berninger et al., 2010; Geary, 2011; Bar-Kochva, 2012; McVay and Kane, 2012).

Retrieval from long-term memory is another domain-general cognitive mechanism strongly tied to executive functioning, as fact retrieval employs bidirectional hippocampal-prefrontal connections (Cho et al., 2012) and is affected by working memory span (Rosen and Engle, 1997; Unsworth et al., 2013) and attentional processes (Kane and Engle, 2000). Some even conceptualize verbal fluency as an EF (Jurado and Rosselli, 2007).

It is known that retrieval underlies both reading and arithmetic (Kulak, 1993; Koponen et al., 2007). In both domains, the sequence of skill development involves a shift from time-consuming procedural strategies – effortful phonemic analysis in reading and counting in arithmetic – to automatic retrieval of high frequency words/arithmetic facts, which enables the learner to devote resources to "higher" tasks like reading comprehension or solving mathematical word problems (Kulak, 1993). It has been also claimed that flawed retrieval can cause a learning difficulty related to reading and arithmetic (Ashkenazi et al., 2013), as both domains rely on the fast retrieval of phonological information from long-term memory (Georgiou et al., 2013). Evidence also shows that retrieval is a main problem for children with dyslexia (Hanly and Vandenberg, 2010) and children with mathematical difficulties (Geary, 2004).

OVERALL RELATIONSHIPS BETWEEN READING AND ARITHMETIC DEVELOPMENT

All findings described above show clearly that shared domain-general mechanisms greatly contribute to performance in both reading and arithmetic. Considering shared underlying mechanisms, it is not surprising that for many years there are consistent findings demonstrating that that gains in reading abilities positively affects arithmetic skills dates (e.g., Gilmary, 1967). Further, recent studies suggest that dyslexics experience in difficulties in calculations (Miles and Miles, 1992; Mammarella et al., 2013). Early reading skills were found to be important for success in math, as reading comprehension in the 3rd grade predicting arithmetic skills in 3rd–8th grades (Grimm, 2008). A more recent study found a positive correlation between growth rates in reading and mathematics abilities throughout 4th–7th grades (Shin et al., 2013). In compliance with Grimm (2008), this correlation was also attributed by the authors to the influence of growth in reading ability on growth in mathematics (Shin et al., 2013).

There are some exceptions to this hypothesis regarding a single-directed influence of reading on arithmetic. For example, a Finnish longitudinal study of 1st and 2nd graders found an association between reading comprehension and mathematical abilities, while mathematical abilities, surprisingly, predicted subsequent reading comprehension rather than vice versa (Lerkkanen et al., 2005). Nevertheless, in general, reading performance seems to positively affect math performance but not vice versa (Jordan et al., 2002; Near, 2014).

To summarize, EF, separately or as a joint construct, have been strongly linked to school achievements in both reading and arithmetic (e.g., Altemeier et al., 2008; Cartwright, 2012; Compton et al., 2012; Ashkenazi et al., 2013; Georgiou et al., 2013; Miller et al., 2013; Davidse et al., 2015). In line with these findings, a correlation emerges between student achievements in reading and achievements in arithmetic (e.g., Grimm, 2008; Shin et al., 2013; Near, 2014).

In light of these strong links, the current study wishes to explore teachers' beliefs and practices regarding EF and their role in learning reading and arithmetic. The importance of teachers' beliefs to their pedagogical practices will be reviewed in the following paragraphs. Afterward, teacher variables which might influence teachers' beliefs are discussed.

TEACHING BELIEFS AND THEIR CONNECTION TO PEDAGOGICAL PRACTICES

A belief, in general, is a proposition held and accepted by an individual as true (Borg, 2001). Beliefs evoke emotional obligation in the individual and guide him/her in their thoughts and behavioral practices (Borg, 2001). Thus, teaching, or pedagogical, beliefs are an individual's beliefs relevant to their teaching abilities, the role of a teacher, the nature of learning etc. (Borg, 2001).

Teachers hold a variety of beliefs about the nature of their field of teaching, the way it should be taught and learned, their teaching ability etc. (e.g., Luciano, 1997; Westwood et al., 1997; Buehl et al., 2002; Baccus, 2004; Cross, 2009). These beliefs hold great importance, since reforms in the curriculum depend on the ability of policy makers to change teachers' beliefs about the way children learn (Lloyd, 2003). It has also been claimed that "attention to teachers' beliefs can inform educational practice in ways that prevailing research agendas have not and cannot" (Pajares, 1992).

Such claims point to the direct relation between teaching beliefs and pedagogical practices, which are the ways teachers choose to transfer knowledge to their students in the classroom. This connection was found as early on as kindergarten, where educational beliefs of teachers predicted children's learning opportunities above teacher's education and experience (Paro et al., 2009). In the field of reading instruction, a relationship was found between 1st grade teachers' theoretical orientation toward reading, ranging from phonics instruction to "whole-language" instruction (TORP questionnaire; DeFord, 1979) and their instructional practices (Luciano, 1997). Another study found an association between teachers' beliefs and the amount of instructional time spent on different aspects of reading instruction (Baccus, 2004). In mathematics, similarly, beliefs of 4th–6th grade teachers correlated with their classroom practices (Stipek et al., 2001) and another qualitative study found an association between beliefs of 9th grade algebra teachers and teaching practices (Cross, 2009).

Evidence showed that teaching practices are associated not only with beliefs, but they were also linked to students' conceptions. Students' conceptions regarding the nature and purpose of reading were affected by their teachers' literacy beliefs and practices (Falcón-Huertas, 2006). Another research found that teachers' beliefs about the importance of children's literature in reading instruction, affected positively their students' reading practices (Kaya, 2014). In the field of mathematics, a correlation was found between math teachers' beliefs and teaching practices and students' beliefs about mathematics (Carter and Norwood, 1997).

Naturally, teaching beliefs are not always aligned with teachers' pedagogical practices. Liu (2011), for example, found that even though most Taiwanese teachers held learner-centered beliefs, most classroom activities, when using technology, were still lecture-based rather than learner-based. Teaching practices are sometimes affected by "classroom realities" (Ertmer et al., 2012). Even though, it is important to note that personal beliefs are still the most influential factor on pedagogical practices (Ertmer et al., 2006), and it has been claimed that a change in practices can be achieved only if teachers' attitudes and beliefs are addressed (Ertmer et al., 2012).

BELIEFS, PRACTICES AND TEACHER VARIABLES

It seems likely that different professional variables may have an effect on teachers' beliefs and practices regarding the effect of EF on learning. Special education teachers may give more weight to the role of EF in the development of literacy and mathematics. First of all, they usually have more in-service training about handling students with ADHD (Martinussen et al., 2011; McKnight, 2015), a difficulty in executive functioning (Barkley, 1997). Previous research has also indicated that special education teachers report a greater executive functioning difficulty in their students, compared to general education students (Wright, 2010). Meltzer et al. (2007) have even claimed that interventions addressing EF would result in less special-education referrals.

Hence, it is likely that the special education teacher, who is both more trained and more regularly exposed to EF difficulties in the classroom, would display more beliefs and teaching practices to address the connection of EF to school achievements.

Teaching experience could also affect teachers' outlook on the connection between EF and school achievements. Previous research has shown that teaching experience is linked to a greater sense of teacher efficacy: More experienced teachers are more confident in their professional ability (Wolters and Daugherty, 2007; Rubie-Davies et al., 2012). Other distinctions between novice and experienced teachers were drawn in other fields, such as pedagogical knowledge (Silberstein and Tamir, 1991), problem solving (Swanson et al., 1990) and decision making (Housner and Griffey, 1985). There is some indication of a possible link between beliefs about EF and teaching experience. Experienced teachers were found to possess higher knowledge of characteristics of and treatments for ADHD than inexperienced ones (Anderson et al., 2012). ADHD, as mentioned, is manifested in difficulties in executive functioning (Barkley, 1997), and these results may suggest that as teachers become more experienced, they understand more about the manifestation of EF in the classroom. Consequently, it seems possible they hold more beliefs and practices concerning the effect EF have on all student achievements.

THE CURRENT STUDY

The main aim of this study was to add to the scarce literature on teachers' beliefs about the importance of EF. It introduces a novel focus on early elementary teachers' beliefs and their correlation with reported classroom practices, regarding EF in reading and arithmetic classes, considering the heavily reported effect of EF on school achievements in reading and arithmetic as early on as kindergarten (e.g., Best et al., 2011; Miller et al., 2013). The current study explored to what extent, in teachers' beliefs, achievements in reading were correlated with achievements in arithmetic and vice versa (e.g., Grimm, 2008; Shin et al., 2013). Different patterns of beliefs and practices in different populations of teachers (differing by level of experience and type of students taught) were being examined. The study was approved by Haifa University's IRB ethics committee.

To achieve these aims, we developed and validated a novel research questionnaire, containing statements tapping teaching beliefs about the contribution of EF to achievements in reading and arithmetic, practices targeting this contribution and the connection teachers perceive between students' achievements in reading and arithmetic. Data was cottlected from a large pool of obtaining early elementary school teachers (of 1st–4th grades).

Findings from the questionnaire were subject to factor analysis and differences between groups analysis.

Using our novel questionnaire, we wished to discover the relationship between teaching beliefs and practices regarding the contribution of EF to academic achievement, amongst early elementary school teachers of reading and arithmetic. We also wanted to characterize the relationship between teaching experience and those beliefs and practices, as well as the relationship between teaching experience and the perception of a connection between achievements in reading and arithmetic. Furthermore, we wanted to examine whether elementary school teachers in general and special education differ in their beliefs and practices regarding EF. Hence, such a questionnaire may facilitate and focus teachers' attention to their own understanding of EF, their role in learning and development, and how they can support its development.

We hypothesized that a positive correlation will be found between teaching beliefs and practices regarding the contribution of EF to academic achievement. We further hypothesized that a positive correlation will be found between teaching experience and those beliefs and practices, along with a stronger perception of a connection between reading and arithmetic achievements. Lastly, we hypothesized that special education teachers, compared to general education teachers, will hold more beliefs about the contribution of EF to academic achievements in both reading and arithmetic class (e.g., McKnight, 2015), apply more teaching practices targeting EF in their classes and see a stronger connection between achievements in reading and arithmetic.

MATERIALS AND METHODS

The Sample

The sample was comprised of 144 respondents. The questionnaire was sent as an online survey or handed in a hard-copy version. The sampling procedure was generally a convenience sample, as respondents were recruited through personal acquaintances and social networks (such as Facebook). Another sampling practice was to recruit teachers attending professional development courses and students in teacher-training programs. Questionnaire responses were collected in five different professional development programs, one of them national and four of them regional courses, half of them held in the northern Haifa district and half in the central Sharon district. Hundred and sixteen participants, who responded to more than 80% of the questionnaire, were included in the statistical analysis (see **Table 1** for demographic characteristics of the sample).

Survey Instrument

A new pilot questionnaire was composed for the purpose of the current study. In the development stage, the conceptual framework was constructed based on EF components identified in the literature. The preliminary questionnaire was divided into two sections. The first section consisted of 15 items inquiring about demographic characteristics of the respondent (See Appendix 1). The second section consisted of a large pool of 69 items, reflecting 10 theoretical themes (See Appendix 2). Seven themes regarded the connection between reading and arithmetic abilities and the following EFs: automatic retrieval, working memory, planning, shifting (cognitive flexibility), inhibition and attentional control. An additional group of items addressed the beliefs about the need to explicitly teach EF-enhancing strategies at school. Two other themes targeted the connection between academic abilities and reading: general verbal ability

TABLE 1 | Individual characteristics of teachers in the study.

Characteristic	Sample ($n = 116$)
Education system	
General	61.21% (71)
Special	38.79% (45)
Teacher's academic education	
B.A.	70.69% (82)
M.A.	29.31% (34)
Certified teacher?	
Yes	74.14% (86)
Student	25.86% (30)
Level of experience teaching reading	
None/Less than 1 year	19.83% (23)
1–5 years	31.90% (37)
Over 5 years	48.28% (56)
Level of experience teaching arithmetic	
None/Less than 1 year	26.72% (31)
1–5 years	31.90% (37)
Over 5 years	41.38% (48)
Homeroom/specialized teacher	
Do not currently teach	17.24% (20)
Homeroom	58.62% (68)
specialized teacher	24.14% (28)
Grades taught by teacher	
Do not currently teach	17.24% (20)
1st–2nd	35.34% (41)
3rd–4th	16.38% (19)
1st–4th	31.03% (36)

and phonological awareness. The last group of items tapped the perceived connection between achievements in reading and arithmetic – are they based on shared mechanisms? The different theoretical themes contained questions about theoretical beliefs and teaching practices. In the pilot phase, the questionnaire was reviewed for relevance, simplicity, clarity and ambiguity by six professionals in the relevant academic field and a group of ten representatives of the relevant population (professional early elementary school teachers), in order to obtain content validity (Yaghmale, 2003).

Items reflecting 7 of the 10 original theoretical scales were included in the analysis, considering the sample size. In order to perform dimension reduction of the data, a completion of missing values and item pruning were first administered. First of all, items with a response rate lower than 80% were not included in the analysis, as well as respondents who answered less than 80% of the items. The remaining missing values were completed by the median of responses to the same item. Due to statistical redundancy, if two or more items were highly correlated ($R > 0.5$), only one of them, chosen according to theoretical considerations, was included in the analysis. Items uncorrelated ($R < 0.2$) with other items which reflect the same theoretical theme, were also not included.

Exploratory factor analyses using maximum likelihood (ML) factoring, followed by direct oblimin rotation, were then administered. The ML factor extraction method was chosen due to normal distribution of the data (distribution of responses to all items met the criteria of skewness <2, kurtosis <7). The direct oblimin rotation, an oblique rotation, was chosen since these rotations can produce a structure with correlated factors, as opposed to orthogonal rotations (such as principal axis), which do not permit correlations among factors (Fabrigar et al., 1999; Costello and Osborne, 2005). It was defined that only items with factor loading of over 0.4 on only one of the factors, were to be included.

Description of Principal Factors

Twenty two items were grouped by the factoring procedure into three factors. Factor score was calculated using the regression method. All three factor scores were normally distributed (skewness <2, kurtosis <7). Each item was given an identifying code, in order to simplify statistical analysis and chart display (see **Table 2**).

The factors extracted reflect three theoretical conceptual subscales: (1) "Teaching practices (TP)," tapping practices regarding the effect of EF on reading and arithmetic, (2) "Reading-Arithmetic connection (RAC)," tapping the perceived connection between reading and arithmetic abilities, and (3) "Teaching beliefs (TB)," tapping beliefs regarding the effect of EF on "reading and arithmetic."

Subscale (1)

Teaching practices*:* contains seven items with factor loadings of 0.426–0.634. (See **Table 2**). To determine subscale reliability, internal consistency (Cronbach's α) was tested and found to be 0.774.

Subscale (2)

Reading-arithmetic connection*:* contains six items with factor loadings of 0.574–0.657. (see **Table 2**). The internal consistency (Cronbach's α) of this subscale was found to be 0.791.

Subscale (3)

Teaching beliefs*:* contains nine items with factor loadings of 0.428–0.599 (see **Table 2**). The internal consistency (Cronbach's α) of this subscale was found to be 0.751.

Subscales TP and TB of the final questionnaire, tapping teaching practices and beliefs regarding the effect of EF on reading and arithmetic, include at least one item about every EF reflected in the preliminary survey instrument (see **Table 3**).

Correlations between Extracted Factors

The factoring process used an oblique rotation, permitting the extraction of a structure with correlated factors. Indeed, such a structure was produced. Factors 1 (TP) and 3 (TB) were highly correlated ($r = 0.512$, $p < 0.01$), in compliance with research hypothesis (1). Factors 2 (RAC) and 3 (TB) were moderately correlated ($r = 0.319$, $p < 0.01$) (see **Table 4**).

Correlations between subscales were also compared across research groups (general and special education teachers). Subscales 1 (TP) and 3 (TB) were correlated for both comparison groups [general education. $r(71) = 0.518$, $p < 0.01$; special education. $r(45) = 0.471$, $p < 0.01$]. Subscales 2 (RAC) and 3 (TB) were correlated for general education teachers only

TABLE 2 | Factor loadings with direct oblimin rotation of final questionnaire items.

Item	(1) Teaching practices (TP)	(2) eading-arithmetic correlation (RAC)	(3) Teaching beliefs (TB)
I teach, in language arts class, strategies to remember in parallel multiple details from the text	0.634		
I teach in math class strategies for planning ahead in task performance	0.594		
I teach in language arts class strategies to focus on task	0.543		
When I teach a student with difficulties in reading, I will work with him on methods to store in his memory multiple bits of information in parallel	0.519		
I devote time in math class to memorizing solutions to common math problems	0.467		
When I teach a student with difficulties in math, I will work with him on methods to store in his memory multiple arithmetical operations in parallel	0.520		
I devote time in language arts class to memorizing common orthographic patterns, to encourage reading them as whole words instead of their phonological decoding	0.426		
Most of the children who read well are also good in math		−0.648	
If a student has difficulty in both reading and math, these difficulties usually stem from the same source		−0.657	
Students who do not read accurately have difficulties in understanding math		−0.613	
There are more students who have difficulties both in reading and math, than students with difficulties in math only and not in reading		−0.649	
There are more students who have difficulties both in reading and math, than students with difficulties in reading only and not in math		−0.589	
The basic mechanisms crucial for learning math are also crucial for learning to read		−0.574	
Children who can plan ahead their actions in performing a task, solve math problems more easily			0.599
The ability to focus on task is important when solving math problems			0.585
Students who are able to plan ahead their actions in performing a task, cope better with math word problems.			0.527
Students with difficulties in reading comprehension also tend to try solving problems again and again in the same way, even if this way was proven wrong			0.518
One has to keep in memory information while reading, in order to achieve reading comprehension			0.455
The ability to focus on task is important for reading comprehension			0.462
Students with difficulties in math also tend to try solving problems again and again in the same way, even if this way was proven wrong			0.474
Inhibition is an important ability in the acquirement of reading			0.455
The student's ability to quickly recall the spelling of words he has previously been exposed to, affects reading rate			0.428

$[r(71) = 0.356, p < 0.01]$. All correlations were compared using a Fischer's Z test, and no significant differences were found between these correlations.

STATISTICAL ANALYSIS AND RESULTS

Descriptive Analysis of Item Responses

Each respondent's score on every subscale was determined as the mean of the respondent's ratings of the statements comprising the subscale. Most respondents scored well above 3 on a likert scale on subscales 1 (TP) and 3 (TB), as reflected in the percentage of respondents who scored over 3.5. On the contrary, there was no clear trend emerging from respondents' scores on subscale 2 (RAC). Approximately half of the respondents scored between 2.5 and 3.5. In addition, the variance of scores is high compared to the other subscales (see **Table 5**).

Analysis by Demographic Variables

Teachers were asked in the questionnaire to state the type of students they teach (general or special education) and their years of experience teaching reading and arithmetic. Both questions regarding experience were highly correlated $[r(116) = 0.74,$

TABLE 3 | The theoretical themes reflected in subscales (TP) and (TB) of the Final Questionnaire (number of items in parentheses).

Executive functions	Reading	Arithmetic
Shifting (cognitive flexibility)	Beliefs (1)	Beliefs (1)
Inhibition	Beliefs (1)	
Attentional control	Beliefs (1), Practices (1)	Beliefs (1)
Planning		Beliefs (2), Practices (1)
Working memory	Beliefs (1), Practices (2)	Practices (1)
Automatic retrieval	Beliefs (1), Practices (1)	Practices (1)

TABLE 4 | Correlations between extracted factors.

Measure	(1) Teaching practices (TP)	(2) Reading-arithmetic correlation (RAC)	(3) Teaching beliefs (TB)
Factor 1. TP	–		
Factor 2. RAC	0.154	–	
Factor 3. TB	0.512**	0.319**	–

$^{**}p < 0.01$; N = 116.

$p < 0.01$], suggesting statistical redundancy, thus their results were transformed into an "overall years of experience" variable.

Testing research hypothesis (2), a negative correlation was found between the average score on subscale 2 (RAC) and overall teaching experience [$r(116) = -0.192$, $p < 0.05$]. No significant correlations were found between the other subscales and overall teaching experience.

Research hypothesis (3) was tested using general linear modeling, with the average scores on the three emergent questionnaire subscales as dependent variables and the independent variable of "Education System," based on demographic information.

To determine the connection between the education system (general/ special) the teacher belongs to and questionnaire subscale scores, multivariate analysis of covariance (MANCOVA) was conducted, with "overall years of experience" as a covariate. The latter variable was considered a confound due to the significant difference in average years of experience in the general education ($M = 9.69$, $SD = 7.68$) and special education ($M = 4.87$, $SD = 7.72$) groups; $t(114) = 3.29$, $p < 0.01$.

It was found that special education teachers scored significantly higher on questionnaire subscales 1 (TP) and 3 (TB) compared to general education teachers. On subscale 2 (RAC), the difference was marginally significant. [Subscale 1. $F(1,113) = 7.850$, $p < 0.01$; Subscale 2. $F(1,113) = 3.673$, $p = 0.058$; Subscale 3. $F(1,113) = 5.042$, $p < 0.05$; Wilk's $\Lambda = 0.911$, see **Table 6** and **Figure 1**).

DISCUSSION

Findings from the current study add an important professional tool for teachers in the area of EF and academic achievement. First we present a new reliable and valid questionnaire that can be used to investigate beliefs of teachers and graduate students in schools of education, regarding the role of EF in reading and arithmetic class. In addition to assessing teachers' current stand on this issue, the act of answering the questionnaire in itself can raise teacher awareness to the importance of EF for academic achievement. Furthermore, our results indicate that special and general education teachers see differently the contribution of EF to student competence in reading and arithmetic.

Mastery of EF processes such as goal setting, planning, organizing, prioritizing, memorizing, initiating, shifting, and self-monitoring are all essential for productive functioning in our progressively complex, technological society. In addition, EF has been a focus of the continuing theoretical debate concerning the origins of cognition and how it develops throughout life. Beginning in the elementary grades, students are asked to complete lengthy reading, writing and arithmetic assignments, all of which profoundly depend on these EF processes. Hence, academic as well as life success are thus dependent on students' ability to plan their time, organize and prioritize materials and information, distinguish main idea from details, shift approaches flexibly, monitor their own progress, and reflect on their work. However, EF is not taught systematically in schools and is not

TABLE 5 | Descriptive measures of questionnaire subscale scores.

Subscale	Min.	Max.	Mean	*SD*	% scores > 3.5	% scores < 2.5
(1) Teaching practices (TP)	1.43	4.86	3.68	0.66	62.93%	6.89%
(2) Reading-arithmetic connection (RAC)	1.67	4.83	2.88	0.81	19.83%	31.03%
(3) Teaching beliefs (TB)	2.56	5	3.97	0.53	82.76%	0%

TABLE 6 | Multivariate analysis of covariance by "education system."

Independent variables (IV)	General education		Special education		Dependent variables (DV)	Mean Square	*F* (df)	Partial eta squared
	M	*SD*	*M*	*SD*				
Education System	3.58	0.68	3.84	0.61	Subscale 1: Teaching practices (TP)	3.195	7.850 (1,113)**	0.065
	2.74	0.81	3.10	0.76	Subscale 2: Reading-arithmetic connection (RAC)	2.260	3.673 (1,113)^	0.031
	3.88	0.56	4.11	0.45	Subscale 3: Teaching beliefs (TB)	1.366	5.042 (1,113)*	0.043
Covariate (years Of experience)					Subscale 1	2.822	6.934 (1,113)*	
					Subscale 2	1.297	2.108 (1,113)	
					Subscale 3	0.009	0.032 (1,113)	

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{\wedge}p = 0.058$, N = 116.

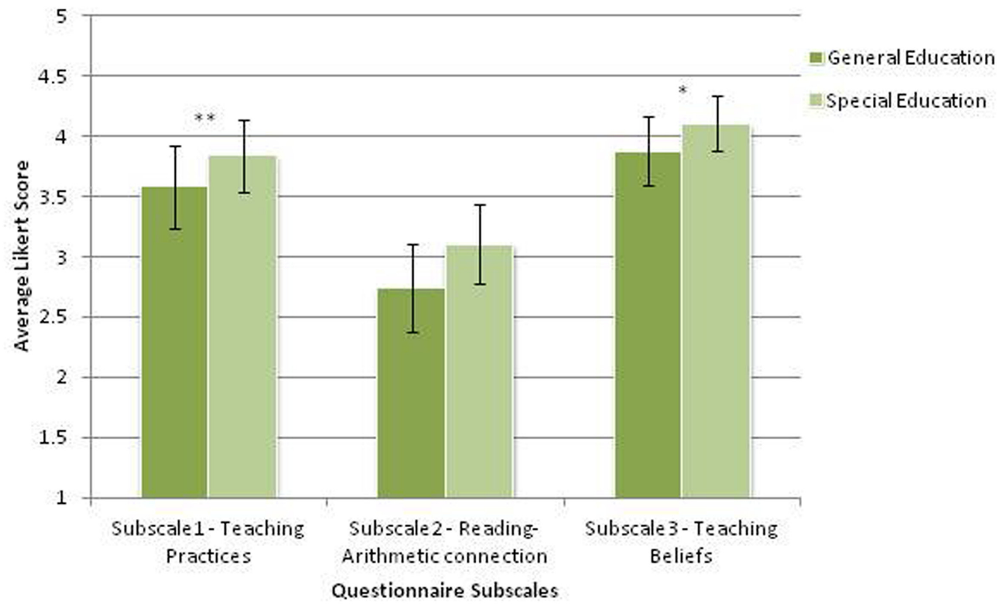


FIGURE 1 | Mean likert scores of questionnaire subscales, for general education and special education teachers. Error bars represent standard errors. $^{*}p < 0.05$, $^{**}p < 0.01$.

a focus of the pedagogical curriculum (Meltzer et al., 2007). In addition, not many programs directly target how EF strategies are developed and implemented. There are a few published studies of such programs, such as "Tools of the mind" (Diamond et al., 2007) and PATHS (Promoting Alternative Thinking Strategies; Riggs, 2004). These studies mostly date back to the last decade and were conducted in North America (Dias and Seabra, 2015).

A strong indication of the neglect of EF in the educational setting, can be found in the guidelines of the National Reading and Math Panels of the United-States, which do not mention in any explicit form the role of underlying EF in the acquirement of reading (National Reading Panel, 2000) and math (National Mathematics Advisory Panel, 2008). The NRP does not address the role of EF in reading-comprehension, for example, or the need to educate teachers about domain-general cognitive variables affecting students' literacy. Under these circumstances, it is of interest to investigate what teachers believe and do, in relation the contribution of EF to their students' reading and arithmetic achievements. This is a question worth answering, since it is known that a change in practices can be achieved only if teachers' attitudes and beliefs are addressed (Ertmer et al., 2012).

To address this issue, a novel questionnaire of 22 items was composed, divided into three subscales by an exploratory factoring procedure: "TP," "RAC" and "TB" The questionnaire was found internally consistent, its content validity reviewed by professional and construct validity evaluated by the factoring process.

As hypothesized, a strong positive correlation ($r = 0.512$) emerged between respondents' scores on the "TP" and "TB" questionnaire subscales, in agreement with the general notion that teaching beliefs are correlated with pedagogical practices (Baccus, 2004; Ertmer et al., 2006; Cross, 2009; Paro et al., 2009).

Scores on the "TB" and "RAC" subscales were also positively correlated, but to a lesser extent, suggesting that beliefs about the contribution of EF to reading and arithmetic are somewhat related to beliefs about a connection between reading and arithmetic abilities. The relative weakness of this correlation implies that these subscales do measure different sets of teaching beliefs. This conclusion is supported by a descriptive analysis of respondents' scores on the different subscales, which suggests that most questionnaire respondents believe in a connection between executive functioning and achievements in reading and arithmetic (as measured by the TB subscale. $M = 3.97$ on a scale of 5). It may also suggest, to a lesser extent (due to higher variance in scores on the TP subscale), that most of them try addressing this connection in their classroom practices ($M = 3.68$). On the contrary, teachers vary greatly in the way they see the connection reading-arithmetic and the existence of shared underlying mechanisms, as measured by the RAC subscale ($M = 2.88$). Approximately half of them (49.14%) scored between 2.5 and 3.5 on this subscale, thus seem to be undecided on this issue, and about a third (31.03%) scored below 2.5, signaling their disagreement.

We can conclude from these findings, that most teachers recognize the effect that student behaviors reflecting cognitive flexibility, inhibition, attentional control, planning, working memory, and automatic retrieval, have on achievements in reading and arithmetic. Moreover, findings indicate that teachers' beliefs about this effect are related to their reported teaching practices.

Furthermore, the fact that half of the teachers did not approve or deny the connection between the cognitive foundations of, and achievements in, reading and arithmetic actually supports the influence they attribute to underlying domain-general mechanisms. How so? Traditionally, cognitive mechanisms underlying reading and arithmetic are viewed as mostly domain-specific and separable (e.g., Lyon et al., 2003; Price et al., 2007). These mechanisms do play a central role, along with domain-general mechanisms as EF. Thus, agreement with statements in the RAC subscale (for example: "If a student has difficulty in both reading and math, these difficulties usually stem from the same source") would deny the important part that phonological awareness does play in reading (Lyon et al., 2003) or the ability to manipulate quantities plays in arithmetic (Price et al., 2007). The "undecided" respondents actually signal in their responses that they believe reading and arithmetic rely on both domain-specific and domain-general mechanisms.

Our findings indicate that beliefs of professionals in the field are in agreement with the abundance of literature about the contribution of EF to reading and arithmetic abilities. However, teachers' knowledge about EF remains intuitive. Without explicit training, teachers will continue to not identify EF as a contributor when a student experiences difficulties in reading or arithmetic. With a scarcity of evidence-based interventions addressing EF (Dias and Seabra, 2015), teachers will not be able to implement interventions suitable for students with EF difficulties. Furthermore, as research indicates, addressing EF in the classroom can help all students, not only struggling ones. As Meltzer et al. (2007) claimed, interventions addressing EF would result in less special-education referrals. It is time to include EF as an important factor in national reports, teacher training and school curriculum.

On another note, a negative correlation ($r = -0.192$) was found between score on the RAC subscale and overall years of experience, contrary to our hypotheses. We can conclude that the more years a person gained as a teacher, he/she tends to hold a more traditional view, of reading and arithmetic being supported mostly by domain-specific mechanisms. Experienced teachers were found in the past, to possess higher knowledge of characteristics of ADHD than inexperienced ones (Anderson et al., 2012), yet it does not necessarily mean they see EF as shared underlying mechanisms of reading and arithmetic abilities. To assess also whether our questionnaire differentiates between groups of teachers. We compared between general and special education teachers, controlling for years of experience, which served as a confounding variable. In compliance with our hypotheses, it was found that special education teachers scored significantly higher than general education teachers on the TP ($F = 7.85$, $p < 0.01$) and TB ($F = 5.04$, $p < 0.05$) questionnaire subscales. Thus, special education teachers reported holding more beliefs about the contribution of EF to achievements in reading and arithmetic, and also reported applying more teaching practices targeting EF in their reading and arithmetic classes. In addition, a marginally significant difference was found in scores on the RAC subscale ($F = 3.67$, $p = 0.058$), suggesting these teachers might also see a stronger connection between the cognitive foundations of, and achievements in, reading and arithmetic.

Although EF is known to affect achievements in reading and arithmetic in the general population (e.g., Altemeier et al., 2008; Miller et al., 2013), there are some reasons why this link may be less noticeable to the general education teacher. On the one hand, one of the central characteristics of the special education system is seeing students in a holistic way, starting by building an Individualized Education Program (IEP; Gartin and Murdick, 2005) for every student. This attention to every student's overall functioning and thinking processes, makes the special education teacher more prone to notice domain-general mechanisms affecting achievements across different school subjects. On the other hand, another possible explanation relies in the fact that special education students do manifest more difficulties in EF (Wright, 2010). Teachers witnessing most of their students struggle greatly with basic executive functioning, such as inhibiting responses in class and shifting between simple tasks, may give more weight to the effect of these mechanisms on school achievement.

There are some limitations to this study which should be taken into account. First of all, the questionnaire developed, being the first of its kind, is still at its first steps in terms of validity and generalizability. In the future, the questionnaire should be administered to more groups of teachers, to enhance its value to the field. Moreover, the comparison made between general and special education teachers did produce interesting findings, but should be addressed carefully, since it was performed on the population used for questionnaire developed.

Lastly, there is no certainty that teaching practices reported are aligned with actual classroom practices. Naturally, they may reflect desirable, optimal classroom situations while actual pedagogical practices are affected by "classroom realities" (Ertmer et al., 2012). In general, questionnaire respondents tend to socially desirable responding, which is "the tendency of people to present a favorable image of themselves on questionnaires" (Van de Mortel, 2008). Yet, consequently, we can at least infer from the reported practices that teachers feel that addressing EF in reading and arithmetic classes would be "the right thing to do." Additionally, the questionnaire, inquiring about such practices, has also an effect of raising teachers' awareness, first to their beliefs about the contribution of EF, and secondly, to the way these beliefs align with their teaching practices.

In summary, the current study introduces a novel research questionnaire, investigating school teachers' beliefs and practices concerning the contribution of EF to students' achievements in reading and arithmetic. Our findings indicate that early elementary teachers hold beliefs about the contribution of EF to students' reading and arithmetic achievements. Additionally, they report addressing this issue in their teaching practices. That is even more so in the case of special education teachers, compared to general education teachers. Further research, in more populations and methodologies, is required to expand our view on the way our school system sees the contribution of EF to academic achievements. It still is to be discovered how current research in this field can be communicated to teachers and manifested in the curriculum, and vice versa, how can teachers' experience inform current research. By that, the bridge between researchers and teachers, science and the classroom, will continue to strengthen and thrive.

AUTHOR CONTRIBUTIONS

SR, OR, and TM contributed to the design of the work, its analysis, and interpretation of data. In addition, SR, OR, and TK drafted and wrote the work and gave final approval of the version to be published.

SUPPLEMANTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2016.01567

REFERENCES

Alloway, T. P., and Alloway, R. G. (2010). Investigating the predictive roles of working memory and IQ in academic attainment. *J. Exp. Child Psychol.* 106, 20–29. doi: 10.1016/j.jecp.2009.11.003

Alloway, T. P., Gathercole, S. E., Adams, A. M., Willis, C., Eaglen, R., and Lamont, E. (2005). Working memory and phonological awareness as predictors of progress towards early learning goals at school entry. *Br. J. Dev. Psychol.* 23, 417–426. doi: 10.1348/026151005X26804

Altemeier, L. E., Abbott, R. D., and Berninger, V. W. (2008). Executive functions for reading and writing in typical literacy development and dyslexia. *J. Clin. Exp. Neuropsychol.* 30, 588–606. doi: 10.1080/13803390701562818

Alvarez, J. A., and Emory, E. (2006). Executive function and the frontal lobes: a meta-analytic review. *Neuropsychol. Rev.* 16, 17–42. doi: 10.1007/s11065-006-9002-x

Anderson, D. L., Watt, S. E., Noble, W., and Shanley, D. C. (2012). Knowledge of attention deficit hyperactivity disorder (ADHD) and attitudes toward teaching children with ADHD: the role of teaching experience. *Psychol. Sch.* 49, 511–525. doi: 10.1002/pits.21617

Ashkenazi, S., Black, J. M., Abrams, D. A., Hoeft, F., and Menon, V. (2013). Neurobiological underpinnings of math and reading learning disabilities. *J. Learn. Disabil.* 46, 549–569. doi: 10.1177/0022219413483174

Baccus, A. A. (2004). *Urban Fourth and Fifth Grade Teachers' Reading Attitudes and Efficacy Beliefs: Relationships to Reading Instruction and to Students' Attitudes and Efficacy Beliefs.* Available at: http://hdl.handle.net/1903/1420

Baddeley, A. (1992). Working memory. *Science* 255, 556–559. doi: 10.1126/science.1736359

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: constructing a unifying theory of ADHD. *Psychol. Bull.* 121:65. doi: 10.1037/0033-2909.121.1.65

Bar-Kochva, I. (2012). What are the underlying skills of silent reading acquisition? A developmental study from kindergarten to the 2nd grade. *Read. Writ.* 26, 1417. doi: 10.1007/s11145-012-9414-3

Berg, D. H. (2008). Working memory and arithmetic calculation in children: the contributory roles of processing speed, short-term memory, and reading. *J. Exp. Child Psychol.* 99, 288–308. doi: 10.1016/j.jecp.2007.12.002

Berninger, V. W., Abbott, R. D., Swanson, H. L., Lovitt, D., Trivedi, P., Lin, S. J. C., et al. (2010). Relationship of word-and sentence-level working memory to reading and writing in second, fourth, and sixth grade. *Lang. Speech Hear. Serv. Sch.* 41, 179. doi: 10.1044/0161-1461(2009/08-0002)

Best, J. R., Miller, P. H., and Naglieri, J. A. (2011). Relations between executive function and academic achievement from ages 5 to 17 in a large, representative national sample. *Learn. Ind. Diff.* 21, 327–336. doi: 10.1016/j.lindif.2011.01.007

Bierman, K. L., Nix, R. L., Greenberg, M. T., Blair, C., and Domitrovich, C. E. (2008). Executive functions and school readiness intervention: impact, moderation, and mediation in the Head Start REDI program. *Dev. Psychopathol.* 20, 821–843. doi: 10.1017/S0954579408000394

Blair, C., and Razza, R. P. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child Dev.* 78, 647–663. doi: 10.1111/j.1467-8624.2007.01019.x

Borella, E., Carretti, B., and Pelegrina, S. (2010). The specific role of inhibition in reading comprehension in good and poor comprehenders. *J. Learn. Disabil.* 43, 541–552. doi: 10.1177/0022219410371676

Borg, M. (2001). Teachers' beliefs. *ELT J.* 55, 186–188. doi: 10.1093/elt/55.2.186

Buehl, M. M., Alexander, P. A., and Murphy, P. K. (2002). Beliefs about schooled knowledge: domain specific or domain general? *Contempor. Educ. Psychol.* 27, 415–449. doi: 10.1006/ceps.2001.1103

Carter, G., and Norwood, K. S. (1997). The relationship between teacher and student beliefs about mathematics. *Sch. Sci. Math.* 97, 62–67. doi: 10.1111/j.1949-8594.1997.tb17344.x

Cartwright, K. B. (2012). Insights from cognitive neuroscience: the importance of executive function for early reading development and education. *Early Educ. Dev.* 23, 24–36. doi: 10.1080/10409289.2011.615025

Cho, S., Metcalfe, A. W., Young, C. B., Ryali, S., Geary, D. C., and Menon, V. (2012). Hippocampal–prefrontal engagement and dynamic causal interactions in the maturation of children's fact retrieval. *J. Cogn. Neurosci.* 24, 1849–1866. doi: 10.1162/jocn_a_00246

Clark, C. A., Pritchard, V. E., and Woodward, L. J. (2010). Preschool executive functioning abilities predict early mathematics achievement. *Dev. Psychol.* 46, 1176. doi: 10.1037/a0019672

Compton, D. L., Fuchs, L. S., Fuchs, D., Lambert, W., and Hamlett, C. (2012). The cognitive and academic profiles of reading and mathematics learning disabilities. *J. Learn. Disabil.* 45, 79–95. doi: 10.1177/0022219410393012

Costello, A. B., and Osborne, J. W. (2005). Best practices in exploratory factor analysis: four recommendations for getting the most from your analysis. *Pract. Assess. Res. Eval.* 10, 173–178.

Cragg, L., and Gilmore, C. (2014). Skills underlying mathematics: the role of executive function in the development of mathematics proficiency. *Trends Neurosci. Educ.* 3, 63–68. doi: 10.1016/j.tine.2013.12.001

Cross, D. I. (2009). Alignment, cohesion, and change: examining mathematics teachers' belief structures and their influence on instructional practices. *J. Math. Teacher Educ.* 12, 325–346. doi: 10.1007/s10857-009-9120-5

Davidse, N. J., de Jong, M. T., and Bus, A. G. (2015). Causal relations among executive functions and academic skills from preschool to end of first grade. *Engl. Linguist. Res.* 4:49. doi: 10.5430/elr.v4n1p49

De Beni, R., and Palladino, P. (2000). Intrusion errors in working memory tasks: are they related to reading comprehension ability? *Learn. Ind. Diff.* 12, 131–143. doi: 10.1016/S1041-6080(01)00033-4

DeFord, D. E. (1979). *The DeFord Theoretical Orientation to Reading Profile (TORP).* Washington, DC: Eric Institute of Education Sciences.

Diamond, A. (2013). Executive functions. *Annu. Rev. Psychol.* 64, 135. doi: 10.1146/annurev-psych-113011-143750

Diamond, A., Barnett, W. S., Thomas, J., and Munro, S. (2007). Preschool program improves cognitive control. *Science* 318, 1387. doi: 10.1126/science.1151148

Dias, N. M., and Seabra, A. G. (2015). The promotion of executive functioning in a Brazilian public school: a pilot study. *Span. J. Psychol.* 18:E8. doi: 10.1017/sjp.2015.4

Durand, M., Hulme, C., Larkin, R., and Snowling, M. (2005). The cognitive foundations of reading and arithmetic skills in 7-to 10-year-olds. *J. Exp. Child Psychol.* 91, 113–136. doi: 10.1016/j.jecp.2005.01.003

Ertmer, P. A., Ottenbreit-Leftwich, A., and York, C. S. (2006). Exemplary technology-using teachers: perceptions of factors influencing success. *J. Comput. Teacher Educ.* 23, 55–61.

Ertmer, P. A., Ottenbreit-Leftwich, A. T., Sadik, O., Sendurur, E., and Sendurur, P. (2012). Teacher beliefs and technology integration practices: a critical relationship. *Comput. Educ.* 59, 423–435. doi: 10.1016/j.compedu.2012.02.001

Fabrigar, L. R., Wegener, D. T., MacCallum, R. C., and Strahan, E. J. (1999). Evaluating the use of exploratory factor analysis in psychological research. *Psychol. Methods* 4, 272. doi: 10.1037/1082-989X.4.3.272

Falcón-Huertas, M. (2006). *Teachers' Literacy Beliefs and Their Students' Conceptions About Reading And Writing*. Doctoral dissertation, University of South Florida, Tampa, FL.

Garon, N., Bryson, S. E., and Smith, I. M. (2008). Executive function in preschoolers: a review using an integrative framework. *Psychol. Bull.* 134:31. doi: 10.1037/0033-2909.134.1.31

Gartin, B., and Murdick, N. (2005). IDEA 2004: the IEP. *Remedial Spec. Educ.* 26, 327–331. doi: 10.1177/07419325050260060301

Geary, D. C. (2004). Mathematics and learning disabilities. *J. Learn. Disabil.* 37, 4–15. doi: 10.1177/00222194040370010201

Geary, D. C. (2011). Cognitive predictors of achievement growth in mathematics: a 5-year longitudinal study. *Dev. Psychol.* 47, 1539. doi: 10.1037/a0025510

Geary, D. C., Hoard, M. K., Byrd-Craven, J., and Catherine DeSoto, M. (2004). Strategy choices in simple and complex addition: contributions of working memory and counting knowledge for children with mathematical disability. *J. Exp. Child Psychol.* 88, 121–151. doi: 10.1016/j.jecp.2004.03.002

Georgiou, G. K., Tziraki, N., Manolitsis, G., and Fella, A. (2013). Is rapid automatized naming related to reading and mathematics for the same reason (s)? A follow-up study from kindergarten to Grade 1. *J. Exp. Child Psychol.* 115, 481–496. doi: 10.1016/j.jecp.2013.01.004

Gilmary, S. (1967). Transfer effects of reading remediation to arithmetic computation when intelligence is controlled and all other school factors are eliminated. *Arith. Teach.* 14, 17–20.

Gilmore, C., Attridge, N., Clayton, S., Cragg, L., Johnson, S., Marlow, N., et al. (2013). Individual differences in inhibitory control, not non-verbal number acuity, correlate with mathematics achievement. *PLoS ONE* 8:e67374. doi: 10.1371/journal.pone.0067374

Grimm, K. J. (2008). Longitudinal associations between reading and mathematics achievement. *Dev. Neuropsychol.* 33, 410–426. doi: 10.1080/87565640801982486

Gunning-Dixon, F. M., and Raz, N. (2003). Neuroanatomical correlates of selected executive functions in middle-aged and older adults: a prospective MRI study. *Neuropsychologia* 41, 1929–1941. doi: 10.1016/S0028-3932(03)00129-5

Hanly, S., and Vandenberg, B. (2010). Tip-of-the-tongue and word retrieval deficits in dyslexia. *J. Learn. Disabil.* 43, 15–23. doi: 10.1177/00222194093 38744

Housner, L. D., and Griffey, D. (1985). Teacher cognition: differences in planning and interactive decision making between experienced and inexperienced teachers. *Res. Q. Exer. Sport* 56, 45–53. doi: 10.1080/02701367.1985.10608430

Jiménez, J. E., Rodríguez, C., Suárez, N., O'Shanahan, I., Villadiego, Y., Uribe, C., et al. (2015). Teachers' implicit theories of learning to read: a cross-cultural study in Ibero-American countries. *Read. Writ.* 28, 1355–1379. doi: 10.1007/s11145-015-9574-z

Jordan, N. C., Kaplan, D., and Hanich, L. B. (2002). Achievement growth in children with learning difficulties in mathematics: findings of a two-year longitudinal study. *J. Educ. Psychol.* 94:586. doi: 10.1037/0022-0663.94.3.586

Jurado, M. B., and Rosselli, M. (2007). The elusive nature of executive functions: a review of our current understanding. *Neuropsychol. Rev.* 17, 213–233. doi: 10.1007/s11065-007-9040-z

Kane, M. J., and Engle, R. W. (2000). Working-memory capacity, proactive interference, and divided attention: limits on long-term memory retrieval. *J. Exp. Psychol. Learn. Mem. Cogn.* 26, 336. doi: 10.1037/0278-7393.26. 2.336

Kaya, M. (2014). The qualities of effective literacy teachers: the dynamics of effective teachers' beliefs, their practices and students' responses. *J. Educ. Hum. Dev.* 3, 41–57. doi: 10.15640/jehd.v3n3a4

Kieffer, M. J., Vukovic, R. K., and Berry, D. (2013). Roles of attention shifting and inhibitory control in fourth-grade reading comprehension. *Read. Res. Q.* 48, 333–348.

Kim, C., Kim, M. K., Lee, C., Spector, J. M., and DeMeester, K. (2013). Teacher beliefs and technology integration. *Teach. Teach. Educ.* 29, 76–85. doi: 10.1016/j.tate.2012.08.005

Koponen, T., Aunola, K., Ahonen, T., and Nurmi, J. E. (2007). Cognitive predictors of single-digit and procedural calculation skills and their covariation with reading skill. *J. Exp. Child Psychol.* 97, 220–241. doi: 10.1016/j.jecp.2007. 03.001

Krajewski, K., and Schneider, W. (2009). Exploring the impact of phonological awareness, visual–spatial working memory, and preschool quantity–number competencies on mathematics achievement in elementary school: findings from a 3-year longitudinal study. *J. Exp. Child Psychol.* 103, 516–531. doi: 10.1016/j.jecp.2009.03.009

Kroesbergen, E. H., Van Luit, J. E. H., Van Lieshout, E. C. D. M., Van Loosbroek, E., and Van de Rijt, B. A. M. (2009). Individual differences in early numeracy the role of executive functions and subitizing. *J. Psychoeduc. Assess.* 27, 226–236. doi: 10.1177/0734282908330586

Kulak, A. G. (1993). Parallels between math and reading disability common issues and approaches. *J. Learn. Disabil.* 26, 666–673. doi: 10.1177/002221949302601004

Lavigne, A. L. (2014). Beginning teachers who stay: beliefs about students. *Teach. Teach. Educ.* 39, 31–43. doi: 10.1016/j.tate.2013.12.002

Lemaire, P. (2010). Executive functions and strategic aspects of arithmetic performance: the case of adults' and children's arithmetic. *Psychol. Bel.* 50, 3–4. doi: 10.5334/pb-50-3-4-335

Lerkkanen, M. K., Rasku-Puttonen, H., Aunola, K., and Nurmi, J. E. (2005). Mathematical performance predicts progress in reading comprehension among 7-year olds. *Eur. J. Psychol. Educ.* 20, 121–137. doi: 10.1007/BF031 73503

Lerman, S. (1990). Alternative perspectives of the nature of mathematics and their influence on the teaching of mathematics. *Br. Educ. Res. J.* 16, 53–61. doi: 10.1080/0141192900160105

Liu, S. H. (2011). Factors related to pedagogical beliefs of teachers and technology integration. *Comput. Educ.* 56, 1012–1022. doi: 10.1016/j.compedu.2010. 12.001

Lloyd, G. (2003). "Mathematics teachers' beliefs and experiences with innovative curriculum materials," in *Beliefs: A Hidden Variable in Mathematics Education?*, eds G. C. Leder, E. Pehkonen, and G. Törner (Dordrecht: Springer), 149–159.

Luciano, J. A. (1997). *An Examination of the Relationship Between First Grade Teachers' Theoretical Orientations Toward Reading Instruction and Their Classroom Instructional Practices*. Doctoral Dissertation, University of North Florida, Jacksonville, FL.

Lyon, G. R., Shaywitz, S. E., and Shaywitz, B. A. (2003). A definition of dyslexia. *Annals Dyslexia* 53, 1–14. doi: 10.1007/s11881-003-0001-9

Mammarella, I. C., Bomba, M., Caviola, S., Broggi, F., Neri, F., Lucangeli, D., et al. (2013). Mathematical difficulties in nonverbal learning disability or co-morbid dyscalculia and dyslexia. *Dev. Neuropsychol.* 38, 418–432. doi: 10.1080/87565641.2013.817583

Martin, M. O., Mullis, I. V., and Kennedy, A. M. (2007). *Progress in International Reading Literacy Study (PIRLS)*. Technical Report PIRLS 2006. Chestnut Hill, MA: TIMSS & PIRLS International Study Center, Boston College.

Martinussen, R., Tannock, R., and Chaban, P. (2011) "Teachers' reported use of instructional and behavior management practices for students with behavior problems: relationship to role and level of training in ADHD. *Child Youth Care Forum* 40, 193–210.

McCabe, D. P., Roediger, H. L. III, McDaniel, M. A., Balota, D. A., and Hambrick, D. Z. (2010). The relationship between working memory capacity and executive functioning: evidence for a common executive attention construct. *Neuropsychology* 24, 222.

McKnight, C. C. (2015). *Teacher Knowledge, Skill, and Willingness To Work With Students with Attention Deficit Hyperactivity DisordeR (ADHD)*. Doctoral dissertation, Rowan University, Glassboro, NJ.

McVay, J. C., and Kane, M. J. (2012). Why does working memory capacity predict variation in reading comprehension? On the influence of mind wandering and executive attention. *J. Exp. Psychol. Gen.* 141, 302. doi: 10.1037/a00 25250

Meltzer, L., Pollica, L., Barzillai, M., and Meltzer, L. (2007). "Executive function in the classroom: embedding strategy instruction into daily teaching practices," in *Executive Function in Education: From Theory to Practice*, eds L. Meltzer, L. S. Pollica, and M. Barzillai (New York: Guilford Press), 165–193.

Miles, T. R., and Miles, E. (1992). *Dyslexia and Mathematics*. London: Routledge.

Miller, M. R., Müller, U., Giesbrecht, G. F., Carpendale, J. I. M., and Kerns, K. A. (2013). The contribution of executive function and social understanding to preschoolers' letter and math skills. *Cogn. Dev.* 28, 331–349. doi: 10.1016/j.cogdev.2012.10.005

Miyake, A., and Friedman, N. P. (2012). The nature and organization of individual differences in executive functions four general conclusions. *Curr. Dir. Psychol. Sci.* 21, 8–14. doi: 10.1177/0963721411429458

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., and Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cogn. Psychol.* 41, 49–100.

National Mathematics Advisory Panel (2008). *Foundations for Success: The Final Report of the National Mathematics Advisory Panel*. Washington, D.C: US Department of Education.

National Reading Panel (2000). *Teaching Children to Read: An Evidence-Based Assessment of the Scientific Research Literature on Reading and its Implications for Reading Instruction (NIH Pub. 00- 4754)*. Washington, DC: Department of Health and Human Services.

Near, S. M. (2014). *Literacy Instruction in Math Classes.* Doctoral dissertation, State University of New York, Fredonia, NY.

Nevo, E., and Breznitz, Z. (2011). Assessment of working memory components at 6 years of age as predictors of reading achievements a year later. *J. Exp. Child Psychol.* 109, 73–90. doi: 10.1016/j.jecp.2010.09.010

Pajares, M. F. (1992). Teachers' beliefs and educational research: cleaning up a messy construct. *Rev. Educ. Res.* 62, 307–332. doi: 10.3102/00346543062003307

Paro, K. M. L., Hamre, B. K., Locasale-Crouch, J., Pianta, R. C., Bryant, D., Early, D., et al. (2009). Quality in kindergarten classrooms: observational evidence for the need to increase children's learning opportunities in early education classrooms. *Early Educ. Dev.* 20, 657–692. doi: 10.1080/10409280802541965

Price, G. R., Holloway, I., Räsänen, P., Vesterinen, M., and Ansari, D. (2007). Impaired parietal magnitude processing in developmental dyscalculia. *Curr. Biol.* 17, R1042–R1043. doi: 10.1016/j.cub.2007.10.013

Riggs, N. (2004). "The PATHS curriculum: theory and research on neurocognitive development and school success," in *Building Academic Success on Social and Emotional Learning: What Does the Research Say*, eds J. E. Zins, R. P. Weissberg, M. C. Wang, and H. J. Walberg (New York, NY: Teachers College Press), 170–188.

Ritchey, K. D., Coker, D. L. Jr., and Jackson, A. F. (2015). The relationship between early elementary teachers' instructional practices and theoretical orientations and students' growth in writing. *Read. Writ.* 28, 1333–1354. doi: 10.1007/s11145-015-9573-0

Robinson, K. M., and Dubé, A. K. (2013). Children's additive concepts: promoting understanding and the role of inhibition. *Learn. Ind. Diff.* 23, 101–107. doi: 10.1016/j.lindif.2012.07.016

Rosen, V. M., and Engle, R. W. (1997). The role of working memory capacity in retrieval. *J. Exp. Psychol. Gen.* 126, 211. doi: 10.1037/0096-3445.126.3.211

Röthlisberger, M., Neuenschwander, R., Cimeli, P., and Roebers, C. M. (2013). Executive functions in 5-to 8-year olds: developmental changes and relationship to academic achievement. *J. Educ. Dev. Psychol.* 3, 153.

Rubie-Davies, C. M., Flint, A., and McDonald, L. G. (2012). Teacher beliefs, teacher characteristics, and school contextual factors: what are the relationships? *Br. J. Educ. Psychol.* 82, 270–288. doi: 10.1111/j.2044-8279.2011.02025.x

Schroeder, S. (2011). What readers have and do: effects of students' verbal ability and reading time components on comprehension with and without text availability. *J. Educ. Psychol.* 103, 877–896. doi: 10.1037/a0023731

Sesma, H. W., Mahone, E. M., Levine, T., Eason, S. H., and Cutting, L. E. (2009). The contribution of executive skills to reading comprehension. *Child Neuropsychol.* 15, 232–246. doi: 10.1080/09297040802220029

Shin, T., Davison, M. L., Long, J. D., Chan, C. K., and Heistad, D. (2013). Exploring gains in reading and mathematics achievement among regular and exceptional students using growth curve modeling. *Learn. Ind. Diff.* 23, 92–100. doi: 10.1016/j.lindif.2012.10.002

Silberstein, M., and Tamir, P. (1991). The expert case study model: an alternative approach to the development of teacher education modules. *J. Educ. Teach.* 17, 165–179. doi: 10.1080/0260747910170205

Stipek, D. J., Givvin, K. B., Salmon, J. M., and MacGyvers, V. L. (2001). Teachers' beliefs and practices related to mathematics instruction. *Teach. Teach. Educ.* 17, 213–226. doi: 10.1016/S0742-051X(00)00052-4

Swanson, H. L., O'Connor, J. E., and Cooney, J. B. (1990). An information processing analysis of expert and novice teachers' problem solving. *Am. Educ. Res. J.* 27, 533–556. doi: 10.3102/00028312027003533

Swanson, H. L., Zheng, X. H., and Jerman, O. (2009). Working memory, short-term memory, and reading disabilities: a selective meta-analysis of the literature. *J. Learn. Disabil.* 42, 260–287. doi: 10.1177/0022219409331958

Sweeting, K. (2011). *Early Years Teachers' Attitudes Towards Mathematics*. Ph.D. thesis, Queensland University of Technology, Brisbane, QLD.

Toll, S. W., Van der Ven, S. H., Kroesbergen, E. H., and Van Luit, J. E. (2011). Executive functions as predictors of math learning disabilities. *J. Learn. Disabil.* 44, 521–532. doi: 10.1177/0022219410387302

Tschannen-Moran, M., and Hoy, A. W. (2007). The differential antecedents of self-efficacy beliefs of novice and experienced teachers. *Teach. Teach. Educ.* 23, 944–956. doi: 10.1016/j.tate.2006.05.003

Unsworth, N., Brewer, G. A., and Spillers, G. J. (2013). Working memory capacity and retrieval from long-term memory: the role of controlled search. *Mem. Cogn.* 41, 242–254. doi: 10.3758/s13421-012-0261-x

Van de Mortel, T. F. (2008). Faking it: social desirability response bias in self-report research. *Aus. J. Adv. Nurs.* 25, 40–48.

van der Sluis, S., de Jong, P. F., and van der Leij, A. (2007). Executive functioning in children, and its relations with reasoning, reading, and arithmetic. *Intelligence* 35, 427–449. doi: 10.1016/j.intell.2006.09.001

Van der Ven, S. H., Kroesbergen, E. H., Boom, J., and Leseman, P. P. (2012). The development of executive functions and early mathematics: a dynamic relationship. *Br. J. Educ. Psychol.* 82, 100–119. doi: 10.1111/j.2044-8279.2011.02035.x

van Uden, J. M., Ritzen, H., and Pieters, J. M. (2014). Engaging students: the role of teacher beliefs and interpersonal teacher behavior in fostering student engagement in vocational education. *Teach. Teach. Educ.* 37, 21–32. doi: 10.1016/j.tate.2013.08.005

Viterbori, P., Usai, M. C., Traverso, L., and De Franchis, V. (2015). How preschool executive functioning predicts several aspects of math achievement in Grades 1 and 3: a longitudinal study. *J. Exp. Child Psychol.* 140, 38–55. doi: 10.1016/j.jecp.2015.06.014

Vukovic, R. K., and Lesaux, N. K. (2012). The relationship between linguistic skills and arithmetic knowledge. *Learn. Ind. Diff.* 23, 87–91. doi: 10.1016/j.lindif.2012.10.007

Waber, D. P., Gerber, E. B., Turcios, V. Y., Wagner, E. R., and Forbes, P. W. (2006). Executive functions and performance on high-stakes testing in children from urban schools. *Dev. Neuropsychol.* 29, 459–477. doi: 10.1207/s15326942dn2903_5

Welsh, J. A., Nix, R. L., Blair, C., Bierman, K. L., and Nelson, K. E. (2010). The development of cognitive skills and gains in academic school readiness for children from low-income families. *J. Educ. Psychol.* 102, 43–53. doi: 10.1037/a0016738

Westwood, P., Knight, B. A., and Redden, E. (1997). Assessing teachers' beliefs about literacy acquisition: the development of the Teachers' Beliefs about Literacy Questionnaire (TBALQ). *J. Res. Read.* 20, 224–235. doi: 10.1111/1467-9817.00034

Windschitl, M., and Sahl, K. (2002). Tracing teachers' use of technology in a laptop computer school: the interplay of teacher beliefs, social dynamics, and institutional culture. *Am. Educ. Res. J.* 39, 165–205. doi: 10.3102/00028312039001165

Wolf, M. (2008). *Proust and the Squid: The Story and Science of the Reading Brain*. Cambridge: Icon.

Wolters, C. A., and Daugherty, S. G. (2007). Goal structures and teachers' sense of efficacy: their relation and association to teaching experience and academic level. *J. Educ. Psychol.* 99, 181–193. doi: 10.1037/0022-0663.99.1.181

Wright, C. L. (2010). *Executive Functioning Skills in a School District: An Examination of Teachers' Perception of Executive Functioning Skills Related* *to Age, Sex, and Educational Classification*. Doctoral dissertation, Indiana University of Pennsylvania, Indiana, PA.

Yaghmale, F. (2003). Content validity and its estimation. *J. Med. Educ.* 3, 25–27.

Yeniad, N., Malda, M., Mesman, J., van IJzendoorn, M. H., and Pieper, S. (2013). Shifting ability predicts math and reading performance in children: a meta-analytical study. *Learn. Ind. Differ.* 23, 1–9. doi: 10.1016/j.lindif.2012.10.004

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

The reviewer LC and the handling Editor declared their shared affiliation, and the handling Editor states that the process nevertheless met the standards of a fair and objective review.

frontiers in Psychology

ORIGINAL RESEARCH
published: 25 May 2016
doi: 10.3389/fpsyg.2016.00775

Predicting Children's Reading and Mathematics Achievement from Early Quantitative Knowledge and Domain-General Cognitive Abilities

Felicia W. Chu[1], *Kristy vanMarle*[1] *and David C. Geary*[1,2]*

[1] *Department of Psychological Sciences, University of Missouri, Columbia, MO, USA,* [2] *Interdisciplinary Neuroscience Program, University of Missouri, Columbia, MO, USA*

One hundred children (44 boys) participated in a 3-year longitudinal study of the development of basic quantitative competencies and the relation between these competencies and later mathematics and reading achievement. The children's preliteracy knowledge, intelligence, executive functions, and parental educational background were also assessed. The quantitative tasks assessed a broad range of symbolic and nonsymbolic knowledge and were administered four times across 2 years of preschool. Mathematics achievement was assessed at the end of each of 2 years of preschool, and mathematics and word reading achievement were assessed at the end of kindergarten. Our goals were to determine how domain-general abilities contribute to growth in children's quantitative knowledge and to determine how domain-general and domain-specific abilities contribute to children's preschool mathematics achievement and kindergarten mathematics and reading achievement. We first identified four core quantitative competencies (e.g., knowledge of the cardinal value of number words) that predict later mathematics achievement. The domain-general abilities were then used to predict growth in these competencies across 2 years of preschool, and the combination of domain-general abilities, preliteracy skills, and core quantitative competencies were used to predict mathematics achievement across preschool and mathematics and word reading achievement at the end of kindergarten. Both intelligence and executive functions predicted growth in the four quantitative competencies, especially across the first year of preschool. A combination of domain-general and domain-specific competencies predicted preschoolers' mathematics achievement, with a trend for domain-specific skills to be more strongly related to achievement at the beginning of preschool than at the end of preschool. Preschool preliteracy skills, sensitivity to the relative quantities of collections of objects, and cardinal knowledge predicted reading and mathematics achievement at the end of kindergarten. Preliteracy skills were more strongly related to word reading, whereas sensitivity to relative quantity was more strongly related to mathematics achievement. The overall results indicate that a combination of domain-general and domain-specific abilities contribute to development of children's early mathematics and reading achievement.

Keywords: mathematics achievement, reading achievement, quantitative abilities, preschool, domain-specific abilities, domain-general abilities

OPEN ACCESS

Edited by:
Bert De Smedt,
Katholieke Universiteit Leuven,
Belgium

Reviewed by:
Luis J. Fuentes,
Universidad de Murcia, Spain
Tuire Katriina Koponen,
University of Jyväskylä, Finland

Correspondence:
David C. Geary
gearyd@missouri.edu

Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *11 February 2016*
Accepted: *09 May 2016*
Published: *25 May 2016*

Citation:
Chu FW, vanMarle K and Geary DC (2016) Predicting Children's Reading and Mathematics Achievement from Early Quantitative Knowledge and Domain-General Cognitive Abilities. Front. Psychol. 7:775. doi: 10.3389/fpsyg.2016.00775

INTRODUCTION

Numeracy and literacy at school completion predict employability and wages in adulthood (Bynner, 2004), and basic quantitative and preliteracy skills at school entry presage numeracy and literacy at school completion (Duncan et al., 2007). Identifying the factors that contribute to poor school entry mathematics and reading achievement has the potential to inform early remediation approaches for at-risk children. Research to date indicates that preschoolers' phonological awareness and letter knowledge predict later reading abilities (e.g., Lonigan et al., 2000; for a review and meta-analysis, see Wagner and Torgesen, 1987; Melby-Lervåg et al., 2012), but the research base on early quantitative skills and later mathematics achievement is not nearly as extensive (cf. Hannula and Lehtinen, 2005; Jordan et al., 2007). In addition to research on domain-specific predictors of later literacy and numeracy, there is a growing literature on the similarities and differences in the factors that predict growth in mathematics and reading achievement, but these studies have focused on elementary-school children (e.g., Koponen et al., 2007, 2013; Geary, 2011; Fuchs et al., 2016). Our study extends previous research by including a more extensive assessment of symbolic and nonsymbolic quantitative knowledge than in most previous studies, and by focusing on children who are younger than those in most previous studies. With this approach, we identify the beginning of preschool competencies that predict mathematics achievement and achievement growth over 2 years of preschool, and the similarities and differences in the competencies that predict mathematics and reading achievement at the end of kindergarten.

Similarities and Differences in Predictors of Mathematics and Reading Achievement

It is now recognized that growth in mathematics and reading competencies are related. In a large-scale longitudinal study, Grimm (2008) showed that third graders' reading comprehension predicted growth in several mathematical areas through eighth grade. It is not clear however whether the relation was due to reading competence *per se* or whether performance on the reading comprehension measure was a proxy for individual differences in domain-general abilities, such as working memory and intelligence, that predict achievement growth across academic domains. In any case, other studies have also found similarities as well as differences in the brain and cognitive systems that support children's reading and mathematical development (Mann Koepke and Miller, 2013; Willcutt et al., 2013; for a review, see Ashkenazi et al., 2013).

As an example of basic brain and cognitive processes that might be common across academic domains, consider that children's ability to rapidly name stimuli (e.g., letters, numbers, colors), measured by Rapid Automatized Naming (RAN) tasks, has been found to predict mathematics and reading achievement. In a kindergarten to eighth grade longitudinal study, Mazzocco and Grimm (2013) found that children with mathematical learning disabilities and reading disabilities both suffered from deficits in RAN performance. Similarly, mathematics and reading skills can be predicted by earlier RAN performance (Koponen et al., 2007, 2013) and some aspects of counting skill, such as counting by 2 s (Koponen et al., 2013). Koponen et al. (2013) suggested their tasks predicted both reading and mathematics performance because they reflected the ease of forming and retrieving arbitrary visual-verbal associations in long-term memory. Individual differences in ease of forming and retrieving these associations may depend on the functional integrity of the hippocampal-dependent memory system that is a domain-general system for associative learning and potentially a linchpin for aspects of children's cognitive development across academic domains (Qin et al., 2014).

More complex domain-general abilities that are often found to predict achievement across domains include, as noted, intelligence (or reasoning abilities), the central executive component of working memory (or executive functions), and in-class attentiveness (e.g., Hoge and Luce, 1979; Clark et al., 2010; Geary, 2011; Fuchs et al., 2016). For example, preschoolers with stronger executive functions showed greater gains in mathematics and reading achievement over the first 3 years of elementary school than their peers with weaker early skills (Bull et al., 2008). Working-memory deficits have also been found to be associated with both reading and mathematics learning disabilities (Geary, 1993, 2004; De Weerdt et al., 2013; Willcutt et al., 2013). The relative importance of these domain-general competencies may vary with the novelty and complexity of the achievement domain and with individual children's level of domain-specific expertise. For instance, in analyses of only domain-general competencies, Geary (2011) found that intelligence predicted school-entry mathematics and reading achievement and grade-to-grade gains in mathematics but not reading achievement. Fuchs et al. found that first graders' intelligence (reasoning), central executive, and in-class attentive behavior predicted arithmetic but not reading achievement in third grade, controlling domain-specific competencies. One possibility is that these domain-general competencies are particularly important for comprehending and learning novel material and become less important as individuals gain domain-specific expertise (Geary, 2005; Tricot and Sweller, 2014; Sweller, 2015). In this view, domain-general competencies may decline in importance as children become more efficient word readers, for instance, but these competencies remain predictive of mathematics because the curriculum and associated achievement tests are continually adding more complex material; word reading tests become more difficult but largely because the more difficult words are low frequency and not because conceptually novel material is added to the associated achievement tests.

As an example of domain-specific expertise, consider Geary's (2011) first-to-fifth grade longitudinal study of quantitative and domain-general cognitive predictors of mathematics achievement and word reading achievement. The only quantitative predictor of school-entry word reading skill was simple addition retrieval, which is dependent on associative learning (Siegler and Shrager, 1984; Qin et al., 2014). The remaining mathematical cognition predictors were unique to mathematics. For instance, early fluency in combining the cardinal value of collections of objects with the cardinal value of Arabic numerals predicted school-entry mathematics but not reading achievement, and children's early knowledge of the mathematical number line predicted growth in mathematics achievement through fifth grade but was unrelated to reading achievement in any grade. In a similar study, Fuchs et al. (2016) found that first graders' phonological memory (e.g., memory for word sounds) and general language competencies predicted reading but not arithmetic achievement 2 years later, controlling working memory, intelligence, and in-class attentive behavior. Children's early skill at identifying letters and simple high-frequency words predicted later word reading and arithmetic achievement, but the magnitude of the effect was 3.5 times stronger for reading than arithmetic. Knowledge of addition facts in second grade predicted word reading and arithmetic achievement in third grade but the effect was 3.5 times larger for arithmetic than reading. Addition retrieval is based on the hippocampal-dependent memory system (Qin et al., 2014) and thus will index ease of forming the visual-verbal associations that are important across reading and mathematics, but is also domain-specific content knowledge for arithmetic but not reading. Similarly, letter and word identification will index individual differences in the same memory system, but is also domain-specific content knowledge for reading but not arithmetic.

In other words, domain-general cognitive and learning systems will influence the acquisition of domain-specific knowledge and thus may be correlated with achievement in unrelated domains. For the latter, the correlations will then reflect the prior influence of domain-general systems and not the importance of content-specific knowledge *per se*. Isolating knowledge and competencies that are specific to one domain (e.g., mathematics) or another (e.g., reading) will thus require simultaneous estimation of the effects of domain-general abilities on each domain and demonstration that content-specific knowledge influences achievement in one domain but not the other.

Longitudinal Predictors of Mathematics and Reading Achievement

Mathematics Achievement

As previously mentioned, our study includes an extensive, longitudinal assessment of symbolic and nonsymbolic quantitative competencies. Early symbolic knowledge involves learning counting words and Arabic numerals and the quantities they represent (i.e., their cardinal values) and the relations between them (e.g., $4 > 3$; Fuson, 1988; Wynn, 1990; Geary, 1994; Le Corre and Carey, 2007). Early nonsymbolic competencies are largely supported by the evolutionarily ancient approximate number system (ANS) that supports an intuitive understanding of the relative magnitudes of collections of items and the ability to manipulate (e.g., add) the associated representations (for reviews, see Feigenson et al., 2004; Geary et al., 2015).

At this time, there is lively debate over the relative importance of early symbolic vs. nonsymbolic magnitude processing for later mathematics achievement. There is evidence that acuity of the ANS, allowing for fine discriminations among nonsymbolic quantities, is correlated with retrodictive, concurrent, and prospective mathematics achievement, controlling working memory and intelligence (e.g., Halberda et al., 2008; Libertus et al., 2011; Mazzocco et al., 2011). However, in a qualitative review of existing studies, De Smedt et al. (2013) concluded there was more consistent evidence for the role of symbolic than nonsymbolic knowledge in predicting mathematics achievement. Schneider et al.'s (2016) recent meta-analysis supports this conclusion, but also provided evidence for a small ($r \sim 0.2$) but consistent relation between measures of ANS acuity and mathematics achievement, in keeping with several earlier meta-analyses (Chen and Li, 2014; Fazio et al., 2014). Several studies suggest more nuanced relations among nonsymbolic and symbolic quantitative competencies and mathematics achievement; specifically, that ANS acuity contributes to the ease of learning the cardinal value of number symbols, which then becomes critical for children's mathematical development (vanMarle et al., 2014; Chu et al., 2015). In any case, the unsettled state of the field necessitates the inclusion of both symbolic and nonsymbolic quantitative tasks in the study of the foundations of children's mathematics achievement and growth in this achievement.

As noted, there is also evidence that preschoolers' executive functions contribute to growth in mathematical competencies (e.g., Blair and Razza, 2007; Bull et al., 2008; Clark et al., 2010). Executive functions and the central executive component of working memory are composed of subskills that may be differentially related to mathematical competencies at different ages. These include the ability to suppress prepotent responses (inhibition), shift attention between tasks (shifting), and explicitly monitor and update information (updating) represented in the phonological loop or visuospatial sketchpad (Miyake et al., 2000). Although updating may be critical for older children (Bull and Lee, 2014), inhibitory control may be especially important for young children's mathematical development (Espy et al., 2004; Blair and Razza, 2007; Fuhs and McNeil, 2013). Several studies have found a relation between inhibitory control and preschoolers' and kindergartners' mathematics achievement, even with control of other factors (e.g., child age, verbal intelligence, maternal education, and other components of executive functions; Espy et al., 2004; Blair and Razza, 2007; Clark et al., 2010).

Fuhs and McNeil (2013) argued that inhibitory control may also be related to children's nonsymbolic magnitude processing. In a study of preschoolers from low-income homes, they found that inhibitory control influenced the strength of the association between nonsymbolic magnitude processing and mathematics ability; specifically, the relation between one component of nonsymbolic quantity processing and mathematics achievement was no longer significant after controlling children's inhibitory control. Keller and Libertus (2015) however found that the relation between measures of ANS acuity and mathematics achievement were significant above and beyond the influence of inhibitory control. The issue of whether or not the relation between ANS acuity and mathematics achievement is mediated by inhibitory control remains to be determined, but the importance of executive functions generally, and inhibitory control in particular, for younger children's mathematics development is clear.

Previous research has also shown that on average, children from lower SES families have lower number knowledge and mathematics achievement than children from middle to high SES families (e.g., Klibanoff et al., 2006). One potential mediating factor is parent education that in turn is related to use of mathematical language in the home (e.g., Levine et al., 2010; McNeil et al., 2011; Purpura and Reid, 2016). Levine et al. found that children whose parents engaged in more number talk (e.g., counting, referring to cardinal values) learned the cardinal values of number words earlier than children of less verbose parents, independent of SES (measured by parent education and income). Generally, however, parents from higher SES homes are more likely to engage in set size comparisons and calculations with their children than parents from low SES families, whereas parents from low SES families engage in more rote counting, numeral recognition, and labeling of numerosities. In other words, even when less educated parents engage in number talk with their children, it is less sophisticated than that of higher-SES parents. Better educated parents also have higher expectations for their children and a better understanding of skills within the child's developmental range (Purpura and Reid, 2016). The latter is consistent with Davis-Kean's (2005) finding that parents who were more educated were better able to adjust their expectations to match their child's ability level. Whatever the mechanisms, these studies indicate that parental education should be controlled when attempting to isolate the contributions of early nonsymbolic and symbolic quantitative competencies on later mathematics achievement.

Reading Achievement

There is evidence that young children's letter knowledge and phonological awareness predict their later reading achievement (e.g., Bond and Dykstra, 1967; Wagner and Torgesen, 1987; Badian, 1994; Lonigan et al., 2000; Melby-Lervåg et al., 2012). Bond and Dykstra, for example, found that young children's ability to recognize letters of the alphabet was the single best predictor of their reading achievement in first grade; phonemic awareness was the second best early predictor. Melby-Lervåg et al. suggested that letter naming ability contributes significantly to reading development and is partly independent of the effects of phonological awareness and phonological processing. The contribution of letter knowledge is related to children's ability to understand the mapping between the letters in written words and the phonemes in spoken language, but they must first know the names of letters.

We thus decided to include a measure of letter knowledge in our study as a potential contrast to quantitative knowledge in predicting later achievement. It would have been preferable to include a wider range of preliteracy measures, especially of phonemic awareness, but based on our focus on mathematical development and constraints on how often we could assess children, we could include only a single measure.

Present Study

Previous studies have largely focused on elementary school children, and to date, have not thoroughly explored differences in how preschool children's quantitative and preliteracy competencies predict later mathematics and reading achievement. In addition to a broad assessment of nonsymbolic and symbolic quantitative competencies and letter knowledge, we assessed the key domain-general abilities of intelligence and executive functions, as well as parental educational background. After identifying the core quantitative abilities that predict later achievement, we document the relation between domain-general abilities, parental background, and preliteracy skills and gains in these quantitative competencies across 2 years of preschool. We then focus on the relation between beginning of preschool quantitative and preliteracy skills and mathematics achievement across the preschool years and mathematics and reading achievement at the end of kindergarten. In all, the study allowed us to identify core predictors of early gains in mathematics achievement and similarities and differences in the predictors of later mathematics and reading achievement.

MATERIALS AND METHODS

Participants

One hundred and fifty-three children (71 boys) were recruited from the Title I preschool program within the public school system in Columbia, Missouri, in the Midwestern United States. Title I preschool is a federally funded program that offers services to 3- to 5- year olds who may be at risk for academic failure. Children were recruited in two cohorts, entering in the fall of 2011 and 2012, and completed assessments during 2 years of preschool and 1 year of Kindergarten. Of the original sample, 107 children had IQ scores >70 (6 had scores <70) and completed all of the testing sessions during both years of preschool and kindergarten. Of these 107 children, 7 of them failed to complete multiple tasks within one or more testing sessions (due largely to inattention) and thus they were also dropped from analyses. The final sample included 100 (44 boys) children whose age at the time of the first assessment was 3 years 10 months (ranging from 3 years 2 months to 4 years 4 months) and 6 years 2 months (ranging from 5 years 7 months to 6 years 10 months) at the time of the final assessment.

Demographic information was obtained through parent survey for a subset of the sample ($n = 88$). This survey included questions on children's and parents' racial and ethnic background, as well as parents' education level, household income, housing (rent/own, monthly rent/mortgage), and whether they received food or housing assistance. The ethnic composition was 83% non-Hispanic, 13% Hispanic/Latino; 4% of parents did not respond to the ethnicity question. The racial composition was 61% White, 20% Black, 13% mixed race, and 6% Asian. The self-reported total household income was: $0 to $25,000 (33%), $25,000 to $50,000 (24%), $50,000 to $75,000 (26%), $75,000 to $100,000 (14%), $100,000 to $150,000 (1%), and $150,000 or above (1%). Seven percent of respondents reported receiving housing assistance, and 37% reported receiving food stamps.

As a proxy for socioeconomic status, we used parental education level. Mother's education and father's education were highly correlated ($r = 0.63$, $p < 0.001$), and thus these variables were collapsed into a parental education category consisting of three levels (no information, high school diploma or less, or at least a college degree) based on the highest attainment of the two parents. Forty-three percent of the children had at least one parent with a high school diploma, and 40% had at least one parent with a college degree. Parental education level was unknown for the remaining 17% of the children.

Materials

Quantitative Tasks

As described below, the children were administered 12 quantitative tasks multiple times during preschool, but with data reduction analyses we reduced this to four key tasks: *give-a-number*, *discrete quantity discrimination*, *numeral recognition*, and *nonverbal calculation*. These four quantitative tasks are described below in more detail, while the remaining tasks are described briefly.

Give-a-number

The give-a-number task is frequently used to measure how well children understand the cardinal values of number words (Wynn, 1990). In the task, children are asked to feed a puppet by placing the requested number of "cookies" (1, 2, 3, 4, 5, or 6) on a plate. All children started at set size 1. Set size increased by 1 following correct answers and decreased by 1 following incorrect answers. The highest number of objects accurately given to the experimenter on at least two out of three attempts was taken as the highest set size for which the child understood cardinality (Le Corre and Carey, 2007).

Numeral recognition

The children were shown cards with an Arabic numeral (ranging from 1 to 15) and asked to name the numeral. The cards were presented in a random order and the score was the number of numerals correctly named.

Discrete quantity discrimination

The children completed a commonly used assessment of ANS acuity, the discrete quantity discrimination task, using the Panamath program (Halberda et al., 2008). For this task, two separate arrays of blue and yellow dots were presented simultaneously on a screen for 2533 ms (to discourage counting), and the children were asked to identify which set "had more dots" (by pointing or by saying "blue" or "yellow"). All dot displays consisted of 5–21 dots. Dot size varied to keep the total area of the dots constant across the two arrays for half of the trials. Children in the first cohort received 24 test trials, and based on low performance for some children in this cohort, 6 relatively easy trials were added for the second cohort and for both cohorts in the second year. On each trial, the ratio of blue:yellow dots was determined randomly on each trial. For the original 24 trials, this ranged between 1.29 and 3.38, and the 6 added trials ranged between 3.5 and 4.0. Scores on this task were determined by accuracy (percent correct out of all trials), which has been shown to be a more reliable measure of ANS acuity for young children than the Weber fraction, which describes the degree of variability in the underlying representations (Inglis and Gilmore, 2014). The Spearman-Brown prediction formula applied to the correlation between percentage correct for the first and second halves of the items provided a reliability estimate of 0.87 for the first cohort and 0.71 for the second cohort in their first year of preschool. For the second year of preschool, the reliability estimates were 0.90 and 0.81 for the first and second cohorts, respectively.

Nonverbal calculation

To measure children's non-symbolic arithmetic abilities, children were shown the addition or subtraction of one or more disks from a hidden set of disks and asked to predict the exact numerical result (Levine et al., 1992; Huttenlocher et al., 1994). Children watched an experimenter place some disks on a mat. The experimenter then covered the disks with a plate, and then added or subtracted disks from under the plate. After the transformation, children were asked to generate the (hidden) result on their mat. After four familiarization trials in which children simply matched a hidden set, children completed 12 test trials, presented in random order: 3−1, 2+2, 4−2, 1+3, 4−1, 4+1, 3+2, 1+4, 5−2, 5−3, 2+4, and 6−4. The score was the percentage of correct trials out of trials attempted.

Remaining quantitative tasks

The remaining quantitative tasks included enumeration, point-to-x, magic box, ordinal choice, verbal counting, numeral comparison, counting knowledge, and continuous quantity discrimination. The enumeration task involved counting an array of 20 stickers. For the point-to-x task, children saw two sets of pictured objects displayed on a laptop and identified which side of the screen contained x objects. The magic box task was a variant of Starkey's (1992) search-box task and assessed children's implicit understanding of addition and subtraction for set sizes less than four. For the ordinal choice task, children watched as the experimenter dropped objects in one cup and then dropped objects in another cup. The children were then asked to identify, without counting, which cup had more objects. Children counted as high as they could (starting from 1) in the verbal counting task. In the numeral comparison task, children were shown pairs of cards (from correctly identified numerals in the numeral recognition task) and asked to identify the larger numeral. The counting knowledge task assessed children's understanding of the counting principles (Gelman and Gallistel, 1978); they watched a puppet count in ways that were consistent with or violated counting principles and then indicated if the puppet counted correctly or incorrectly. The continuous quantity discrimination task was similar to the discrete quantity discrimination task, but children viewed a large rectangle that was composed of red and blue portions and were asked to identify whether there was "more red" or "more blue" in the picture.

Cognitive and Achievement Measures

Intelligence

The children completed three subtests of the Wechsler Preschool and Primary Scale of Intelligence-III (WPPSI; Wechsler, 2002);

Receptive Vocabulary, Block Design, and Information. Following standard procedures, scores were scaled and prorated to generate an estimate of full scale IQ. The mean performance of the children here was average ($M = 98$, $SD = 16$).

Executive functions

Executive functions was assessed using the Conflict Executive Function (EF) scale developed for 2- to 6-year-olds (Beck et al., 2011; Carlson, 2012). The Conflict EF scale consists of a card-sorting task. Children were presented with two boxes with target cards affixed to the front. They were given a rule and asked to place a card in the appropriate box. There were 7 levels with 10 trials each (the first four included two sublevels of five trials each). Each level consisted of normal sorting trials, followed by conflict trials in which children sorted cards according to the opposite rule. For example, children first placed "big kitties" in the "big kitty" box and "little kitties" in the "little kitty" box; on conflict trials, they were asked to place, for example, "big kitties" in the "little kitty" box. For later trials, children sorted the cards depending on shape or color of the card (the rule was reversed for conflict trials). More advanced trials required children to sort cards according to their shape or color, depending on whether a black border was present or absent on the card. In order to advance to the next sublevel, children had to complete four out of five trials correctly, and in levels with 10 trials, children had to complete four shape trials and four color trials correctly in order to advance. The score was the total number of correct trials (max score = 70).

TABLE 1 | Sequence of tasks and ages.

Sequence of tasks	Age of children
YEAR 1 PRESCHOOL	
Quant 1 (Fall) – Enumeration – Give-a-Number – Point-to-X – Magic Box – Discrete Quantity Discrimination – Ordinal Choice	Mean: 3 years 10 months Range: 3 years 2 months –4 years 4 months
Quant 2 (Fall) – Verbal Counting – Nonverbal Calculation – Numeral Recognition – Numeral Comparison – Counting Knowledge – Continuous Quantity Discrimination	Mean: 3 years 11 months Range: 3 years 4 months–4 years 4 months
Cognitive battery (Spring) – Executive Functions (Card Sorting) – WPPSI-III (Receptive Vocabulary, Block Design, Information) – Preliteracy (Upper-Case Alphabet Recognition)	Mean: 4 years 1 month Range: 3 years 5 months–4 years 8 months
Mathematics Achievement (Spring; Test of Early Mathematics Ability-3; TEMA-3)	Mean: 4 years 4 months Range: 3 years 9 months–4 years 10 months
YEAR 2 PRESCHOOL	
Cognitive battery (Spring) – Executive Functions	Mean: 5 years 0 months Range: 4 years 5 months–5 years 6 months
Quant 1 (Spring)	Mean: 5 years 2 months Range: 4 years 7 months–5 years 8 months
Quant 2 (Spring)	Mean: 5 years 3 months Range: 4 years 8 months–5 years 10 months
Mathematics Achievement (Spring; TEMA-3)	Mean: 5 years 4 months Range: 4 years 9 months–5 years 10 months
KINDERGARTEN	
WIAT (Spring)—Numerical Operations; Word Reading	Mean: 6 years 2 months Range: 5 years 7 months–6 years 8 months

TEMA-3, Test of Early Mathematics Ability-3 (Ginsburg and Baroody, 2003); WIAT, Wechsler Individual Achievement Test (Wechsler, 2001).

Preliteracy skills

Early preliteracy skills were assessed using the Upper-Case Alphabet Recognition subtest of the Phonological Awareness Literacy Screening-PreK (PALS; Invernizzi et al., 2004). For this task, children identified the upper-case alphabet letters on a card, and the score was the total number of letters correctly identified.

Preschool mathematics achievement

To measure mathematics achievement, children completed the Test of Early Mathematics Ability-3 (TEMA-3; Ginsburg and Baroody, 2003). This standardized test consists of items that require producing finger displays to represent different quantities, counting, making numerical comparisons, and using some informal arithmetic. Children started on the first item of

TABLE 2 | Descriptive statistics for tasks assessed.

Variable	Mean	SD	Min	Max
YEAR 1				
Give-a-number	3.38	1.88	0	6
Numeral recognition	4.76	4.28	0	15
Nonverbal calculation	23.30	16.83	0	66.67
Discrete quantity discrimination	66.80	16.53	36.67	100
EF	32.67	13.87	11	69
IQ	98.06	15.60	73	135
Preliteracy (alphabet knowledge)	12.97	9.18	0	26
Mathematics achievement	92.69	14.44	68	129
YEAR 2				
Give-a-number	5.57	1.05	2	6
Numeral recognition	9.76	3.98	0	15
Nonverbal calculation	44.96	21.46	0	91.67
Discrete quantity discrimination	86.04	16.36	43.33	100
EF	46.02	13.22	15	70
Mathematics achievement	95.48	13.63	70	134
KINDERGARTEN				
Word reading	112.11	13.11	84	158
Numerical operations	106.63	11.83	75	146

N = 100 for all tasks.

the test and continued until they failed five consecutive items. Achievement was in the average range for the first ($M = 93$, $SD = 14$) and second ($M = 95$, $SD = 14$) year of preschool. To make scores comparable across years, the raw score was divided by the maximum score for our sample for each year. We chose to use the maximum score for our sample rather than the maximum possible score because the TEMA-3 is designed for children ages 3–8, and our children were on the younger side of the target age range. Thus, they were unlikely to achieve the maximum possible score.

Kindergarten achievement tests

During the spring semester of kindergarten, children completed the Numerical Operations and Word Reading subtests of the Wechsler Individual Achievement Test (WIAT; Wechsler, 2001). The achievement of the sample was in the average range for Numerical Operations ($M = 107$, $SD = 12$) and Word Reading ($M = 112$, $SD = 13$). To make the scores comparable across tests, we used the raw score divided by the maximum score for our sample on each subtest. We again chose to use the maximum score of our sample rather than maximum possible score because our children were on the younger side of the target age range of the tests.

The Numerical Operations test included items that assessed children's knowledge of counting and arithmetic. Simpler problems involved single digit addition and subtraction, while more complex problems involved multi-digit addition and subtraction. The Word Reading test assessed children's knowledge of letters, letter sounds, and ability to read common words. Words became more difficult further into the test. Following standard procedure, the Numerical Operations test was discontinued when children answered six consecutive questions incorrectly, and the Word Reading test was discontinued after children failed seven consecutive items.

Procedure

As shown in **Table 1**, the children participated in six assessments during each of the 2 years of preschool and two assessments in kindergarten. For all assessments, children were tested individually in a quiet location at their preschool or kindergarten. The quantitative tasks were administered in two sessions in the fall and spring semesters of the preschool year and a different set of quantitative measures (not reported here) during the fall of kindergarten. The domain-general and preliteracy measures were administered at the beginning of the spring semester; the IQ test was only administered in the first year of preschool. At the end of each year of preschool, children completed the TEMA-3 and the WIAT at the end of kindergarten. Each test session lasted 20–40 min. The experimental procedure was reviewed and approved by the Institutional Review Board of the University of Missouri. Written consent was obtained from all parents, and all participants provided verbal assent for all assessments.

Analyses

Although the children completed the vast majority of tasks, 2% of the data were missing. These missing values were imputed using the multiple imputations procedure in SAS 9.4 (SAS Institute, 2012).

TABLE 3 | Correlations of tasks assessed.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
DOMAIN-GENERAL ABILITIES																	
1	Y1 EF	–															
2	Y2 EF	0.41***	–														
3	IQ	0.41***	0.40***	–													
4	Preliteracy	0.22*	0.29**	0.30**	–												
QUANTITATIVE TASKS																	
5	Y1 GN	0.45***	0.54***	0.44***	0.44***	–											
6	Y1 NR	0.15	0.24*	0.28**	0.69***	0.51***	–										
7	Y1 NVC	0.25*	0.32**	0.33**	0.19	0.31**	0.20*	–									
8	Y1 DQD	0.36***	0.35***	0.32**	0.10	0.36***	0.09	0.17	–								
9	Y2 GN	0.38***	0.23*	0.31**	0.37***	0.37**	0.27**	0.24*	0.35***	–							
10	Y2 NR	0.21*	0.28**	0.30**	0.59***	0.41***	0.55***	0.16	0.20*	0.53***	–						
11	Y2 NVC	0.22*	0.35***	0.22*	0.26**	0.44***	0.29**	0.36***	0.38***	0.44***	0.33**	–					
12	Y2 DQD	0.20	0.28**	0.39***	0.30**	0.40***	0.24*	0.30**	0.38***	0.62***	0.33**	0.48***	–				
PRESCHOOL MATHEMATICS ACHIEVEMENT																	
13	Y1 TEMA	0.38***	0.48***	0.51***	0.54***	0.69***	0.60***	0.28**	0.43***	0.46***	0.57***	0.39***	0.46***	–			
14	Y2 TEMA	0.19	0.33**	0.34**	0.55***	0.49***	0.50***	0.27**	0.26**	0.48***	0.67***	0.45***	0.42***	0.68***	–		
KINDERGARTEN ACHIEVEMENT																	
15	WIAT WR	0.28**	0.43***	0.34**	0.62***	0.54***	0.57***	0.29**	0.25*	0.39***	0.58***	0.35***	0.33**	0.64***	0.69***	–	
16	WIAT NO	0.26*	0.35***	0.34**	0.46***	0.50***	0.43***	0.34**	0.43***	0.39***	0.47***	0.49***	0.45***	0.54***	0.48***	0.64***	–

EF, Executive Functions; GN, Give-a-Number; NR, Numeral Recognition; NVC, Nonverbal Calculation; DQD, Discrete Quantity Discrimination; TEMA, Test of Early Mathematics Ability; WR, Word Reading; and NO, Numerical Operations. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Variable Reduction

To reduce the number of variables in the main analyses, and thus reduce false positives, we used a Bayes factor analysis using the "BayesFactor" program (Morey and Rouder, 2015) in R to determine the best quantitative predictors of each kindergarten achievement test. These analyses identified give-a-number, discrete quantity discrimination, nonverbal calculation, and numeral recognition as the best predictors of Numerical Operations, and give-a-number and numeral recognition as the best predictors of Word Reading. Thus, we only included the give-a-number, discrete quantity discrimination, nonverbal calculation, and numeral recognition tasks in our main analyses.

Main Analyses

In the first of three sets of analyses, we examined beginning (i.e., fall semester of Year 1) to end (i.e., spring semester of Year 2) of preschool change in the four quantitative tasks identified above. Second, we examined the relation between beginning of preschool performance on these four variables and mathematics achievement across the 2 years of preschool, controlling for parental education, and beginning of preschool IQ, EF, and preliteracy skills. Finally, we redid these analyses substituting WIAT scores for TEMA-3 scores, focusing on the differential relations between early quantitative knowledge and mathematics and reading achievement at the end of kindergarten. All analyses were conducted using the PROC MIXED procedure in SAS 9.4 (SAS Institute, 2012). Intercept values were random effects, and predictor variables were standardized ($M = 0$, $SD = 1$).

Following Geary (2011), the first set of analyses included domain-general predictors (i.e., parental education, Y1 and Y2 EF, IQ, and preliteracy) and interactions with year. Interactions with $p > 0.10$ were dropped, starting with the highest p-value, and the model was re-estimated. The procedure continued until all interactions were significant. The iterative procedure was then continued for main effects. In the analyses predicting preschool mathematics achievement, the first step involved specifying a model using only the domain-general predictors and their interaction with preschool year. The same iterative procedure was followed until only significant interactions were remaining in the model; all main effects for the domain-general predictors were retained because they are standard covariates. Next, the four quantitative predictors and their interactions with preschool year were added to the final domain-general model. The same iterative procedure was then implemented for the quantitative variables. The same approach was used in the analyses of kindergarten achievement.

TABLE 4 | Change in quantitative task performance during preschool.

Effect	Estimate	*se*	*df*	*t*	*p*
GIVE-A-NUMBER (MAX VALUE = 6)					
Intercept	5.57	0.12	96	44.81	0.001
Year					
1	−2.19	0.17	97	−13.03	0.001
2	0.00	–	–	–	–
IQ	0.07	0.14	97	0.53	0.599
EF	0.41	0.10	97	4.08	0.001
Preliteracy	0.27	0.13	97	2.08	0.040
IQ * Year					
1	0.41	0.18	97	2.30	0.024
2	0.00	–	–	–	–
Preliteracy * Year					
1	0.31	0.18	97	1.77	0.081
2	0.00	–	–	–	–
DISCRETE QUANTITY DISCRIMINATION (MAX VALUE = 100)					
Intercept	86.04	1.49	96	57.82	0.001
Year					
1	−19.24	1.76	97	−10.94	0.001
2	0.00	–	–	–	–
IQ	4.39	1.36	97	3.23	0.002
EF	0.67	1.61	97	0.42	0.677
Preliteracy	3.37	1.56	97	2.16	0.033
EF * Year					
1	3.49	1.81	97	1.93	0.056
2	0.00	–	–	–	–
Preliteracy * Year					
1	−3.89	1.81	97	−2.15	0.034
2	0.00	–	–	–	–
NONVERBAL CALCULATION (MAX VALUE = 100)					
Intercept	44.96	1.80	97	24.94	0.001
Year					
1	−21.66	2.19	99	−9.91	0.001
2	0.00	–	–	–	–
Age	4.22	1.44	99	2.94	0.004
IQ	5.19	1.44	99	3.61	0.001
NUMERAL RECOGNITION (MAX VALUE = 15)					
Intercept	9.76	0.32	99	30.94	0.001
Year					
1	−4.99	0.39	98	−12.71	0.001
2	0.00	–	–	–	–
Preliteracy	2.65	0.25	98	10.72	0.001

Dependent variables are raw scores, and other continuous variables are standardized. EF, Executive Functions. Age, age at beginning of first year of preschool.

RESULTS

Descriptive information (min, max, mean, and SD) for the different tasks and measures are provided in **Table 2**, and correlations are given in **Table 3**.

Quantitative Tasks

The final models are shown in **Table 4**, and the summary results for the nested model comparisons in **Table 5**. As shown in the first section of **Table 4**, children's performance on the give-a-number task improved significantly from the beginning to the end of preschool, $t_{(97)} = 13.03$, $p < 0.001$. More developed executive functions in year 1 were associated with higher give-a-number scores in both years, $t_{(97)} = 4.08$, $p < 0.001$, whereas IQ was only important for year 1, $t_{(97)} = 2.3$, $p = 0.024$. Similarly, preliteracy skills predicted give-a-number performance in both years ($p < 0.05$), but there was a trend for these being more important in the first than second year, $t_{(97)} = 1.77$, $p = 0.081$.

TABLE 5 | Fit statistics for nested models predicting quantitative development during preschool.

	−2LL	χ^2	$\Delta\chi^2$	Parameters	p	BIC	ΔBIC
GIVE-A-NUMBER							
1. Full	646.0	0.71	–	12	–	719.7	–
2. Drop Year with Age, IQ and EF interactions	649.7	0.43	−0.28	9	$p > 0.10$	705.0	−14.7
3. Drop Age and Parent Education main effects	654.0	0.76	0.33	7	$p > 0.10$	695.4	−9.6
DISCRETE QUANTITY DISCRIMINATION							
1. Full	1630.7	9.27		12	–	1704.4	–
2. Drop Year with IQ, Y1 EF, and parent education interactions	1633.9	8.45	−0.82	9	$p > 0.10$	1684.6	−19.8
3. Drop main effect of Age	1634.2	8.42	−0.03	8	$p > 0.10$	1684.9	0.3
4. Drop main effect of parent education	1637.9	9.61	1.19	7	$p > 0.10$	1679.3	−5.6
NONVERBAL CALCULATION							
1. Full	1706.7	7.26	–	12	–	1780.4	–
2. Drop Year with Y1 EF, Age, parent education, IQ, and Preliteracy interactions	1711.8	5.96	−1.30	7	$p > 0.10$	1757.9	−22.5
3. Drop main effect of IQ	1712.4	6.10	0.14	6	$p > 0.10$	1753.8	−4.1
4. Drop main effect of parent education	1714.2	6.54	0.44	5	$p > 0.10$	1746.4	−7.4
5. Drop main effect of Preliteracy	1717.0	7.26	0.72	4	$p > 0.05$	1744.6	−1.8
NUMERICAL RECOGNITION							
1. Full	1008.7	3.68		12	–	1064.0	–
2. Drop Year with Y1 EF, Age, IQ, parent education, and Preliteracy interactions	1011.8	3.12	−0.56	7	$p > 0.10$	1057.8	−6.2
3. Drop main effect of Y1 EF	1012.2	3.19	0.07	6	$p > 0.10$	1053.6	−4.2
4. Drop main effect of IQ	1013.4	3.41	0.22	5	$p > 0.10$	1050.2	−3.4
5. Drop main effect of Age	1016.4	3.98	0.57	4	$p > 0.05$	1048.6	−1.6
6. Drop main effect of parent education	1021.9	5.13	1.15	3	$p > 0.05$	1044.9	−3.7

EF, Executive Functions; Age, age at beginning of first year of preschool.

Children also showed improvement on the discrete quantity discrimination task, $t_{(97)} = 10.94$, $p < 0.001$. In contrast to give-a-number, the relation between IQ and discrete quantity discrimination was significant across both years; that is, the main effect was significant with no interaction, $t_{(97)} = 3.23$, $p = 0.002$. Year 1 EF was only important in the first year of preschool, $t_{(97)} = 1.93$, $p = 0.056$. Preliteracy skills were significant overall, $t_{(97)} = 2.16$, $p = 0.034$, and significantly less important for year 1 than year 2, $t_{(97)} = -2.15$, $p = 0.034$. Nonverbal calculation performance also improved across years, $t_{(97)} = 9.91$, $p < 0.001$. Both age at the start of preschool, $t_{(99)} = 2.94$, $p = 0.004$, and IQ, $t_{(99)} = 3.61$, $p < 0.001$, were significantly related to nonverbal calculation performance. Neither of these variables interacted with year, indicating they were important in both years. Finally, children's numeral recognition also improved from the beginning of preschool to the end of preschool, $t_{(99)} = 12.71$, $p < 0.001$, and the only predictor of this change in performance was preliteracy skills, $t_{(98)} = 10.72$, $p < 0.001$.

Preschool Mathematics Achievement

The final models are shown in **Table 6** and the summary results for the nested model comparisons in **Table 7**. As shown in **Table 6**, there was a trend for children's mathematics achievement scores to increase from the beginning to the end of preschool, $t_{(95)} = 1.89$, $p = 0.062$. Give-a-number scores at the beginning of preschool predicted mathematics achievement at the end of preschool, $t_{(95)} = 2.81$, $p = 0.006$, but more strongly in the first than second year, $t_{(95)} = 2.01$, $p = 0.047$. A similar pattern was evident for numeral recognition. Accuracy on the discrete quantity discrimination task at the beginning of preschool did not predict mathematics achievement at the end of preschool, $t_{(95)} = 1.34$, $p = 0.183$, but there was a trend for it to be more strongly related to mathematics achievement at the end of the first than second year of preschool, $t_{(95)} = 1.70$, $p = 0.095$. Preliteracy skill was the only non-quantitative measure that predicted mathematics achievement, $t_{(95)} = 2.57$, $p = 0.012$, with no differences in the prediction of first and second year scores.

Kindergarten Achievement

The tasks used to estimate intelligence can be split into nonverbal IQ (block design) and verbal IQ (information and receptive vocabulary). Preliminary analyses indicated that there was no evidence of differential relations between nonverbal and verbal IQ and mathematics and reading achievement. Thus, we used full scale IQ in our final models. The final models are shown in **Table 8** and the summary results for the nested model comparisons in **Table 7**. As shown in **Table 8**, children had a lower average score on Numerical Operations than Word Reading, $t_{(96)} = -5.92$, $p < 0.001$. The critical findings were that beginning of preschool preliteracy scores predicted kindergarten Word Reading more strongly than Numerical Operations scores, $t_{(96)} = 2.94$, $p = 0.007$, whereas beginning of preschool discrete quantity discrimination accuracy predicted Numerical Operations more strongly than Word Reading scores, $t_{(96)} = -2.46$, $p = 0.023$. In contrast, beginning of

TABLE 6 | Predictors of mathematics achievement during preschool.

Effect	Estimate	*se*	*df*	*t*	*p*
Intercept	39.96	1.91	90	20.96	0.001
Year					
1	−2.57	1.36	95	−1.89	0.062
2	0.00	–	–	–	–
Age	1.76	1.20	95	1.47	0.145
Parent Education					
No info	−0.90	3.41	95	−0.26	0.792
HS degree	−0.19	2.49	95	−0.08	0.940
College degree	0.00	–	–	–	–
IQ	0.49	1.60	95	0.31	0.761
EF	0.30	1.37	95	0.22	0.829
Preliteracy	3.85	1.50	95	2.57	0.012
Give-a-number	4.81	1.71	95	2.81	0.006
Discrete quantity discrimination	1.90	1.42	95	1.34	0.183
Numeral recognition	4.06	1.78	95	2.28	0.025
IQ * YEAR					
1	2.65	1.56	95	1.70	0.092
2	0.00	–	–	–	–
Give-a-number * Year					
1	3.57	1.78	95	2.01	0.047
2	0.00	–	–	–	–
Discrete quantity discrimination * Year					
1	2.54	1.51	95	1.68	0.095
2	0.00	–	–	–	–
Numeral recognition * Year					
1	3.19	1.61	95	1.98	0.051
2	0.00	–	–	–	

EF, Executive Functions; Age, age at beginning of first year of preschool.

preschool give-a-number performance predicted overall WIAT performance, $t_{(96)} = 2.71, p = 0.008$.

DISCUSSION

Domain-General Predictors of Quantitative Task Performance

Children's competence for each of the four key early quantitative skills improved significantly across the preschool years and, with the exception of numeral recognition, overall performance across years or gains in performance was related to one or both of the domain-general abilities of intelligence or executive functions, in keeping with previous studies (e.g., Clark et al., 2010; Geary, 2011; Fuchs et al., 2016). Intelligence was significantly related to first year knowledge of the cardinal value of number words (i.e., give-a-number), accuracy at discriminating sets of discrete quantities, and competence with nonverbal calculations, as well as second year performance for the two latter tasks. The importance of executive functions, controlling intelligence, emerged for give-a-number in both years and discrete quantity discrimination in the first year. It is not surprising that intelligence and executive functions are related to children's discrete quantity discrimination performance, given the results of Fuhs and McNeil (2013), who found that ANS acuity was significantly correlated with inhibitory control. Overall, it appears that the combination of intelligence and executive functions is significantly related to initial, beginning of preschool quantitative competencies but that only one or the other is important thereafter. Because these two domain-general abilities are correlated, leading to collinearity in the regression results, we cannot say with certainty whether one is more important than the other after the first year of preschool, but the pattern suggests an overall reduction in the importance of domain-general abilities across the 2 years (Geary, 2005; Tricot and Sweller, 2014; Sweller, 2015).

Children's preliteracy skill was also significantly related to several quantitative abilities, and especially their recognition of Arabic numerals. The latter is very similar to our alphabet recognition preliteracy measure and both, in theory, should reflect individual differences in the ease of forming visual-verbal associative relations, in keeping with Koponen et al.'s (2013) proposal. Ease of forming these relations might also contribute to children's performance on the give-a-number task; specifically, mapping number words to representations of associated quantities (Rousselle and Noël, 2007). Associative learning, however, would not explain the relation between preliteracy scores and accuracy on the discrete quantity discrimination task. This is because associative learning should not be necessary for the latter task (Feigenson et al., 2004). Moreover, unlike the numeral recognition and give-a-number tasks, preliteracy only predicted accuracy on the discrete quantity discrimination task in the second year of preschool. Whether this finding reflects basic processes, such as visual attention (Anobile et al., 2012), common to letter learning and nonsymbolic quantity discriminations remains to be determined.

Predictors of Preschool Mathematics Achievement

In keeping with studies of older children (e.g., Geary, 2011; Fuchs et al., 2016), a combination of domain-general and domain-specific competencies predicted preschoolers' mathematics achievement. In the final model, there were trends for intelligence and discrete quantity discrimination performance to predict beginning but not end of preschool mathematics achievement. There is also evidence that intelligence may influence the estimate of the relation between ANS acuity and mathematics achievement across years; dropping the interaction of either variable with year results in the other interaction becoming significant (**Table 6**). Since there is collinearity between intelligence and executive functions (e.g., inhibitory control), this would be consistent with Fuhs and McNeil's (2013) finding that there was a weak association between ANS acuity and mathematics achievement in a low-income sample, and that this association was influenced by inhibitory control. These results suggest that acuity of the ANS may contribute to aspects of early mathematics achievement, consistent with some previous studies (e.g., Libertus et al., 2011; Mazzocco et al., 2011). Our results

TABLE 7 | Fit statistics for nested models predicting mathematics achievement during preschool and kindergarten.

Model	-2LL	χ^2	$\Delta\chi^2$	Parameters	p	BIC	ΔBIC
PRESCHOOL MATHEMATICS ACHIEVEMENT							
Domain general predictors							
1. Full	1621.1	37.13		12	–	1694.8	–
2. Drop non-significant interaction (Preliteracy)	1621.1	37.12	−0.01	11	$p > 0.10$	1690.2	−4.6
3. Drop non-significant interaction (EF)	1622.4	36.43	−0.69	10	$p > 0.10$	1686.9	−3.3
4. Drop non-significant interaction (parent education)	1624.6	35.23	−1.20	9	$p > 0.10$	1679.8	−7.1
Add Quantitative predictors							
1. Model 4 above and Quantitative predictors	1556.7	18.76		17	–	1648.8	–
2. Drop non-significant interaction (Age)	1557.8	18.29	−0.47	16	$p > 0.10$	1645.3	−3.5
3. Drop non-significant interaction (NVC)	1558.8	17.90	−0.39	15	$p > 0.10$	1641.7	−3.6
4. Drop main effect (NVC)	1561.1	18.83	0.93	14	$p > 0.10$	1639.4	−2.3
KINDERGARTEN ACHIEVEMENT							
Domain general predictors							
1. Full	1467.6	21.90		14	–	1550.5	–
2. Drop non-significant interaction (IQ)	1467.8	21.80	−0.10	13	$p > 0.10$	1546.1	−4.4
3. Drop non-significant interaction (Y1 EF)	1468.1	21.70	−0.10	12	$p > 0.10$	1541.8	−4.3
4. Drop non-significant interaction (Y2 EF)	1469.0	21.27	−0.43	11	$p > 0.10$	1538.1	−3.7
5. Drop non-significant interaction (parent education)	1471.6	20.15	−1.12	10	$p > 0.10$	1531.5	−6.6
Add Quantitative predictors							
1. Model 5 above and Quantitative predictors	1445.0	14.85		18	–	1541.7	–
2. Drop non-significant interaction (NR)	1445.3	14.73	−0.12	17	$p > 0.10$	1537.4	−4.3
3. Drop non-significant interaction (NVC)	1445.6	14.62	−0.11	16	$p > 0.10$	1533.1	−4.3
4. Drop non-significant interaction (GN)	1446.5	14.29	−0.33	15	$p > 0.10$	1529.1	−4.0
5. Drop non-significant main effect (NVC)	1448.9	15.18	0.89	14	$p > 0.10$	1527.2	−1.9
6. Drop non-significant main effect (NR)	1451.6	16.23	1.05	13	$p > 0.05$	1525.3	−1.9

EF, Executive Functions; GN, Give-a-Number; DQD, Discrete Quantity Discrimination; NR, Numeral Recognition; NVC, Nonverbal Calculation. Age, age at beginning of first year of preschool.

however are not definitive (see also vanMarle et al., 2014; Chu et al., 2015) and in the broader literature, the contribution of the ANS to mathematics achievement remains contentious (e.g., De Smedt et al., 2013).

In line with Schneider et al.'s (2016) recent meta-analysis, we found evidence that symbolic quantitative knowledge is relatively more important that nonsymbolic knowledge in predicting early mathematics achievement. In particular, children's understanding of the cardinal value of number words (give-a-number) and their recognition of numerals predicted mathematics achievement across both years of preschool, but were more strongly related to first year than second year mathematics achievement. This would suggest that recognizing numerals and understanding the quantities represented by number symbols serve as a foundation for early mathematics ability. The across-year decline in the importance of cardinal knowledge was related in part to ceiling effects; that is, most children scored near the top of this scale by the end of preschool. The mathematical competencies assessed by the TEMA-3 were also more complex at the end than the beginning of preschool, that is, the children correctly solved more items at the end of preschool. The test thus begins to measure competencies that move beyond numeral recognition and cardinality, but this does not undermine their importance at the start of preschool.

Finally, control of preliteracy scores, parental education, intelligence, and executive functions in these analyses suggests that the results for cardinal knowledge and numeral recognition represent the contributions of domain-specific knowledge rather than ease of associative learning or other domain-general abilities, or informal parental teaching. The latter could of course contribute to individual differences in children's cardinal knowledge and numeral recognition, as suggested by previous studies (Levine et al., 2010; McNeil et al., 2011; Purpura and Reid, 2016). Our point is that the control of parental education, preliteracy, and domain-general abilities suggests that it is this domain-specific knowledge that is critical to later mathematics achievement, regardless of how children acquired this knowledge.

Predictors of Kindergarten Achievement

Children in our sample had higher word reading than mathematics achievement at the end of kindergarten, but their mathematics achievement was still in the average range. Unlike previous studies that have found a link between domain-general abilities such as intelligence and executive functions in predicting later mathematics and reading achievement (e.g., Geary, 2011; Fuchs et al., 2016), we did not find such a relation for our sample. Although preschool intelligence was not predictive of reading

TABLE 8 | Predictors of kindergarten achievement.

Effect	Estimate	se	df	*t*	*p*
Intercept	57.71	1.43	90	40.35	0.001
Test					
NO	−6.23	1.05	96	−5.92	0.001
WR	0.00	–	–	–	–
Age	1.34	1.04	96	1.29	0.201
Parent Education					
No Information	−1.57	2.55	96	−0.62	0.539
H.S. Degree	0.31	1.85	96	0.17	0.867
College Degree	0.00	–	–	–	–
IQ	0.94	1.05	96	0.90	0.370
Y1 EF	−0.69	1.02	96	−0.68	0.499
Y2 EF	0.93	1.00	96	0.93	0.355
Preliteracy	3.63	1.05	96	3.46	0.001
Give-a-Number	2.95	1.09	96	2.71	0.008
Discrete Quantity Discrimination	3.47	1.05	96	3.31	0.001
Age * Test					
WR	−1.88	1.07	96	−1.75	0.083
NO	0.00	–	–	–	–
Preliteracy * Test					
WR	2.94	1.07	96	2.74	0.007
NO	0.00	–	–	–	–
Discrete Quantity Discrimination * Test					
WR	−2.46	1.07	96	−2.31	0.023
NO	0.00	–	–	–	–

EF, Executive Functions; Age, age at beginning of first year of preschool; NO, Numerical Operations subtest of WIAT; WR, Word Reading subtest of WIAT; Numerical Operations and Word Reading were both scored as raw score/maximum score from our sample to generate an accuracy score. The maximum score for Numerical Operations was 14, and the maximum score for Word Reading was 93.

and mathematics achievement in kindergarten, controlling many other variables, it still contributed to beginning of preschool mathematics achievement and to more specific aspects of quantitative development. For example, intelligence predicted overall performance in the give-a-number, discrete quantity discrimination, and nonverbal calculation tasks across both years of preschool, but was more strongly related to give-a-number performance at the beginning of preschool. Similarly, there was a trend for executive functions to be more strongly related to discrete quantity discrimination performance at the beginning of preschool. The overall pattern supports the view that domain-general competencies may be more important for initial learning, but then decline in importance as children begin to rely on more domain-specific skills (e.g., Geary, 2005),

Consistent with the results for the individual quantitative tasks, children's early preliteracy skills contributed to their overall achievement, both word reading and mathematics. These findings are consistent with studies of older children and the associative learning hypothesis (Koponen et al., 2007, 2013; Fuchs et al., 2016). Critically, however, early preliteracy skills had an effect on later word reading achievement above and beyond the relation to later mathematics achievement. This important interaction is consistent with a domain-specific contribution of early letter knowledge on word reading skills 2.5 years later (Blatchford et al., 1987), controlling multiple other factors.

A similar pattern emerged for the discrete quantity discrimination task, which predicted overall achievement but was relatively less important for word reading than mathematics achievement. As noted, the effects on overall achievement are not likely to be related to associative learning, but could be related to attentional factors above and beyond those captured by our executive functions scale (e.g., Anobile et al., 2013). In any case, the added contribution to the prediction of mathematics achievement is consistent with a relation between ANS acuity and mathematics achievement (Libertus et al., 2011), but given the weaker relation during the preschool years it is possible that symbolic mathematics skills are influencing the acuity of the ANS rather than vice versa (Halberda et al., 2012).

The finding that children's early knowledge of the cardinal value of number words predicted later achievement was not too surprising, given previous results (vanMarle et al., 2014; Chu et al., 2015), but we were surprised that it was not more strongly related to mathematics than word reading achievement. It is possible that the give-a-number task has a strong domain-general component to it, such as ease of concept formation. On the other hand, performance on the task does involve a clear natural language component, understanding the meaning of number words (Le Corre and Carey, 2007), and this may be the source of the result. The resolution of these alternative explanations for our finding will have to await follow up studies.

Limitations and Future Directions

There are several limitations that call for caution in interpreting our results. First, although the longitudinal component allows for reasonably strong inferences, the data are still correlational and any definitive conclusions will require experimental follow up studies. Second, our inclusion of multiple quantitative tasks and 3 years of mathematics achievement data relative to one preliteracy task and 1 year of word reading achievement means that the study was better designed (by intention) to identify predictors of mathematics than reading achievement. We attempted to control the most commonly identified domain-general abilities and parental background but this does not mean that we identified all of them. Moreover, we argued that domain-general associative learning mechanisms may contribute to learning in both mathematics and reading, following studies with older children (e.g., Koponen et al., 2013; Fuchs et al., 2016), but we did not measure these mechanisms directly. Despite these limitations, our overall results are consistent with previous studies of both academic domains, and point to a combination of domain-general and domain-specific contributors to preschool children's emerging competencies with mathematics and reading.

AUTHOR CONTRIBUTIONS

FC contributed to collecting and analyzing the data and writing the manuscript. DG contributed to designing the research, analyzing the data, and writing the manuscript. KV contributed to designing the research and writing the manuscript.

FUNDING

The study was supported by grants from the University of Missouri Research Board and DRL-1250359 from the National Science Foundation.

ACKNOWLEDGMENTS

We thank Mary Rook for her help in facilitating our assessments of the Title I preschool children. We are also grateful for the cooperation of Columbia Public Schools and especially the children and parents involved in the study. We thank Tim Adams, Melissa Barton, Sarah Becktell, Sam Belvin, Erica Bizub, Kaitlyn Bumberry, Lex Clarkson, Stephen Cobb, Danielle Cooper, Dillon Falk, Lauren Johnson-Hafenscher, Jared Kester, Morgan Kotva, Brad Lance, Kate Leach, Kayla Legow, Natalie Miller, Lexi Mok, Molly O'Byrne, Rebecca Peick, Kelly Regan, Nicole Reimer, Laura Roider, Sara Schroeder, Claudia Tran, Hannah Weise, Melissa Willoughby, and Grace Woessner for help with data collection and entry, and Mary Hoard and Lara Nugent for help with managing the project.

REFERENCES

Anobile, G., Cicchini, G. M., and Burr, D. C. (2012). Linear mapping of numbers onto space requires attention. *Cognition* 122, 454–459. doi: 10.1016/j.cognition.2011.11.006

Anobile, G., Stievano, P., and Burr, D. C. (2013). Visual sustained attention and numerosity sensitivity correlate with math achievement in children. *J. Exp. Child Psychol.* 116, 380–391. doi: 10.1016/j.jecp.2013.06.006

Ashkenazi, S., Black, J. M., Abrams, D. A., Hoeft, F., and Menon, V. (2013). Neurobiological underpinnings of math and reading learning disabilities. *J. Learn. Disabil.* 46, 549–569. doi: 10.1177/0022219413483174

Badian, N. A. (1994). Preschool prediction: orthographic and phonological skills, and reading. *Ann. Dyslexia* 44, 1–25. doi: 10.1007/BF02648153

Beck, D. M., Schaefer, C., Pang, K., and Carlson, S. M. (2011). Executive function in preschool children: test-retest reliability. *J. Cogn. Dev.* 12, 169–193. doi: 10.1080/15248372.2011.563485

Blair, C., and Razza, R. P. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child Dev.* 78, 647–663. doi: 10.1111/j.1467-8624.2007.01019.x

Blatchford, P., Burke, J., Farquhar, C., Plewis, I., and Tizard, B. (1987). Associations between pre-school reading related skills and later reading achievement. *Br. Educ. Res. J.* 13, 15–23. doi: 10.1080/0141192870130102

Bond, G. L., and Dykstra, R. (1967). The cooperative research program in first-grade reading instruction. *Read. Res. Q.* 2, 5–142. doi: 10.2307/746948

Bull, R., Espy, K. A., and Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: longitudinal predictors of mathematical achievement at age 7 years. *Dev. Neuropsychol.* 33, 205–228. doi: 10.1080/87565640801982312

Bull, R., and Lee, K. (2014). Executive functioning and mathematics achievement. *Child Dev. Perspect.* 8, 36–41. doi: 10.1111/cdep.12059

Bynner, J. (2004). Literacy, numeracy and employability: evidence form the British birth cohort studies. *Lit. Numer. Stud.* 13, 31–48.

Carlson, S. M. (2012). *Executive Function Scale for Preschoolers*. Test Manual, Institute of Child Development, University of Minnesota.

Chen, Q., and Li, J. (2014). Association between individual differences in non-symbolic number acuity and math performance: a meta-analysis. *Acta Psychol. (Amst).* 148, 163–172. doi: 10.1016/j.actpsy.2014.01.016

Chu, F. W., vanMarle, K., and Geary, D. C. (2015). Early numerical foundations of young children's mathematical development. *J. Exp. Child Psychol.* 132, 205–212. doi: 10.1016/j.jecp.2015.01.006

Clark, C. A. C., Pritchard, V. E., and Woodward, L. J. (2010). Preschool executive functioning abilities predict early mathematics achievement. *Dev. Psychol.* 46, 1176–1191. doi: 10.1037/a0019672

Davis-Kean, P. E. (2005). The influence of parent education and family income on child achievement: the indirect role of parental expectations and the home environment. *J. Fam. Psychol.* 19, 294–304. doi: 10.1037/0893-3200.19.2.294

De Smedt, B., Noël, M.-P., Gilmore, C., and Ansari, D. (2013). How do symbolic and non-symbolic numerical magnitude processing skills relate to individual differences in children's mathematical skills? A review of evidence from brain and behavior. *Trends Neurosci. Educ.* 2, 48–55. doi: 10.1016/j.tine.2013.06.001

De Weerdt, F., Desoete, A., and Roeyers, H. (2013). Working memory in children with reading disabilities and/or mathematical disabilities. *J. Learn. Disabil.* 46, 461–472. doi: 10.1177/0022219412455238

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., et al. (2007). School readiness and later achievement. *Dev. Psychol.* 43, 1428–1446. doi: 10.1037/0012-1649.43.6.1428

Espy, K. A., McDiarmid, M. M., Cwik, M. F., Stalets, M. M., Hamby, A., and Senn, T. E. (2004). The contribution of executive functions to emergent mathematic skills in preschool children. *Dev. Neuropsychol.* 26, 465–486. doi: 10.1207/s15326942dn2601_6

Fazio, L. K., Bailey, D. H., Thompson, C. A., and Siegler, R. S. (2014). Relations of different types of numerical magnitude representations to each other and to mathematics achievement. *J. Exp. Child Psychol.* 123, 53–72. doi: 10.1016/j.jecp.2014.01.013

Feigenson, L., Dehaene, S., and Spelke, E. (2004). Core systems of number. *Trends Cogn. Sci.* 8, 307–314. doi: 10.1016/j.tics.2004.05.002

Fuchs, L. S., Geary, D. C., Fuchs, D., Compton, D. L., and Hamlett, C. L. (2016). Pathways to third-grade calculation versus word-reading competence: are they more alike or different? *Child Dev.* 87, 558–567. doi: 10.1111/cdev.12474

Fuhs, M. W., and McNeil, N. M. (2013). ANS acuity and mathematics ability in preschoolers from low-income homes: contributions of inhibitory control. *Dev. Sci.* 16, 136–148. doi: 10.1111/desc.12013

Fuson, K. C. (1988). *Children's Counting and Concepts of Number*. New York, NY: Springer-Verlag.

Geary, D. C. (1993). Mathematical disabilities: cognitive, neuropsychological, and genetic components. *Psychol. Bull.* 114, 345–362. doi: 10.1037/0033-2909.114.2.345

Geary, D. C. (1994). *Children's Mathematical Development: Research and Practical Applications.* Washington, DC: American Psychological Association.

Geary, D. C. (2004). Mathematics and learning disabilities. *J. Learn. Disabil.* 37, 4–15. doi: 10.1177/00222194040370010201

Geary, D. C. (2005). *The Origin of Mind: Evolution of Brain, Cognition, and General Intelligence*. Washington, DC: American Psychological Association.

Geary, D. C. (2011). Cognitive predictors of achievement growth in mathematics: a 5-year longitudinal study. *Dev. Psychol.* 47, 1539–1552. doi: 10.1037/a0025510

Geary, D. C., Berch, D. B., and Mann Koepke, K., (eds.). (2015). *Evolutionary Origins and Early Development of Number Processing,* Vol. 1. San Diego, CA: Elsevier Academic Press.

Gelman, R., and Gallistel, C. R. (1978). *The Child's Understanding of Number*. Cambridge, MA: Harvard University Press.

Ginsburg, H. P., and Baroody, A. J. (2003). *Test of Early Mathematics Ability, 3rd Edn*. Austin, TX: Pro-ed.

Grimm, K. J. (2008). Longitudinal associations between reading and mathematics achievement. *Dev. Neuropsychol.* 33, 410–426. doi: 10.1080/87565640801982486

Halberda, J., Ly, R., Wilmer, J. B., Naiman, D. Q., and Germine, L. (2012). Number sense across the lifespan as revealed by a massive Internet-based sample. *Proc. Natl. Acad. Sci. U.S.A.* 109, 11116–11120. doi: 10.1073/pnas.1200196109

Halberda, J., Mazzocco, M. M. M., and Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature* 455, 665–668. doi: 10.1038/nature07246

Hannula, M. M., and Lehtinen, E. (2005). Spontaneous focusing on numerosity and mathematical skills of young children. *Learn. Instr.* 15, 237–256. doi: 10.1016/j.learninstruc.2005.04.005

Hoge, R. D., and Luce, S. (1979). Predicting academic achievement from classroom behavior. *Rev. Educ. Res.* 49, 479–496. doi: 10.3102/00346543049003479

Huttenlocher, J., Jordan, N. C., and Levine, S. C. (1994). A mental model for early arithmetic. *J. Exp. Psychol.* 123, 284–296. doi: 10.1037/0096-3445.123.3.284

Inglis, M., and Gilmore, C. (2014). Indexing the approximate number system. *Acta Psychol.* 145, 147–155. doi: 10.1016/j.actpsy.2013.11.009

Invernizzi, M., Sullivan, A., Meier, J., and Swank, L. (2004). *PreK Teacher's Manual: Phonological Awareness Literacy Screening.* Charlottesville, VA: University of Virginia.

Jordan, N. C., Kaplan, D., Locuniak, M. N., and Ramineni, C. (2007). Predicting first-grade math achievement from developmental number sense trajectories. *Learn. Disabil. Res. Pract.* 22, 36–46. doi: 10.1111/j.1540-5826.2007.00229.x

Keller, L., and Libertus, M. (2015). Inhibitory control may not explain the link between approximation and math abilities in kindergarteners from middle class families. *Front. Psychol.* 6:685. doi: 10.3389/fpsyg.2015.00685

Klibanoff, R. S., Levine, S. C., Huttenlocher, J., Vasilyeva, M., and Hedges, L. V. (2006). Preschool children's mathematical knowledge: the effect of teacher 'math talk.' *Dev. Psychol.* 42, 59–69. doi: 10.1037/0012-1649.42.1.59

Koponen, T., Aunola, K., Ahonen, T., and Nurmi, J.-E. (2007). Cognitive predictors of single-digit and procedural calculation skills and their covariation with reading skill. *J. Exp. Child Psychol.* 97, 220–241. doi: 10.1016/j.jecp.2007.03.001

Koponen, T., Salmi, P., Eklund, K., and Aro, T. (2013). Counting and RAN: predictors of arithmetic calculation and reading fluency. *J. Educ. Psychol.* 105, 162–175. doi: 10.1037/a0029285

Le Corre, M., and Carey, S. (2007). One, two, three, four, nothing more: an investigation of the conceptual sources of the verbal counting principles. *Cognition* 105, 395–438. doi: 10.1016/j.cognition.2006.10.005

Levine, S. C., Jordan, N. C., and Huttenlocher, J. (1992). Development of calculation abilities in young children. *J. Exp. Child Psychol.* 53, 72–103. doi: 10.1016/S0022-0965(05)80005-0

Levine, S. C., Suriyakham, L. W., Rowe, M. L., Huttenlocher, J., and Gunderson, E. A. (2010). What counts in the development of young children's number knowledge? *Dev. Psychol.* 46, 1309–1319. doi: 10.1037/a0019671

Libertus, M. E., Halberda, J., and Feigenson, L. (2011). Preschool acuity of the approximate number system correlates with math abilities. *Dev. Sci.* 14, 1292–1300. doi: 10.1111/j.1467-7687.2011.01080.x

Lonigan, C. J., Burgess, S. R., and Anthony, J. L. (2000). Development of emergent literacy and early reading skills in preschool children: evidence from a latent-variable longitudinal study. *Dev. Psychol.* 36, 596–613. doi: 10.1037/0012-1649.36.5.596

Mann Koepke, K., and Miller, B. (2013). At the intersection of math and reading disabilities: introduction to the special issue. *J. Learn. Disabil.* 46, 483–489. doi: 10.1177/0022219413498200

Mazzocco, M. M. M., Feigenson, L., and Halberda, J. (2011). Preschoolers' precision of the Approximate Number System predicts later school mathematics performance. *PLoS ONE* 6:e23749. doi: 10.1371/journal.pone.0023749

Mazzocco, M. M. M., and Grimm, K. J. (2013). Growth in rapid automatized naming from grades K to 8 in children with math or reading disabilities. *J. Learn. Disabil.* 46, 517–533. doi: 10.1177/0022219413477475

Melby-Lervåg, M., Lyster, S.-A. H., and Hulme, C. (2012). Phonological skills and their role in learning to read: a meta-analytic review. *Psychol. Bull.* 138, 322–352. doi: 10.1037/a0026744

McNeil, N. M., Fuhs, M. W., Keultjes, M. C., and Gibson, M. H. (2011). Influences of problem format and SES on preschoolers' understanding of approximate addition. *Cogn. Dev*. 26, 57–71. doi: 10.1016/j.cogdev.2010.08.010

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., and Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cogn. Psychol.* 41, 49–100. doi: 10.1006/cogp.1999.0734

Morey, R. D., and Rouder, J. N. (2015). *BayesFactor: Computation of Bayes Factors for Common Designs. R Package Version 0.9.11-1*. Available online at: http://CRAN.R-project.org/package=BayesFactor

Purpura, D. J., and Reid, E. E. (2016). Mathematics and language: individual and group differences in mathematical language skills in young children. *Early Child. Res. Q.* 36, 259–268. doi: 10.1016/j.ecresq.2015.12.020

Qin, S., Cho, S., Chen, T., Rosenberg-Lee, M., Geary, D. C., and Menon, V. (2014). Hippocampal-neocortical functional reorganization underlies children's cognitive development. *Nat. Neurosci.* 17, 1263–1269. doi: 10.1038/nn.3788

Rousselle, L., and Noël, M.-P. (2007). Basic numerical skills in children with mathematics learning disabilities: a comparison of symbolic vs non-symbolic number magnitude. *Cognition* 102, 361–395. doi: 10.1016/j.cognition.2006.01.005

SAS Institute (2012). *The SAS System for Windows. Release 9.4*. Cary, NC.

Schneider, M., Beeres, K., Coban, L., Merz, S., Susan Schmidt, S., Stricker, J., et al. (2016). Associations of non-symbolic and symbolic numerical magnitude processing with mathematical competence: a meta-analysis. *Dev. Sci*. doi: 10.1111/desc.12372. [Epub ahead of print].

Siegler, R. S., and Shrager, J. (1984). "Strategy choices in addition and subtraction: how do childrenknow what to do," in *Origins of Cognitive Skills,* ed C. Sophian (Hillsdale, NJ: Erlbaum), 229–293.

Starkey, P. (1992). The early development of numerical reasoning. *Cognition* 43, 93–126. doi: 10.1016/0010-0277(92)90034-F

Sweller, J. (2015). In academe, what is learned, and how is it learned? *Curr. Dir. Psychol. Sci.* 24, 190–194. doi: 10.1177/0963721415569570

Tricot, A., and Sweller, J. (2014). Domain-specific knowledge and why teaching generic skills does not work. *Educ. Psychol. Rev*. 26, 265–283. doi: 10.1007/s10648-013-9243-1

vanMarle, K., Chu, F. W., Li, Y., and Geary, D. C. (2014). Acuity of the approximate number system and preschoolers' quantitative development. *Dev. Sci.* 17, 492–505. doi: 10.1111/desc.12143

Wagner, R. K., and Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychol. Bull.* 101, 192–212. doi: 10.1037/0033-2909.101.2.192

Wechsler, D. (2001). *Wechsler Indvidual Achievement Test - II*. San Antonio, TX: The Psychological Corporation, Harcourt Brace & Co.

Wechsler, D. (2002). *Wechsler Preschool and Primary Scale of Intelligence-III*. San Antonio, TX: The Psychological Corporation, Harcourt Brace & Co.

Willcutt, E. G., Petrill, S. A., Wu, S., Boada, R., DeFries, J. C., Olson, R. K., et al. (2013). Comorbidity between reading disability and math disability: concurrent psychopathology, functional impairment, and neuropsychological functioning. *J. Learn. Disabil.* 46, 500–516. doi: 10.1177/00222194134 77476

Wynn, K. (1990). Children's understanding of counting. *Cognition* 36, 155–193. doi: 10.1016/0010-0277(90)90003-3

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

frontiers in Psychology

ORIGINAL RESEARCH
published: 07 July 2016
doi: 10.3389/fpsyg.2016.01020

CrossMark

Early Literacy and Numeracy Skills in Bilingual Minority Children: Toward a Relative Independence of Linguistic and Numerical Processing

Paola Bonifacci[1], Valentina Tobia[2], Luca Bernabini[1] and Gian Marco Marzocchi[2]*

[1] *Laboratory Assessment Learning Disabilities, Department of Psychology, University of Bologna, Bologna, Italy,*
[2] *Department of Psychology, University of Milano-Bicocca, Milan, Italy*

Many studies have suggested that the concept of "number" is relatively independent from linguistic skills, although an increasing number of studies suggest that language abilities may play a pivotal role in the development of arithmetic skills. The condition of bilingualism can offer a unique perspective into the role of linguistic competence in numerical development. The present study was aimed at evaluating the relationship between language skills and early numeracy through a multilevel investigation in monolingual and bilingual minority children attending preschool. The sample included 156 preschool children. Of these, 77 were bilingual minority children (mean age = 58.27 ± 5.90), and 79 were monolinguals (mean age = 58.45 ± 6.03). The study focused on three levels of analysis: group differences in language and number skills, concurrent linguistic predictors of early numeracy and, finally, profile analysis of linguistic skills in children with impaired vs. adequate numeracy skills. The results showed that, apart from the expected differences in linguistic measures, bilinguals differed from monolinguals in numerical skills with a verbal component, such as semantic knowledge of digits, but they did not differ in a pure non-verbal component such as quantity comparison. The multigroup structural equation model indicated that letter knowledge was a significant predictor of the verbal component of numeracy for both groups. Phonological awareness was a significant predictor of numeracy skills only in the monolingual group. Profile analysis showed that children with a selective weakness in the non-verbal component of numeracy had fully adequate verbal skills. Results from the present study suggest that only some specific components of language competence predict numerical processing, although linguistic proficiency may not be a prerequisite for developing adequate early numeracy skills.

Keywords: early numeracy, language skills, bilingualism, letter-knowledge, phonemic awareness, Approximate Number System

OPEN ACCESS

Edited by:
Orly Rubinsten,
University of Haifa, Israel

Reviewed by:
Miriam Gade,
Catholic University of Eichstatt-Ingolstadt, Germany
Laura Babcock,
University of Padova, Italy

****Correspondence:***
Paola Bonifacci
paola.bonifacci@unibo.it

Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *26 January 2016*
Accepted: *21 June 2016*
Published: *07 July 2016*

Citation:
Bonifacci P, Tobia V, Bernabini L and Marzocchi GM (2016) Early Literacy and Numeracy Skills in Bilingual Minority Children: Toward a Relative Independence of Linguistic and Numerical Processing. Front. Psychol. 7:1020. doi: 10.3389/fpsyg.2016.01020

INTRODUCTION

The development of calculation skills is a strong predictor of academic achievement and a key goal of education, but few studies have addressed the determinants of the intuitive development of these skills in preschool years (Purpura et al., 2011), that is, how basic calculation and number skills spontaneously develop in children prior to formal instruction. In the present study, we took into account three main topics in the literature. First, researchers have suggested that children's mathematical development is primarily determined by an innate approximate number sense (ANS; Dehaene, 1992), which is typically assessed through tasks in which participants are required to discriminate object numerosity (Piazza et al., 2010). In contrast, an increasing number of studies also suggest that language abilities may play a pivotal role in the development of arithmetic skills (e.g., LeFevre et al., 2010; Purpura and Ganley, 2014). Third, the study of calculation skills in the bilingual population (e.g., Mondt et al., 2011; Prior et al., 2015; Rinsveld et al., 2015) has recently received increasing interest with the assumption that bilingualism, and specifically the case of language minority children, may offer a unique opportunity to disentangle the role of language skills in the development of calculation skills.

This assumption is based on the consideration that in many cases bilinguals are less proficient than monolinguals in verbal measures of linguistic proficiency in their L2, and, if numerical processing tested in L2 is highly dependent on linguistic abilities, it follows that bilinguals should underperform compared to monolinguals. Conversely, if numerical skills are primarily based on ANS-related skills, a scarce linguistic proficiency should not necessarily be accompanied by inadequate performance in numerical tasks. An investigation into the linguistic basis of mathematics in language minority children permits a thorough analysis of the relationship between language and mathematics and represents an opportunity to better evaluate individual differences in mathematical development (Vukovic and Lesaux, 2013). However, to our knowledge, few studies so far (Kleemans et al., 2011) have conducted a comparison of bilingual and monolingual children in the preschool years in order to comprehend the relationship between linguistic and numerical knowledge.

Relationships between Linguistic Skills and Number Knowledge in Monolinguals

According to Von Aster and Shalev's (2007) four-step model, the development of number acquisition starts from a core-system representation of cardinal magnitude referred to as "Number Sense" (Dehaene, 1997), which provides the basic meaning of numbers. This is a necessary precondition for children to learn to associate a perceived number of objects with verbal labels (Step 2) and Arabic symbols (Step 3). The development of the mental number line (Step 4) is considered to be the fourth and final step, which allows for arithmetic thinking. According to this model, mechanisms of magnitude comparison, language skills and working memory are all prerequisites for an adequate development of calculation skills, although it is suggested that only deficits in the ANS may characterize pure forms of dyscalculia (Von Aster and Shalev, 2007; Piazza et al., 2010; Libertus et al., 2011).

Many studies have suggested that the concept of "number" is relatively independent from linguistic skills (Gelman and Butterworth, 2005; Frank et al., 2008). Nonetheless, it is acknowledged that language plays a role at least in some aspects of numerical cognition; in particular, it seems that verbal processing is a necessary condition for a precise cognitive representation of large numbers (e.g., Dehaene et al., 1999; Spaepen et al., 2011). An increasing amount of evidence is emerging supporting a major role for linguistic skills in arithmetic development (Colomé et al., 2010; Cirino, 2011; Mazzocco et al., 2011; Purpura et al., 2011; Göbel et al., 2014; Purpura and Ganley, 2014). This also seems to be sustained by developmental changes in brain networks underlying numerical processing, with the left angular gyrus supporting the manipulation of numbers in verbal form (Dehaene et al., 2003). Furthermore, studies on clinical populations have documented a high comorbidity of reading and math difficulties (Swanson and Jerman, 2006; Landerl and Moll, 2010; Tobia et al., 2016b), and this has fostered research investigating the role of non-mathematical predictors in mathematical development (Purpura and Ganley, 2014).

Many studies have investigated the role of phonological processing, which is involved in tasks such as number reading (grapheme–phoneme correspondence). If phonological processing is impaired, it may reduce the capacity of working memory (Butterworth, 2005), leading to difficulties in storing and remembering arithmetic facts (e.g., Swanson and Sachse-Lee, 2001; Simmons and Singleton, 2008; Koponen et al., 2013; Vanbinst et al., 2015). There is, however, contrasting evidence regarding the predictive role of phonological skills on mathematical development. For example, in Passolunghi et al. (2007), phonological ability was not found to be a significant predictor in mathematical learning ability in the first year of primary school. In a more recent longitudinal study by Passolunghi et al. (2015), children underwent testing for their phonological skills at the beginning and at the end of the last year of preschool. The results indicated that the children's levels of phonological awareness that were evaluated at the beginning of the year predicted their numerical abilities that emerged from the assessment at the end of the year. The authors suggested that the influence of phonological skills may be mediated by the age of the children, indicating that it is not constant across development.

One of the other non-mathematical factors that may play a role in mathematical development is lexical amplitude (vocabulary), which is necessary to understand specific language terms (Adams, 2003; Purpura et al., 2011) used in specific instructions, and is highly involved in problem solving (Fuchs et al., 2005). Instruction comprehension and problem solving also involve morphosyntactic comprehension, which has received minor attention in the analysis of the relationship between language and mathematics (Centeno-Cortés and Jiménez Jiménez, 2004). An additional variable that the literature includes among the key predictors of reading development is letter knowledge; because numbers may be considered "special" letters, it might be hypothesized that letter knowledge might as well be a predictor of calculation skills, at least as an indirect index of exposure to print (Caravolas et al., 2005) or as an index of symbolic representation. Finally, there is a broad consensus that both verbal and spatial components of working memory are some of the main predictors of calculation ability. In particular, counting knowledge appears to be more strongly correlated with visuo-spatial working memory than with language precursors (Cirino, 2011). Although some evidence has suggested that the individual components of working memory are related differentially to mathematics (Wilson and Swanson, 2001; Simmons et al., 2012), other results note that the whole working memory system (rather than a specific working memory process) is linked to mathematical knowledge development (Bull et al., 2008; Simmons et al., 2008; Zhang et al., 2014).

Some longitudinal studies are available that consider the predictive role of numerical and non-numerical skills on early calculation abilities in pre-schoolers or in children upon entry into school. As far as numerical skills are concerned, quantity comparison, subitizing, size, and number seriation, counting, and number knowledge have been found to have a predictive role in calculation ability (Göbel et al., 2014; Purpura and Ganley, 2014; Tobia et al., 2016a). Additionally, several linguistic skills are predictive of later calculation skills; this is the case for vocabulary (Purpura and Ganley, 2014), phonological abilities, and verbal IQ (Passolunghi and Lanfranchi, 2012). Finally, some general cognitive factors, such as speed of processing and working memory (Passolunghi and Lanfranchi, 2012; Östergren and Träff, 2013), have a role in predicting early numeracy skills. LeFevre et al. (2010) and Sowinski et al. (2015) tested a set of cognitive precursors of early numerical skills, referred to as the Pathways to Mathematics Model, which, in its latest version (Sowinski et al., 2015), includes three main components – quantitative, linguistic, and working memory – as predictors of numerical (backward counting, arithmetic fluency, calculation, and number system knowledge) and reading variables. It emerged that the quantitative pathway (subitizing, counting, and magnitude comparison) accounted for substantial portions of variance in numerical skills and that the linguistic pathway (vocabulary and phonological awareness) was related to all numerical dependent variables and was also the sole significant predictor of reading.

To summarize, contrasting results have emerged as to the differential role of linguistic competence in calculation ability, and one of the main methodological shortcomings in this line of research is related to the fact that both domains (language and number processing) develop concurrently and with reciprocal interactions in typically developing monolingual children.

Language and Number Skills in Bilinguals

Some studies have directly addressed the relationship between language and arithmetic skills in adult bilinguals, and, in particular, have analyzed the role of language proficiency and language of training in numerical processing. Among these, Spelke and Tsivkin (2001) highlighted the fact that bilinguals retrieved information about exact numbers more effectively in the instructional language (language of training), whereas they were able to retrieve approximate numbers equally in both of their languages. In secondary school students enrolled in a bilingual program, Saalbach et al. (2013) found a cognitive cost related to language switching from the instructional to the non-instructional language in arithmetic tasks. Similarly, Rinsveld et al. (2015) found that adolescents and young adults were always better at solving complex mathematical tasks in their instructional language; on the other hand, their skills in solving complex calculations in the other language improved with their language proficiency. Another important aspect is the influence of language-specific number word structures in bilinguals' arithmetic performances (Prior et al., 2015; Rinsveld et al., 2015). These findings suggest that arithmetic processing is sensitive to the linguistic representations of number, and that numerical processing is preferentially processed in the instructional language. This was also shown in an fMRI study (Mondt et al., 2011) on children who learnt mathematics in an instructional language but spoke a different language at home. The authors found that children who performed the task in the instructional language showed a more efficient and specialized pattern of neural activation compared to those performing the same task in their home language. The latter relied more on working memory and visual attentional resources.

Other evidence for the intrinsic relationship between language and mathematics comes from a few studies of bilingual language minority children who were in the course of acquiring their second language (L2) within the scholastic environment. These children can be defined as bilinguals because they speak and are exposed to two or more languages in everyday life (De Lamo White and Jin, 2011). Although bilingualism *per se* does not constitute a risk factor for either linguistic or mathematical skill development, bilingual language minority children often score lower on phonological awareness, vocabulary size, and morphosyntactic competence in their second language during the preschool years (Genesee and Geva, 2006). This offers a new window into the study of the relationship between linguistic competence and number development because, if linguistic competence is a determinant of mathematical skill development, bilingual children may be expected to show lower numerical skills than their monolingual peers.

In summary, if the two domains (linguistic and mathematical) were relatively separate, it would be possible to assume that bilingual children in preschool, although they may have poorer linguistic competences in L2, should not necessarily fall behind monolingual peers in the domain of calculation and mathematical prerequisites. Our research has focused on this aspect, investigating what happens in very young children who have not yet been exposed to formal academic instruction and who learn Italian as their L2. To date, the research that has been conducted with language minority students has focused mainly on their literacy development. An analysis of early numeracy skills in this population and of the relationship with linguistic competence not only provides important theoretical contributions to the connection between language and mathematics but also has implications for assessment procedures and targeted interventions in this understudied population.

MATERIALS AND METHODS

Ethics Statement

The research ethics committee of the University of Bologna approved the LOGOS project, of which the present study is part. Parents of children involved in the study gave informed consent.

Aims of the Study

To unravel the relationship between language skills and early numeracy in monolingual and bilingual pre-schoolers, the present study focused on three main topics:

(1) Differences between bilingual and monolingual children in linguistic skills and early numeracy abilities. According to the literature review, we expected to find a significant difference in the language domain (Genesee and Geva, 2006). If it emerges that bilingual children underperform in the linguistic domain, and if the linguistic domain is a crucial determinant of numerical skills (Sowinski et al., 2015), these children should also underperform in numeracy skills. On the other hand, if bilinguals show similar numerical skills to monolinguals, this should support the independence of the numeracy domain in relation to the language one.

(2) Linguistic predictors of early numeracy. The second aim of this study was to identify the pattern of concurrent predictors of early numeracy in monolinguals and bilinguals. In particular, numeracy skills with a language component were considered separately from those involving non-verbal numeracy skills, in order to investigate an eventual discrepancy in the pattern of predictors. Among the potential predictors, we considered variables reported by the literature to be significantly linked to numerical abilities in children. We expected at least some linguistic variables to predict the verbal component of numeracy skills in monolinguals. Furthermore, we want to explore whether this pattern is replicated in the bilingual sample. Finally, we expected the non-verbal components of early numeracy to be relatively independent from the linguistic predictors both in monolinguals and bilinguals.

(3) To further investigate the link between linguistic skills and early numeracy, we ran a profile analysis grouping participants based on their profile in numeracy skills, thus identifying children with (1) no difficulties, (2) difficulties only in numerical tasks with a linguistic component, (3) difficulties only in non-verbal number tasks, and (4) difficulties in both components of early numeracy. Verbal skills of these groups were then compared. Profile analysis is an approach that allows for a qualitative understanding of the strengths and weaknesses of the examined population, beyond and above the information derived from group mean scores (Bonifacci and Tobia, 2016). In this study profile analysis was directly aimed at verifying whether a weakness in different components of numerical skills was associated with a deficit in language skills. Considering past studies that found a link between language and some early mathematical skills (e.g., Passolunghi et al., 2015), we expected to find poorer language skills in both monolinguals and bilinguals with difficulties in numerical tasks that have a linguistic component. On the contrary, children with globally adequate skills in early numeracy, or with a selective difficulty in non-verbal numerical tasks, should show unimpaired language abilities, in light of the relative independence of language and non-symbolic numerical skills.

These three methodologies together, applied to a sample of pre-schoolers, offer new and original insight into the relationship between language and number skills before the beginning of formal instruction.

Participants

A total of 156 children attending 12 public all-day preschool programs in northern Italy took part in this study, which was part of a wider study, the LOGOS Project, aimed at monitoring and reinforcing early indicators of language development and learning difficulties. Of the children, 49.4% were L2 learners of Italian ($n = 77$, 51.9% females; mean age = 58.27 ± 5.90 months, range = 50–77 months), whereas the remaining children were native Italian speakers ($n = 79$, 53.2% females; mean age = 58.45 ± 6.03 months, range = 48–75 months). Children in the two groups were balanced for gender ($\chi^2(1) = 0.879$, $p = 0.503$) and age ($t(154) = 0.192$, $p = 0.848$). The two groups were recruited from within the same schools and therefore matched for educational exposure, considering, among other aspects, that all the teachers were enrolled in the LOGOS Project, which provides teacher training and pooling of didactic strategies. The schools were in urban and suburban areas that served children from both low-income and middle-income families. This study was carried out in accordance with the recommendations of American Psychological Association (2010), and the research ethics committee of the University of Bologna approved the LOGOS project. Parents of children involved in the study gave informed consent.

Children with Italian as their L2 all spoke minority languages at home. All of these children could be considered early bilinguals because, as specified below, they were all exposed to the Italian language before the age of 3 (Kovelman et al., 2008), as established by consulting their entry into the school system and by collecting information from teachers. The selection criteria were:

(a) exposure to an L1 different from Italian (L2) within the family context;
(b) being born in Italy or arriving in Italy within their first year of life;
(c) having at least 1.5 years of continued exposure to Italian within a school setting;
(d) not being referred to neuropsychiatric units for any range of developmental disorder or sensory or neurological impairment.

The parents of L2 children were mostly from Arabic speaking (20.8%) and Russian-Slavic speaking (22%) countries, but also came from South America (10.4%), Bangladesh (6.5%), Philippines (7.8%), and Romania (10.4%); The remaining participants, 22.1%, originated from other areas (e.g., African French).

For the monolingual group, inclusion criteria were being born in Italy from Italian speaking parents and not being exposed to any other foreign language at home. None of the children had been referred for any range of developmental disorder or sensory or neurological impairment.

The children were attending the second or third year of the Italian preschool program that involves children from 3 to 6 years old. Italian preschool programs do not provide formal instruction in literacy or mathematical skills. However, during the last preschool year, children participate in pre-reading and pre-writing activities, to familiarize them with letters and letter-sound correspondence, and in pre-mathematical games including number songs, classification and seriation of objects, counting and use of worksheets to familiarize with shapes and quantities. These activities tend to occur in the second semester of the last year of preschool, and the children included in the present study were assessed at an earlier age.

Materials

Learning Difficulties Indexes (IDA; Bonifacci et al., 2015)

This assessment battery was developed to evaluate a wide range of linguistic skills in pre-schoolers. It includes six tasks that measure vocabulary, phonological awareness, morpho-syntactic comprehension, phonological memory, story sequencing, and letter knowledge. The internal consistency and reliability values reported refer to the normative sample ($N = 1416$; Bonifacci et al., 2015). The battery is composed of the following subscales:

(1) Vocabulary

Children were asked to name 36 images selected for decreasing frequency in spoken language (Barca et al., 2002). The accuracy score, ranging from 0 to 36, was considered. The scale's Cronbach's alpha was 0.85. This subtest also allows for an evaluation of speech sound skills, testing 52 main sounds of the Italian language (single phonemes or consonant groups).

(2) Phonological Awareness

The battery included four different subtests aimed at assessing phonological awareness: syllable blending (e.g., To-po → Topo; Mouse; six items); syllable segmentation (e.g., Carota → Ca-ro-ta; Carrot; six items); first syllable recognition (e.g., <u>ca</u>ne-<u>ca</u>sa; dog-house; four items); and rhymes (e.g., Porta–Torta; Door-Cake; (four items). For the first two tasks, stimuli were presented orally and children were required to provide a verbal answer by blending or segmenting sounds. For the second pairs of tasks, children were presented with a target picture and were required to choose, from among four pictures, which one started or ended with the same sound. Each item received a score of 1 for correct responses and a score of 0 for incorrect answers, for a maximum total score of 20. The scale's Cronbach's alpha was 0.84.

(3) Morpho-Syntactic comprehension

Children saw three pictures representing three different scenarios and were asked to individuate or manipulate elements of the scenes by comprehending different types of sentences (e.g., active, passive) pronounced by the examiner. For example, the child had to correctly place a picture of a book after hearing the sentence "The book is under the pillow". Eighteen sentences were presented, and for each of them a score of 2 (correct answer on the first attempt), 1 (correct answer on the second attempt), or 0 (incorrect answer) was assigned. The total score (0–36), was considered. The scale's Cronbach's alpha was 0.70.

(4) Story sequencing

This task is composed of five pictures depicting a brief tale of a little dinosaur, named Dino, preparing a cake. Each participant was presented with four pictures presented in the wrong order (fixed and predetermined). Image number 1 was given as a prompt, and then the child was asked to arrange pictures in the correct order and to tell the story aloud (this narrative task was not considered in the present study). A score of 1 was given for each picture in the correct order (maximum score: 4). The scale's Cronbach's alpha was 0.82.

(5) Phonological memory

Children were presented with a non-word repetition task of eight non-words, two 2-syllable, two 3-syllable, two 4-syllable, and two 5-syllable items. Incorrect repetitions were scored 0. Then, a score of 2 was given for perfectly repeated non-words, and a score of 1 was assigned when an articulatory error that had already been detected in the vocabulary task was made. For example, if a child had a difficulty with the phoneme "r" and pronounced the word "rana" (frog) as "lana" in the vocabulary task, a repetition of the non-word "fimedura" as "fimedula" would be scored 1. The total score ranged from 0 to 16, and the scale's Cronbach's alpha was 0.72.

(6) Letter Knowledge

Children were presented with a picture of a train with one letter (from a to z) in each coach. The experimenter had to choose four letters within the child's name or first letters of the surname, thus considered to be familiar letters, and four letters chosen randomly but not part of the child's name, considered to be unfamiliar letters. Then, the experimenter indicated these letters randomly on the train picture, and the child was required to say the sound or the name of the letter. A score of 1 was given for each correct response for a maximum score of 8. The scale's Cronbach's alpha was 0.70.

Number Sense: Prerequisites (SNUP; Tobia et al., in preparation)

This battery assesses early numeracy skills in pre-schoolers. To be appealing to such young children, each task is presented in a narrative way, and there is a main character, the dragon SNUP, who guides children through the tasks. It is composed of six subtests:

(1) Quantity comparison

Children were shown two illustrated baskets and were asked to quickly choose the one with a greater number of fruits in it. The number of fruits varied from 3 to 20, and differences between sets was from 1 to 6 units. A total of 24 items were presented. A score of 1 (correct answer) or 0 (wrong answer) was given for each of them, for a maximum total score of 24. The scale's Cronbach's alpha was 0.69.

(2) Counting (from 1 to 20)

Children were asked to count 20 buttons dispersed on a board measuring approximately 20 cm × 30 cm. Both knowledge of the verbal sequence of numbers and the acquisition of the biunivocal correspondence principle of counting, namely the ability to link each number word to an individual object, were evaluated. Scores range from 0 to 40, and one point was given for each number word named correctly on the scale of 1–20 and when the child linked one number word to one button. The scale's Cronbach's alpha was 0.93.

(3) Number line

Children were asked to indicate the point corresponding to 2, 3, 6, 7, and 9 elements (apples placed in a basket) on a 25-cm long line ranging from 0 (empty basket) to 10. The percentage of absolute error (PE; Siegler and Booth, 2004) was calculated. The scale's Cronbach's alpha was 0.58.

(4) Size seriation, including three tasks

(a) First, children were asked to put four sets of four pictures of the same object (e.g., a house), drawn in different dimensions, in ascending order (seriation with perceptual cues, maximum score: 16); (b) second, a fifth picture for each set was presented, and the child had to put it in the correct place in the ordered composition (insertion, maximum score: 4); (c) finally, children were presented with four series of four pictures of different items (e.g., a bee, a mouse, a cat, and a giraffe), all depicted as the same size, and had to put them in ascending order using their knowledge of the items' real size (seriation without perceptual cues, maximum score: 16). For each item placed in the correct position, a score of 1 was assigned. The total score ranged from 0 to 36. The Cronbach's alpha of the size seriation subtest was 0.89.

(5) Semantic knowledge of digits

(a) Recognition, (b) reading, and (c) number-quantity association were assessed for digits 1 to 9. The task was organized as a game similar to bingo with numbers. A card containing the digits 1 to 9 randomly distributed on a grid amongst blank squares was used, together with a small bag containing nine number cards, each representing a digit. In the digit recognition subtask, children pointed to the number on the bingo card that had been picked out of the bag and read aloud by the examiner. For the digit reading subtask, children picked a number from the bag and read it aloud. Finally, in the number-quantity association test, children were provided with a card representing sets of elements (baskets of fruit containing from 1 to 9 bananas). The examiner picked and named a digit and children had to choose the set with the corresponding number of elements. For each digit correctly (a) recognized, (b) read, or (c) associated with the corresponding quantity, a score of 1 was given (total score: 0–27). The subtest's Cronbach's alpha was 0.93.

(6) Visual-spatial memory

Children were asked to remember the position of one to four items (drawings of the dragon SNUP) on 3×3 and 4×4 grids that were presented for 2 and 4 s, respectively, and then covered. Six 3×3 grids containing one, two, or three dragons were presented, and four 4×4 grids with three or four dragons on them were shown, for a total of 10 grids. A score of 1 was assigned for each item remembered in the correct position. The maximum total score was 26; Cronbach's alpha was 0.80.

The Cronbach's alpha values refer to the normative sample ($N = 804$; Tobia et al., in preparation).

For the administration of both batteries, special attention was given to ascertaining that children correctly understood the instructions: verbal instructions were minimized and examples for each task were provided, in order to make the tasks clear to children. Before starting with the experimental test, participants tried the tasks and feedback was given for both correct and incorrect answers. In this phase, if a child showed difficulties understanding the task, the instructions and an example were repeated.

Data Analysis

All the raw scores were converted into scaled scores (Mean = 10, $SD = 3$), according to the batteries' norms. Differences between L2 and native Italian speakers in the linguistic and mathematical prerequisites of learning were analyzed with two multivariate analyses of variance (MANOVA), one including the subscales from the IDA battery, and one including the ones from the SNUP battery.

As a second analysis, a multigroup structural equation model (SEM; e.g., Kline, 2010) including a confirmatory factor analysis (CFA) and a path analysis was applied using MPlus (Muthén and Muthén, 1998–2010). The CFA identified two latent variables within the SNUP battery. The first one included the early numeracy tasks that had a linguistic component (i.e., Counting and Semantic knowledge of digits), whereas the second factor included early numeracy variables without a linguistic component (i.e., Quantity comparison, Number line, and Size seriation). Visual−spatial memory was not considered because it is a prerequisite of mathematical skills, but it is not an effective component of number sense as it is a general cognitive precursor. A path analysis was used to examine the relationship between these dependent variables and the linguistic tasks included in the IDA battery that were considered as potential predictors. The model was tested on monolinguals and bilinguals with the multigroup technique. The complete model analyzed is presented in **Figure 1**.

Multiple indices were used to evaluate model fit, including Chi-square, Root Mean Square Error of Approximation (RMSEA), Comparative Fit Index (CFI), Tuker-Lewis Index (TLI), and Standardized Root Mean Squared Residual (SRMR). A non-significant Chi-square, an RMSEA result no greater than 0.06, CFI and TLI results of 0.95 or better, and an SRMR result of less than 0.08 suggested good model fit for the ML estimator used for this analysis (Hu and Bentler, 1999).

Finally, profile analysis in early numeracy was performed. Children were classified as follows:

(1) no difficulties in early numeracy: scaled scores on all the SNUP tasks > 6;
(2) difficulties only in the early numeracy tasks with a linguistic component: a scaled score ≤ 6 in Counting and/or in Semantic knowledge of digits;
(3) difficulties only in the non-verbal early numeracy tasks: a scaled score ≤ 6 in one or more tasks among Quantity comparison, Number line, and Size seriation;

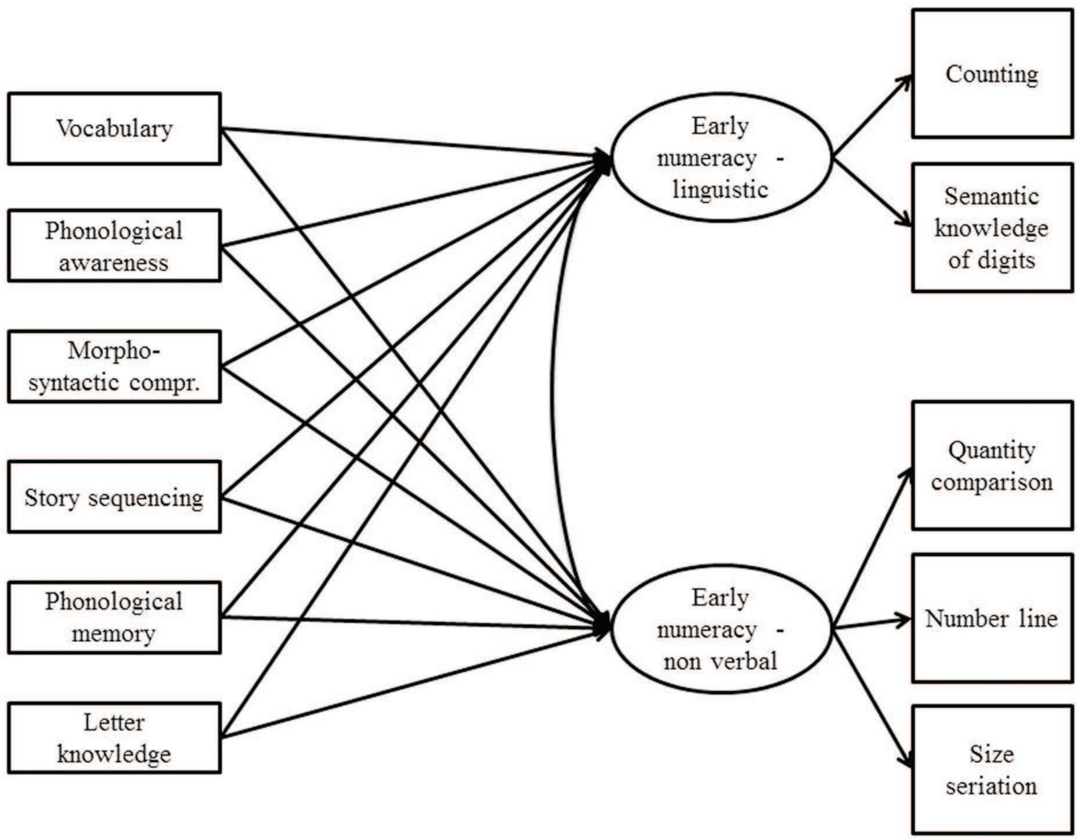


FIGURE 1 | Model tested with structural equation modeling.

(4) difficulties in both the components of early numeracy: scaled scores ≤ 6 in at least one task between Counting and Semantic knowledge of digits, and in at least one task among Quantity comparison, Number line, and Size seriation.

The cut-off of a scaled score of 6 was chosen because it corresponds to a *z* score of about −1,3 SD, which is usually adopted as a criterion for identifying at risk performances. Then, a chi-square test for independence was performed to analyze the links between the categories of difficulties in early numeracy and the monolingual or bilingual condition. Finally, a MANOVA investigating the effect of the different types of profiles of early numeracy on the performance to the IDA tasks was performed. Tukey *post hoc* tests were run to analyze differences between the four profiles. All of the analyses, with the exception of the SEM, were conducted using SPSS 21 (SPSS Chicago, IL USA).

RESULTS

Differences in the Prerequisites of Learning

The MANOVA revealed a significant multivariate effect for Group (Pillai's Trace = 0.313, $F(6,144) = 10.920$, $p < 0.001$, $\eta^2 = 0.313$) on the set of subtests included in the IDA battery. Scaled scores obtained by the children and the results of the univariate analyses are presented in **Table 1**.

In **Table 1**, descriptive results of the children's performance on the SNUP battery are also reported. A significant multivariate effect of Group was also found for early numeracy skills (Pillai's Trace = 0.127, $F(6,144) = 3.479$, $p = 0.003$, $\eta^2 = 0.127$). However, as shown in **Table 1**, the results of only half of the early numeracy tasks significantly differed between the two groups.

Language Predictors of Early Numeracy

All the fit indices suggested that the multigroup SEM fit the data well: $\chi^2(50) = 50.993$, $p > 0.05$; RMSEA = 0.016 (90% confidence interval = 0.000–0.076); CFI = 0.995; TLI = 0.992; SRMR = 0.061.

Figures 2 and **3** describe the model fitted to the data obtained from the monolingual and bilingual groups, respectively. The CFA's results were similar in the two groups, showing that the two latent variables corresponding to linguistic and non-verbal components of early numeracy were consistent across groups. On the contrary, the path analyses revealed a different pattern of predictors. As far as monolingual children were

TABLE 1 | Descriptive statistics and results of the univariate analysis for monolinguals and bilinguals on the “Learning Difficulties Indexes” (IDA) and “Number Sense: Prerequisites” (SNUP) batteries.

		Monolinguals mean (SD)	Bilinguals mean (SD)	F(1,150)	P	η^2
IDA	Vocabulary	10.55 (2.43)	7.51 (2.33)	61.72	<0.01	0.293
	Phonological Awareness	9.95 (2.89)	8.55 (2.68)	9.53	0.002	0.060
	Morpho-syntactic comprehension	10.39 (2.72)	8.11 (2.32)	30.95	<0.01	0.172
	Story sequencing	9.70 (2.24)	9.08 (2.41)	2.65	NS	0.018
	Phonological memory	8.78 (2.73)	7.69 (2.59)	6.24	<0.05	0.040
	Letter knowledge	9.30 (2.35)	8.17 (2.20)	9.31	<0.01	0.059
SNUP	Quantity comparison	10.36 (2.99)	9.74 (2.89)	1.670	NS	0.011
	Counting	9.35 (3.12)	8.82 (3.12)	1.062	NS	0.007
	Number line	13.41 (3.16)	12.27 (3.08)	4.991	<0.05	0.032
	Size seriation	10.72 (3.20)	9.14 (3.08)	9.525	<0.01	0.060
	Semantic knowledge of digits	10.43 (2.77)	9.41 (2.79)	5.120	<0.05	0.033
	Visual−spatial memory	9.77 (2.80)	10.52 (2.68)	2.837	NS	0.019

concerned, the linguistic component of numeracy was predicted by letter knowledge and, marginally, by vocabulary. The non-verbal component was predicted by the phonological awareness task.

In bilinguals, as in monolinguals, letter knowledge predicted the linguistic component of early numeracy. On the contrary, none of the linguistic variables considered predicted the non-verbal component.

Profiles of Early Numeracy Difficulties

The number of monolingual and bilingual children in each of the four early numeracy profiles, derived by the classification of early numeracy difficulties, is reported in **Table 2**.

The chi square test showed that there was independence between profiles of early numeracy abilities and being monolingual or bilingual ($\chi^2(3) = 5.646, p = 0.130$). Considering this result, a MANOVA was run on the entire sample.

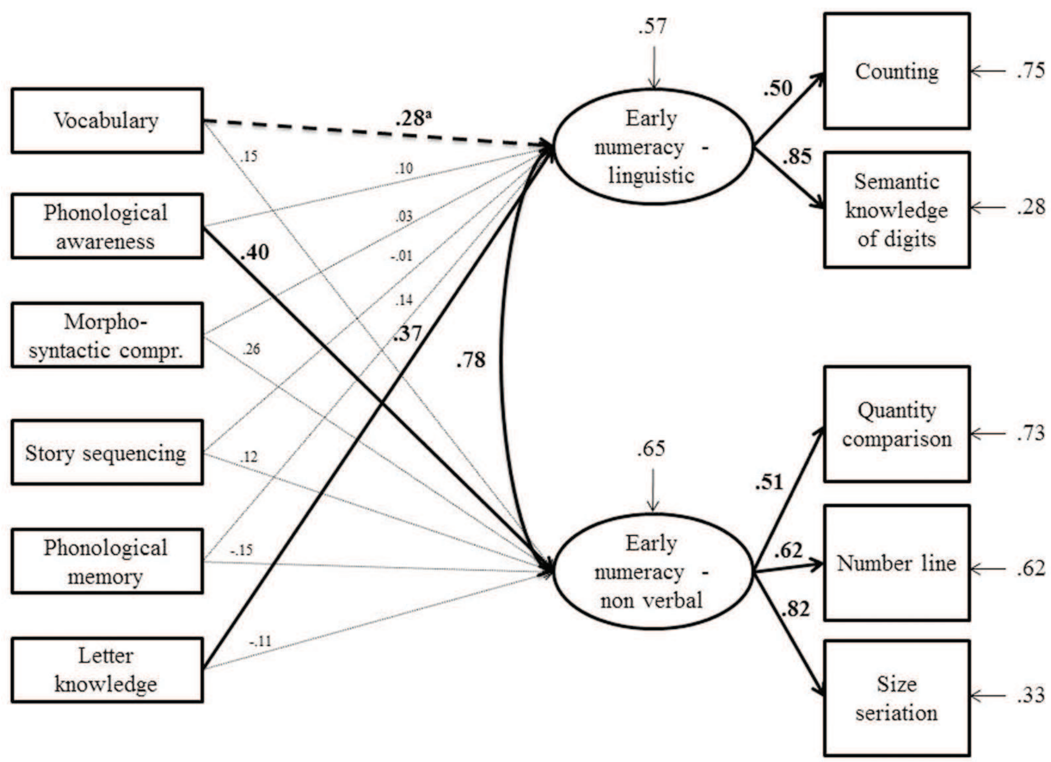


FIGURE 2 | Model tested with structural equation modeling on monolinguals. Bold arrows and coefficients represent significant relationships at $p < 0.01$; $^{a}p = 0.068$. The arrows above the latent variables represent the residual variance for the dependent variables.

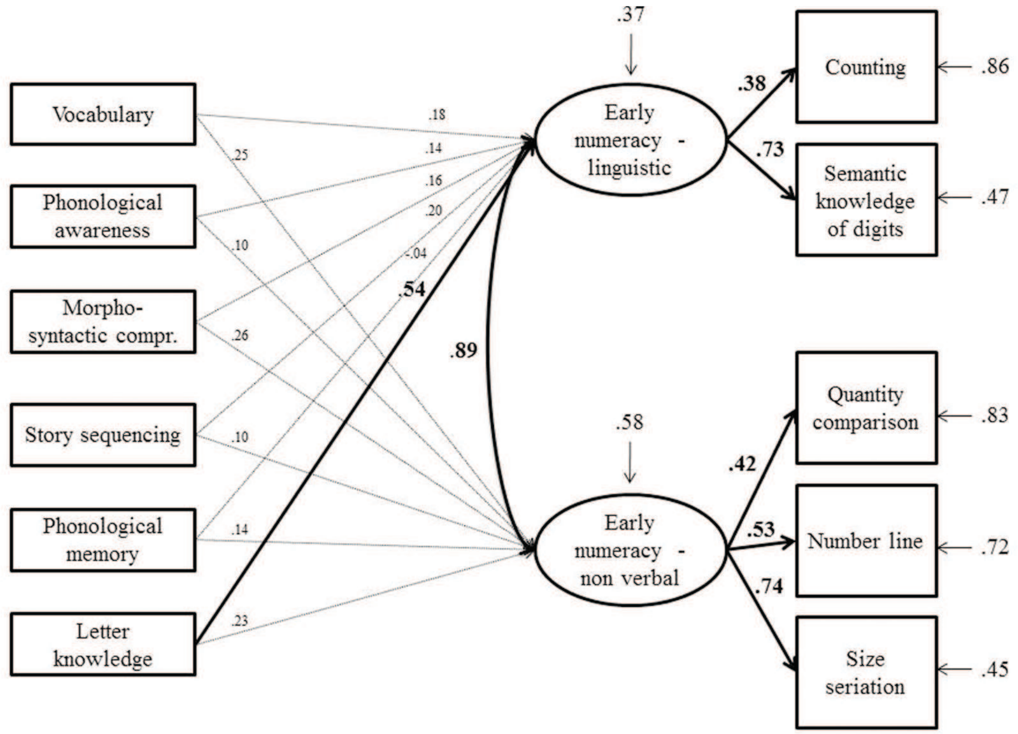


FIGURE 3 | Model tested with structural equation modeling on bilinguals. Bold arrows and coefficients represent significant relationships at $p < 0.01$. The arrows above the latent variables represent the residual variance for the dependent variables.

A MANOVA was performed to analyze the main effect of Profile on early numeracy on the language tasks included in the IDA battery. The results showed a significant multivariate effect of the children's Profile (Pillai's Trace = 0.327, $F(18,432) = 2.934$, $p < 0.001$, $\eta^2 = 0.109$). Descriptive statistics, results of the univariate analysis and *post hoc* tests are presented in **Table 3**.

Globally, it emerged that the group with impaired performance in both verbal and non-verbal components of numeracy was similar to the one with only verbal numeracy difficulties, whereas children with typically developing numeracy skills and with a weakness involving only the non-verbal component of numeracy did not differ from each other in the language skills analyzed, and outperformed the other two groups.

DISCUSSION

The present study was aimed at providing a thorough examination of the relationship between language skills and early numeracy through a multilevel investigation of these skills in monolingual and bilingual children attending preschool. To our knowledge, this is the first study that has analyzed language-numeracy relationship in young pre-schoolers, with three levels of investigation being considered: group comparisons, predictors, and individual differences. A group of bilingual language minority children was included in order to offer a unique perspective into the role of linguistic competence in numerical development, and the profile analysis included in the study fosters the qualitative understanding of the strengths and weaknesses of the examined population, beyond and above the information derived from group mean scores.

The first aim of the present study was to investigate differences between bilingual and monolingual children in linguistic skills and early numeracy abilities. It was intended that this kind of analysis would help to ascertain the profile of the two populations in a wide set of tasks, in order to define patterns of strengths and weaknesses across multiple measures. As expected, there was a difference between groups in their linguistic profiles on all the linguistic tasks and this difference allowed us to look for a dissociation between linguistic and numerical skills. There was,

TABLE 2 | Number of monolingual and bilingual children included in the four categories describing early numeracy difficulties.

		Monolinguals	Bilinguals
Profiles based on performance on the SNUP tasks	(1) No difficulties	48 (60.8%)	33 (42.9%)
	(2) Difficulties only in tasks with a linguistic component	14 (17.7%)	16 (20.8%)
	(3) Difficulties only in non-verbal tasks	9 (11.4%)	16 (20.8%)
	(4) Difficulties in both the components of early numeracy	8 (10.1%)	12 (15.5%)

TABLE 3 | Profile analysis.

		Vocabulary	Phonological awareness	Morpho-syntactic comprehension	Story sequencing	Phonological memory	Letter knowledge
Profiles based on the performance at the SNUP tasks	(1) No difficulties	9.87 (2.74)	10.24 (2.90)	10.29 (2.67)	9.99 (2.14)	9.01 (2.52)	9.38 (2.34)
	(2) Difficulties only in tasks with a linguistic component	8.47 (2.94)	7.93 (2.50)	8.27 (2.68)	8.43 (2.19)	6.80 (2.80)	7.83 (1.93)
	(3) Difficulties only in non verbal tasks	8.48 (2.60)	9.40 (2.35)	8.56 (2.22)	8.76 (2.54)	8.52 (2.62)	8.80 (2.25)
	(4) Difficulties in both the components of early numeracy	7.45 (2.28)	7.30 (2.13)	7.70 (2.49)	9.35 (2.50)	7.10 (2.29)	7.60 (2.23)
MANOVA	*F*(3,150)	5.487	9.642	8.572	4.171	6.879	5.454
	P	≤0.001	≤0.001	≤0.001	≤0.01	≤0.001	≤0.001
	η^2	0.101	0.164	0.149	0.078	0.123	0.100
	Post hoc	4 < 1	2, 4 < 1 4 < 3	2, 3, 4 < 1	2 < 1	2, 4 < 1	2, 4 < 1

Descriptive statistics (mean and SD) and F, p, and η^2 values of the univariate analysis and post hoc tests of group differences.

however, an exception in the story sequencing task, for which the two groups did not differ. This task was the only one in the IDA battery with a non-verbal request and it was included because it was followed by a narrative task, which was not considered in the present study. When examining the significant differences, the smallest effect was found for phonological memory, a task involving non-word repetition. Despite involving non-familiar material for both monolinguals and bilinguals, the significant differences found for this task may depend on the fact that the stimuli were legal non-words; thus, their morphological structure adhered to Italian rules of word composition. It has been shown that, at least to a certain degree, bilinguals are sensitive to the morphological and distributional properties of the target L2 language (Bellocchi et al., 2016), and this is influenced by age of exposure. This may explain why in the non-word repetition task bilinguals lagged only marginally behind their monolingual peers.

The assessment of bilingual performance in L2 should be accompanied by an evaluation of L1 linguistic skills because highlighting weaknesses in L2 does not necessarily mean that the same pattern stands for L1 linguistic competencies. This is in line with International guidelines (American Speech-Language-Hearing Association [ASHA], 1985, 2004) on clinical assessment in multilingual contexts, and the lack of assessment of linguistic skills in L1 limits data interpretation as regards linguistic and working memory competence in the bilingual sample. However, considering the difficulties in assessing L1 competencies, particularly for language minority children, many studies have been aimed at studying linguistic and numerical competencies in L2, in order to gain information as to a typical bilingual developmental trajectory in L2 acquisition. Furthermore, in the case of numerical processing, it has been shown that bilingual children tend to be more proficient in solving numerical tasks when tested in their instructional language (Mondt et al., 2011), compared to those who were tested in their home language. In that case, the sole analysis of the L2 might be considered useful because it provides information about the instructional language; therefore, the identification of patterns of strengths and weaknesses in L2 may help to pinpoint potential risks and protective factors in the learning paths of bilingual children.

The pattern of difficulties in numerical skills was mixed. Bilinguals underperformed monolinguals in some numerical skills with a verbal component, such as semantic knowledge of digits, but they did not differ in pure non-verbal components such as quantity comparison. This pattern supports an independence of magnitude comparison from linguistic processing (Dehaene et al., 1999). Furthermore, they were similar to their monolingual peers in visuo-spatial memory. This task had very simple and mainly non-verbal instructions, and required a non-verbal answer. The similar performance observed in visuo-spatial memory that resulted in scores around the mean for both groups suggests that this important general cognitive non-verbal prerequisite was equally developed. Bilinguals' gap in linguistic knowledge compared to monolinguals may explain their failing in the semantic knowledge of digits that involved the lexical retrieval of number names and grapheme-phoneme correspondences of Arabic digits. Despite this trend, bilinguals did not fail in counting ability, maybe because of the high frequency of the use of early counting sequences (i.e., 1–10) in everyday life or the high automaticity of sequencing number names. For an alternative explanation, the model of early counting competence with three basic components by Ferrara and Turner (1993) could be considered. They theorized (1) a verbal component involving knowledge of the conventional number-word sequence, (2) an action component involving knowledge of tagging behaviors in object-counting procedures, and (3) a contextual component involving knowledge of the basic goals and uses of counting. We can hypothesize that only the first component may be poorer in bilinguals compared to monolingual peers, and therefore the similar competence in the two remaining abilities would lead to a similar performance in the counting task. Finally, bilinguals underperformed monolinguals in some non-verbal components of number processing, such as number line and size seriation. This counterintuitive result might be explained by the characteristics of the verbal instructions given for these tasks, which were slightly more complex than the ones given for the other tasks, even though morpho-syntactic comprehension was not a significant predictor of these skills. An alternative hypothesis may be related to cultural characteristics of the stimuli such as the direction of the number line, as documented by studies with the SNARC effect in Arab populations (Dehaene et al., 1993). Further investigation is needed to increase knowledge on how these competencies develop in bilingual groups and, as discussed below, the lack of socio economic status (SES) measures limits the possibility to sustain definitive conclusions on the bilingual sample altogether.

The second aim was to analyze the pattern of linguistic predictors of number skills, in particular by investigating the two separate domains of verbal and non-verbal components of early numeracy. The analysis showed partially different patterns of predictors for the two groups considered. First, in both bilinguals and monolinguals, letter knowledge was a significant predictor of the verbal component of numeracy. The letter knowledge task required a grapheme-phoneme association as was, in some way, required by the semantic knowledge of the digits task included in the verbal component of numeracy. In other words, both tasks involved symbol processing. Furthermore, past studies showed medium to high correlations between tasks, such as naming speed, involving letters and digits (e.g., Bowey et al., 2005). These results suggest that symbol processing of letters and digits share a common underlying cognitive component independent from specific knowledge in one of the two domains. In monolinguals, there was also a marginally significant effect of vocabulary on the verbal component of numeracy, which is in line with past studies (e.g., Purpura and Ganley, 2014). Additionally, phonological awareness was, for the monolingual group, a significant predictor of the nonverbal component of numeracy skills. This result could be explained by the component of working memory involved in this task. In fact, working memory may serve as a link between phonological awareness and non-verbal early numeracy. In particular, the tasks of syllable blending and segmentation, beyond phonological processing, required an active component of working memory, namely the ability to manipulate phonological material before giving the target word. Working memory, as supported by past studies (Simmons et al., 2008; Zhang et al., 2014), is highly involved in early numeracy and was similarly involved in tasks included in the present study such as the mental number line where children were required to actively manipulate position in space depending on the target stimuli. Another mnemonic task, non-word repetition, had a passive memory component (rehearsal and repetition) that did not significantly predict numeracy skills.

The results from the bilingual group demonstrated, on the other hand, a substantial independence between linguistic skills and non-verbal numerical skills, because none of the linguistic measures were significant predictors of pure non-verbal numerical tasks. As far as pre-schoolers are concerned, only one study to date has analyzed cognitive (general intelligence, working memory) and linguistic precursors (phonological awareness, grammatical ability) to early numeracy in monolinguals and bilinguals (Kleemans et al., 2011). In line with results from the present study, the authors found that bilinguals had lower scores than first language learners in both linguistic and early numeracy tasks. Furthermore, correlation analysis showed that both phonological awareness and grammatical ability were needed for early numeracy development. Finally, no differences were detected in the pattern of correlations between language precursors and early numeracy for monolinguals versus bilinguals. The authors concluded that, in addition to cognitive factors, both phonological awareness and grammatical ability play equally important roles in the early numeracy of monolinguals and bilinguals. In Kleemans' study children had a mean age of 6 years, all attended the last year of kindergarten, and thus were moderately exposed to literacy and number activities. Moreover, vocabulary, phonological memory and letter knowledge tasks were not included, although these linguistic measures are known to potentially influence number processing (Cirino, 2011; Purpura et al., 2011). In the present study, the reported pattern of relationships was observed in a very young sample of pre-schoolers (mean age 4.8 years) who had not yet been exposed to formal schooling, or to systematic activities on literacy and numerical skills. In fact, in the Italian school system activities on precursors of reading and math skills are mainly introduced by the second semester of the last year of preschool and these activities are mainly developed by class teachers. The National Indications (Istruzione, 2012) for the curriculum of preschool give general guidelines on the importance of promoting lexical and narrative skills, logical reasoning and spatio-temporal orientation. Thus, in the first two years of preschool, children are mainly exposed to playful didactic activities that have the broad aim of promoting the development of learning skills, but that do not include systematic and formal activities. Thus, the pattern of results described in the present study mainly refers to the spontaneous developmental trajectory of reading and math related skills. It is thus intriguing that letter knowledge plays a significant role from this early age. This observation reinforces previous studies (e.g., Caravolas et al., 2012) that proposed that the spontaneous ability of the child to acquire letter knowledge can be considered as a marker of his/her sensitivity to print exposure and of his/her ability to access some phonologic representations of speech. Thus, individual differences in letter knowledge in preschool years may be good predictors of literacy outcomes, and, based on the present study, also of numerical skills involving a verbal component.

Finally, the last aim of the study was to compare performance in verbal tasks for children with different profiles of early numeracy skills. Consequently, participants were further classified as having (1) no difficulties, (2) difficulties only in numerical tasks with a linguistic component, (3) difficulties only in non-verbal number tasks, and (4) difficulties in both components of early numeracy. First, an analysis of the frequency of monolinguals and bilinguals across the four categories showed a similar distribution, suggesting that numerical weaknesses were equally distributed in the two subsamples. This is in line with Kleemans et al. (2011), who suggested that a gap in numerical skills in bilingual children, also found in the present study in some numerical skill group comparisons, might be better accounted for as an educational delay rather than as a clinical impairment. In fact, analysis of differences in early numerical skills showed a small to medium (Cohen, 1988) gap between bilinguals and monolinguals, and their mean scores fell within the typical range (see scaled scores). This result, together with the additional information offered by the profile analysis, delineates a group of children with mild difficulties in precursors of mathematical abilities. This outcome suggests the potential role that an early targeted intervention could play, together with good practices in the classroom, in reducing this gap (e.g., Fuchs et al., 2005; Klibanoff et al., 2006). These measures would be more effective if the specific profile of difficulties showed by each child were considered. Profile analysis also showed that children with a selective weakness in the non-verbal component of numeracy had mostly adequate verbal skills. This represents a complementary perspective on the relative independence of linguistic and numeracy domains, at least for those skills related to magnitude comparison and for what is referred to as the ANS. An interesting result is the profile of language skills that emerged for children with a poor verbal component of numeracy: they showed good vocabulary skills and particularly lower scores in phonological tasks (phonological memory and awareness) and in letter knowledge. This result is in line with past studies that showed the importance of these variables in influencing some key components of mathematical abilities (e.g., Simmons and Singleton, 2008), and adds information regarding the influential and early role of letter knowledge.

This study had some limitations, specifically the paucity of information regarding participants' SES and the level of L1 proficiency in the bilingual group, which may limit the generalizability of the results and makes it difficult to draw any firm conclusions regarding the bilingual sample as a whole. These variables need to be better accounted for in future cross-group comparisons. However, the main aim of the present study was to evaluate predictors and patterns of strengths and weaknesses in linguistic and numerical skills, rather than absolute levels of performance and group differences between bilinguals and monolinguals. Furthermore, studies investigating the effects of SES on early mathematics found that preschoolers from low socio-economic backgrounds have difficulties in most early mathematical skills, such as counting, comparing magnitudes and performing simple calculations (e.g., Jordan et al., 2006). The pattern of results we found, with only some components of early mathematical abilities being affected, suggests a main role for language-related underexposure, rather than SES, in explaining our results. We suggest that the selection criteria adopted, together with the minor predictive role of SES in Italy (OCSE-Programme for International Student Assessment [PISA], 2006), contribute to substantially minimize the role of SES in explaining the pattern of results discussed here.

Finally, it is worth underlining the importance of children's capability to understand instructions when the relationship between their linguistic and numerical skills is being analyzed. Previous studies (Vukovic and Lesaux, 2013) found that in 6- to 9-year old monolingual and bilingual children, significant correlations emerged between language and skills in data analysis and geometry, whereas there were no correlations with arithmetic or algebra skills. The authors suggested that linguistic abilities are helpful in understanding meaning, but they are not essential to perform well in tasks requiring the use and elaboration of Arabic symbols and quantities. In this study, we tried to minimize verbal instructions of tasks; furthermore, we used examples and we checked carefully that all children understood what they were requested to do in each task. However, it is plausible that L2 instructions represented a stronger challenge for bilingual than monolingual participants. Nevertheless, in the present study no significant relationships between morpho-syntactic comprehension and early numerical skills were found, suggesting that the ability to perform in numerical tasks was not primarily related to the ability to comprehend L2 sentences.

CONCLUSION

To conclude, this is the first study that investigates cognitive and linguistic underpinnings of early numeracy in preschool bilingual and monolingual children at different levels of analysis; the results suggest that only some specific components of language competence may predict specific numerical processing. However, having a good level of linguistic proficiency may not be a necessary condition in order to develop adequate abstract representation of numbers, as supported by the absence of a relationship between language and numeracy in bilingual children with overall adequate number competencies and weak linguistic skills (as shown when discussing the first aim). Linguistic weaknesses may lead to poorer performance with numeracy but not to impaired numerical abilities. In fact, the scaled scores for all the number and number-related tasks administered were in the average range for the children's age, and there were no differences in the proportion of monolinguals and bilinguals showing significant weaknesses in numeracy skills.

The lack of L1 measures of proficiency requires further evaluation in future studies, in order to better disentangle the role of language skills in specific numerical processing. However, in the present study children were tested in their instructional language and, although they are still in preschool years, it is reasonable to hypothesize that they have acquired basic number abilities in the school setting, albeit in the absence of a formal instruction. Therefore, the results from the present study allow us to assume that there is a relative independence of linguistic and numerical processing in bilingual language minority children with a gap in linguistic development, compared to their monolingual peers. In order to investigate the relationship between linguistic and numerical skills in depth we included a sample of bilingual children because of their particular differential language exposition. Further investigations might focus on clinical populations of children with language impairments, who are known to have specific weaknesses in the phonological and lexical domains.

In summary, these findings offer new insight both for clinical and educational settings, suggesting the importance of defining proper assessment of strengths and weaknesses, and targeting intervention to specific domains in minority bilingual children. Furthermore, from a theoretical perspective, the present study suggests that at the very beginning of literacy and numerical development the two domains are relatively independent.

AUTHOR CONTRIBUTIONS

PB, VT, and GM contributed to the conception and design of the work; VT, LB contributed substantially to data acquisition. All authors were involved in analysis and interpretation of data for the work. PB, VT, and LB drafted the work and GM revised it critically. All authors finally approved the present version of the manuscript and agree on all aspects of the work.

FUNDING

The present study was part of a wider study, the LOGOS Project (Monitoring and reinforcement of early indicators of language development and learning difficulties), funded by Bologna City Council for the year 2014.

REFERENCES

Adams, T. L. (2003). Reading mathematics: more than words can say. *Read. Teach.* 56, 786–795.

American Psychological Association (2010). *Ethical Principles of Psychologists and Code of Conduct*. Washington, DC: American Psychological Association.

American Speech-Language-Hearing Association [ASHA] (1985). *Clinical Management of Communicatively Handicapped Minority Language Populations [Position Statement]*. Rockville, MD: American Speech-Language-Hearing Association.

American Speech-Language-Hearing Association [ASHA] (2004). *Knowledge and Skills Needed by Speech-Language Pathologists and Audiologists to Provide Culturally and Linguistically Appropriate Services [Knowledge and Skills]*. Rockville, MD: American Speech-Language-Hearing Association.

Barca, L., Burani, C., and Arduino, L. S. (2002). Word naming times and psycholinguistic norms for Italian nouns. *Behav. Res. Methods Instrum. Compt.* 34, 424–434. doi: 10.3758/BF03195471

Bellocchi, S., Bonifacci, P., and Burani, C. (2016). Lexicality, frequency and stress assignment effects in bilingual children reading Italian as a second language. *Biling. Lang. Cogn.* 19, 89–105.

Bonifacci, P., Pellizzari, C., Giuliano, P., and Serra, P. (2015). *IDA: Indicatori Difficoltà di Apprendimento [Learning Difficulties Indexes]*. Firenze: Hogrefe.

Bonifacci, P., and Tobia, V. (2016). Crossing barriers: profiles of reading and comprehension skills in early and late bilinguals, poor comprehenders, reading impaired, and typically developing children. *Learn. Individ. Differ.* 47, 17–26. doi: 10.1016/j.lindif.2015.12.013

Bowey, J. A., McGuigan, M., and Ruschena, A. (2005). On the association between serial naming speed for letters and digits and word-reading skill: towards a developmental account. *J. Res. Read.* 28, 400–422. doi: 10.1111/j.1467-9817.2005.00278.x

Bull, R., Espy, K. A., and Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: longitudinal predictors of mathematical achievement at age 7 years. *Dev. Neuropsychol.* 33, 205–228. doi: 10.1080/87565640801982312

Butterworth, B. (2005). The development of arithmetical abilities. *J. Child. Psychol. Psyc.* 46, 3–18. doi: 10.1111/j.1469-7610.2004.00374.x

Caravolas, M., Kessler, B., Hulme, C., and Snowling, M. (2005). Effects of orthographic consistency, frequency, and letter knowledge on children's vowel spelling development. *J. Exp. Child. Psychol.* 92, 307–321. doi: 10.1016/j.jecp.2005.08.001

Caravolas, M., Lervåg, A., Mousikou, P., Efrim, C., Litavský, M., Onochie-Quintanilla, E., et al. (2012). Common patterns of prediction of literacy development in different alphabetic orthographies. *Psychol. Sci.* 23, 678–686. doi: 10.1177/0956797611434536

Centeno-Cortés, B., and Jiménez Jiménez, A. F. (2004). Problem-solving tasks in a foreign language: the importance of the L1 in private verbal thinking. *Int. J. Appl. Ling.* 14, 7–35. doi: 10.1111/j.1473-4192.2004.00052.x

Cirino, P. (2011). The interrelationships of mathematical precursors in kindergarten. *J. Exp. Child Psychol.* 108, 713–733. doi: 10.1016/j.jecp.2010.11.004

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Colomé, À, Laka, I., and Sebastián-Gallés, N. (2010). Language effects in addition: how you say it counts. *Q. J. Exp. Psychol.* 63, 965–983. doi: 10.1080/17470210903134377

De Lamo White, C., and Jin, L. (2011). Evaluation of speech and language assessment approaches with bilingual children. *Int. J. Lang. Commun. Disord.* 46, 613–627. doi: 10.1111/j.1460-6984.2011.00049.x

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition* 44, 1–42. doi: 10.1016/0010-0277(92)90030-L

Dehaene, S. (1997). *The Number Sense. How the Mind Creates Mathematics*. New York, NY: Oxford University Press.

Dehaene, S., Bossini, S., and Giraux, P. (1993). The mental representation of parity and number magnitude. *J. Exp. Psychol. Gen.* 122, 371–396. doi: 10.1037/0096-3445.122.3.371

Dehaene, S., Piazza, M., Pinel, P., and Cohen, L. (2003). Three parietal circuits for number processing. *Cogn. Neuropsych.* 20, 487–506. doi: 10.1080/02643290244000239

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., and Tsivkin, S. (1999). Sources of mathematical thinking: behavioral and brain-imaging evidence. *Science* 284, 970–974. doi: 10.1126/science.284.5416.970

Ferrara, R. A., and Turner, T. (1993). The structure of early counting competence. *Bull. Psychon. Soc.* 31, 257–260. doi: 10.1371/journal.pone.0022501

Frank, M. C., Everett, D. L., Fedorenko, E., and Gibson, E. (2008). Number as a cognitive technology: evidence from Pirahã language and cognition. *Cognition* 108, 819–824. doi: 10.1016/j.cognition.2008.04.007

Fuchs, L. S., Compton, D. L., Fuchs, D., Paulsen, K., Bryant, J. D., and Hamlett, C. L. (2005). The prevention, identification, and cognitive determinants of math difficulty. *J. Educ. Psychol.* 97, 493–513. doi: 10.1037/0022-0663.97.3.493

Gelman, R., and Butterworth, B. (2005). Number and language: how are they related? *Trends Cogn. Sci.* 9, 6–10. doi: 10.1016/j.tics.2004.11.004

Genesee, F., and Geva, E. (2006). "Cross-linguistic relationships in working memory, phonological processes, and oral language," in *Report of the National Literacy Panel on K-12 Youth and Adolescents*, eds D. August and T. Shanahan (Lawrence, KS: Erlbaum), 169–177.

Göbel, S., Watson, S., Lervåg, A., and Hulme, C. (2014). Children's arithmetic development: it is number knowledge, not the approximate number sense, that counts. *Psychol. Sci.* 25, 789–798. doi: 10.1177/0956797613516471

Hu, L. T., and Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: conventional criteria versus new alternatives. *Struct. Equ. Modeling.* 6, 1–55. doi: 10.1080/10705519909540118

Istruzione, M. D. P. (2012). *Indicazioni Nazionali per il Curricolo della Scuola dell'Infanzia e del Primo Ciclo d'Istruzione*. Firenze: Le Monnier.

Jordan, N. C., Kaplan, D., Oláh, L., and Locuniak, M. N. (2006). Number sense growth in kindergarten: a longitudinal investigation of children at risk for mathematics difficulties. *Child Dev.* 77, 153–175. doi: 10.1111/j.1467-8624.2006.00862.x

Kleemans, T., Segers, E., and Verhoeven, L. (2011). Cognitive and linguistic precursors to numeracy in kindergarten: evidence from first and second language learners. *Learn. Individ. Differ.* 21, 555–561. doi: 10.1016/j.lindif.2011.07.008

Klibanoff, R. S., Levine, S. C., Huttenlocher, J., Vasilyeva, M., and Hedges, L. V. (2006). Preschool children's mathematical knowledge: the effect of teacher "math talk". *Dev. Psyc.* 42, 59–69. doi: 10.1037/0012-1649.42.1.59

Kline, R. B. (2010). *Principles and Practice of Structural Equation Modeling,* 3rd Edn. New York, NY: The Guilford Press.

Koponen, T., Salmi, P., Eklund, K., and Aro, T. (2013). Counting and RAN: predictors of arithmetic calculation and reading fluency. *J. Educ. Psychol.* 105, 162–175. doi: 10.1037/a0029285

Kovelman, I., Baker, S., and Petitto, L. A. (2008). Age of first bilingual language exposure as a new window into bilingual reading development. *Biling. Lang. Cogn.* 11, 203–223. doi: 10.1017/S1366728908003386

Landerl, K., and Moll, K. (2010). Comorbidity of learning disorders: prevalence and familial transmission. *J. Child Psychol. Psyc.* 51, 287–294. doi: 10.1111/j.1469-7610.2009.02164.x

LeFevre, J. A., Fast, L., Skwarchuk, S. L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., et al. (2010). Pathways to mathematics: longitudinal predictors of performance. *Child Dev.* 81, 1753–1767. doi: 10.1111/j.1467-8624.2010.01508.x

Libertus, M. E., Feigenson, L., and Halberda, J. (2011). Preschool acuity of the approximate number system correlates with school math ability. *Dev. Sci.* 14, 1292–1300. doi: 10.1111/j.1467-7687.2011.01080.x

Mazzocco, M. M., Feigenson, L., and Halberda, J. (2011). Preschoolers' precision of the approximate number system predicts later school mathematics performance. *PLoS ONE* 6:e23749. doi: 10.1371/journal.pone.0023749

Mondt, K., Struys, E., Noort, M., Balériaux, D., Metens, T., Paquier, P., et al. (2011). Neural differences in bilingual children's arithmetic processing depending on language of instruction. *Mind Brain Educ.* 5, 79–88. doi: 10.1111/j.1751-228X.2011.01113.x

Muthén, L. K., and Muthén, B. O. (1998–2010). *Mplus User's Guide*, 6th Edn. Los Angeles, CA: Muthén & Muthén.

OCSE-Programme for International Student Assessment [PISA] (2006). *Rapporto Nazionale OCSE-PISA 2003. Il Livello di Competenza dei Quindicenni in Matematica, Lettura, Scienze e Problem Solving [National Report OCSE-PISA 2003. Level of competence of fifteen-year-old students in math, reading, science e problem solving]*. Roma: Armando Editore.

Östergren, R., and Träff, U. (2013). Early number knowledge and cognitive ability affect early arithmetic ability. *J. Exp. Child Psychol.* 115, 405–421. doi: 10.1016/j.jecp.2013.03.007

Passolunghi, M. C., and Lanfranchi, S. (2012). Domain-specific and domain-general precursors of mathematical achievement: a longitudinal study from kindergarten to first grade. *Brit. J. Educ. Psychol.* 82, 42–63. doi: 10.1111/j.2044-8279.2011.02039.x

Passolunghi, M. C., Lanfranchi, S., Altoè, G., and Sollazzo, N. (2015). Early numerical abilities and cognitive skills in kindergarten children. *J. Exp. Child Psychol.* 135, 25–42. doi: 10.1016/j.jecp.2015.02.001

Passolunghi, M. C., Vercelloni, B., and Schadee, H. (2007). The precursors of mathematics learning: working memory, phonological ability and numerical competence. *Cogn. Dev.* 22, 165–184. doi: 10.1016/j.cogdev.2006.09.001

Piazza, M., Facoetti, A., Trussardi, A. N., Berteletti, I., Conte, S., Lucangeli, D., et al. (2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition* 116, 33–41. doi: 10.1016/j.cognition.2010.03.012

Prior, A., Katz, M., Mahajna, I., and Rubinsten, O. (2015). Number word structure in first and second language influences arithmetic skills. *Front. Psychol.* 6:266. doi: 10.3389/fpsyg.2015.00266

Purpura, D., Hume, L., Sims, D., and Lonigan, C. (2011). Early literacy and early numeracy: the value of including early literacy skills in the prediction of numeracy development. *J. Exp. Child Psychol.* 110, 647–658. doi: 10.1016/j.jecp.2011.07.004

Purpura, D. J., and Ganley, C. M. (2014). Working memory and language: skill-specific or domain-general relations to mathematics? *J. Exp. Child Psychol.* 122, 104–121. doi: 10.1016/j.jecp.2013.12.009

Rinsveld, A., Brunner, M., Landerl, K., Schiltz, C., and Ugen, S. (2015). The relation between language and arithmetic in bilinguals: insights from different stages of language acquisition. *Front. Psychol.* 6:265. doi: 10.3389/fpsyg.2015.00265

Saalbach, H., Eckstein, D., Andri, N., Hobi, R., and Grabner, R. (2013). When language of instruction and language of application differ: cognitive costs of bilingual mathematics learning. *Learn. Instr.* 26, 36–44. doi: 10.1016/j.learninstruc.2013.01.002

Siegler, R. S., and Booth, J. L. (2004). Development of numerical estimation in young children. *Child Dev.* 75, 428–444. doi: 10.1111/j.1467-8624.2004.00684.x

Simmons, F., Singleton, C., and Horne, J. (2008). Brief report—phonological awareness and visual-spatial sketchpad functioning predict early arithmetic attainment: evidence from a longitudinal study. *Eur. J. Cogn. Psychol.* 20, 711–722. doi: 10.1080/09541440701614922

Simmons, F. R., and Singleton, C. (2008). Do weak phonological representations impact on arithmetic development? A review of research into arithmetic and dyslexia. *Dyslexia* 14, 77–94.

Simmons, F. R., Willis, C., and Adams, A. M. (2012). Different components of working memory have different relationships with different mathematical skills. *J. Exp. Child Psychol.* 111, 139–155. doi: 10.1016/j.jecp.2011.08.011

Sowinski, C., LeFevre, J.-A., Skwarchuk, S.-L., Kamawar, D., Bisanz, J., and Smith-Chant, B. (2015). Refining the quantitative pathway of the Pathways to mathematics model. *J. Exp. Child Psychol.* 131, 73–93. doi: 10.1016/j.jecp.2014.11.004

Spaepen, E., Coppola, M., Spelke, E. S., Carey, S. E., and Goldin-Meadow, S. (2011). Number without a language model. *Proc. Natl. Acad. Sci.* 108, 3163–3168. doi: 10.1073/pnas.1015975108

Spelke, E., and Tsivkin, S. (2001). Language and number: a bilingual training study. *Cognition* 78, 45–88. doi: 10.1016/S0010-0277(00)00108-6

Swanson, H. L., and Jerman, O. (2006). Math disabilities: a selective meta-analysis of the literature. *Rev. Educ. Res.* 76, 249–274. doi: 10.1016/j.ridd.2015.01.002

Swanson, H. L., and Sachse-Lee, C. (2001). Mathematical problem solving and working memory in children with learning disabilities: both executive and phonological processes are important. *J. Exp. Child Psychol.* 79, 294–321. doi: 10.1006/jecp.2000.2587

Tobia, V., Bonifacci, P., and Marzocchi, G. M. (2016a). Concurrent and longitudinal predictors of calculation skills in pre-schoolers. *Eur. J. Psychol. Educ.* 31, 155–174. doi: 10.1007/s10212-015-0260-y

Tobia, V., Fasola, A., Lupieri, A., and Marzocchi, G. M. (2016b). Numerical magnitude representation in children with mathematical difficulties with or without reading difficulties. *J. Learn. Disabil.* 49, 115–129. doi: 10.1177/0022219414529335

Vanbinst, K., Ceulemans, E., Ghesquière, P., and De Smedt, B. (2015). Profiles of children's arithmetic fact development: a model-based clustering approach. *J. Exp. Child Psychol.* 133, 29–46. doi: 10.1016/j.jecp.2015.01.003

Von Aster, M. G., and Shalev, R. S. (2007). Number development and developmental dyscalculia. *Dev. Med. Child Neurol.* 49, 868–873. doi: 10.1111/j.1469-8749.2007.00868.x

Vukovic, R., and Lesaux, N. (2013). The language of mathematics: investigating the ways language counts for children's mathematical development. *J. Exp. Child Psychol.* 115, 227–244. doi: 10.1016/j.jecp.2013.02.002

Wilson, K. M., and Swanson, H. L. (2001). Are mathematics disabilities due to a domain-general or a domain-specific working memory deficit? *J. Learn. Disabil.* 34, 237–248. doi: 10.1177/002221940103400304

Zhang, X., Koponen, T., Räsänen, P., Aunola, K., Lerkkanen, M., and Nurmi, J. (2014). Linguistic and spatial skills predict early arithmetic development via counting sequence knowledge. *Child Dev.* 85, 1091–1107. doi: 10.1111/cdev.12173

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

frontiers in Psychology

ORIGINAL RESEARCH
published: 07 March 2016
doi: 10.3389/fpsyg.2016.00306

CrossMark

Spatial Ability Explains the Male Advantage in Approximate Arithmetic

Wei Wei[1,2], Chuansheng Chen[3] and Xinlin Zhou[2]*

[1] Department of Psychology and Behavioral Sciences, Zhejiang University, Hangzhou, China, [2] State Key Laboratory of Cognitive Neuroscience and Learning, Siegler Center for Innovative Learning, Beijing Normal University, Beijing, China, [3] Department of Psychology and Social Behavior, University of California, Irvine, CA, USA

Previous research has shown that females consistently outperform males in exact arithmetic, perhaps due to the former's advantage in language processing. Much less is known about gender difference in approximate arithmetic. Given that approximate arithmetic is closely associated with visuospatial processing, which shows a male advantage we hypothesized that males would perform better than females in approximate arithmetic. In two experiments (496 children in Experiment 1 and 554 college students in Experiment 2), we found that males showed better performance in approximate arithmetic, which was accounted for by gender differences in spatial ability.

Keywords: gender difference, approximate arithmetic, spatial ability

OPEN ACCESS

Edited by:
Sarit Ashkenazi,
The Hebrew University of Jerusalem, Israel

Reviewed by:
Patrizia Silvia Bisiacchi,
University of Padova, Italy
Fuhong Li,
Jiangxi Normal University, China

****Correspondence:***
Xinlin Zhou
zhou_xinlin@bnu.edu.cn

Specialty section:
This article was submitted to Cognition,
a section of the journal Frontiers in Psychology

Received: *02 December 2015*
Accepted: *17 February 2016*
Published: *07 March 2016*

Citation:
Wei W, Chen C and Zhou X (2016) Spatial Ability Explains the Male Advantage in Approximate Arithmetic. Front. Psychol. 7:306. doi: 10.3389/fpsyg.2016.00306

INTRODUCTION

Gender differences in mathematical performance have been an important area of research because researchers and policy makers alike have been concerned about the under representation of women in mathematics-intensive fields or Science, Technology, Engineer, and Mathematics (STEM; Hyde and Linn, 2006; Halpern et al., 2007; Guiso et al., 2008; Hyde et al., 2008; Ceci et al., 2009; Nosek et al., 2009; Else-Quest et al., 2010; Shen, 2013). Many studies have been conducted to investigate the cognitive, socio-cultural, and biological origins of these differences (Halpern et al., 2007; Kovas et al., 2007; Guiso et al., 2008).

Although male advantage in mathematics has been widely reported, it is by no means the only story in town (Spelke, 2005). For example, Hyde and Linn (2006), Hyde et al. (2008) have emphasized the gender similarity hypothesis. Moreover, there is evidence that at an early age females show better performance in arithmetic than do males (Linn and Hyde, 1989; Wei et al., 2012). One possible explanation of such an advantage is that arithmetic tends to rely on language processing (Dehaene et al., 1999; Lemer et al., 2003), which shows a female advantage (Wei et al., 2012). As Wei et al. (2012) found, after controlling for verbal ability, gender differences in mathematical performance disappeared.

Some arithmetic tasks, however, may not involve much language processing. Distinct from exact arithmetic, approximate arithmetic (e.g., "Of 3 and 8, which number is closer to the answer to the problem 4+5?") is believed to involve less verbal processing but more number sense and visuospatial processing (Dehaene et al., 1999). Studies have found that approximate arithmetic could be performed without symbols and language (Pica et al., 2004). Young children without formal education can perform large-number symbolic approximate arithmetic (Gilmore et al., 2007). Neuroimaging studies further supported the distinction between exact and approximate arithmetic. It has been found that exact arithmetic relies on the language system, whereas approximate arithmetic relies on the numerical magnitude processing system or the internal "number line" (Dehaene et al., 1999). Specifically, approximate arithmetic recruits the parietal lobe, which is involved in visuo-spatial processing.

In the current study, we recruited two age groups of students to examine gender differences in approximate arithmetic. Given that males show better performance in spatial ability (Voyer et al., 1995) and that spatial ability is linked to approximate arithmetic as mentioned above, we hypothesized that males would outperform females in approximate arithmetic, and that spatial ability would be the cognitive mechanism for the gender difference in approximate arithmetic.

EXPERIMENT 1

Materials and Methods

Participants

Children in 6th—8th grades students were recruited for the study. Children came from two Chinese cities, Liuzhou (Guangxi Province) and Beijing. There were 496 children (234 males and 262 females), 11.0–15.9 years old. All participants were native Chinese speakers and had normal or corrected-to-normal eyesight. This study was approved by the Institute of Cognitive Neuroscience and Learning at Beijing Normal University and the principals of the schools.

Procedure

Participants took computerized mathematical and other cognitive tests in a computer room in groups of about 30–40 students per class. They were monitored by 2–3 experimenters and, in the case of 6th–8th grade students, by the class's teacher as well. Instructions and a practice session were given before each formal test. The tasks were administered in the same order for all students. Participants responded by pressing "P" or "Q" on the keyboard for three of the five tasks (see below), using the mouse for the spatial working memory task, and entering a numerical value for the approximate arithmetic task. Participants' responses were automatically recorded and sent over the internet to a server located in our laboratory at the university.

Tasks

All the tasks were programmed using Web-based applications available at: www.dweipsy.com/lattice (Wei et al., 2012).

Symbolic approximate arithmetic

This task was based on Levine's (1982) *Test of Estimation Ability (TEA)*. The open–ended paradigm (Levine, 1982; Rubenstein, 1985; Dowker, 1992; Dowker et al., 1996) was adopted in the current study to test the ability of approximate arithmetic. An equation was presented in the middle of the screen. On the top the screen, there was a time bar, indicating 15 s. To ensure that the participants could not calculate the exact answer in 15 s, we used multiple digits for all equations (see **Table 1**). Participants were asked to come up with the best approximate answer for the equation in 15 s. Participants entered the answer into an input box at the bottom of the screen. The formal test included 40 trials, including addition, subtraction, multiplication, and division. The four operations were presented randomly for each participant. Both integral and decimal arithmetic was used in this task.

Three-dimensional mental rotation

This task was based on Shepard's mental rotation task (Shepard and Metzler, 1971). For each trial, one three-dimensional image was presented on the upper part of the screen, and two others on the lower part. Participants were asked to choose one from the bottom to match with the top; the matching image could be identified only by mental rotation. Participants were asked to press the "Q" key if he/she chose the image on the left, or the "P" key he/she chose the image on the right. The formal test included 180 trials and was limited to 3 min. The rotation angles of the images were 15°, 30°, . . ., 345°, with a step of 15°. Each trial would remain on the screen until participants responded by pressing "P" or "Q".

Raven's progressive matrices

The Raven's Progressive Matrices test (Raven, 1998) was used to assess general intelligence. In this test, participants needed to identify the missing segment of a figure according to the figure's inherent regularity. They should press "Q" if the missing segment was on the left or "P" if it appeared on the right. The formal test included 80 trials and was limited to 4 min.

TABLE 1 | The test of symbolic approximate arithmetic.

Item \ Operation	Addition	Subtraction	Multiplication	Division
1	1752 + 9339	8473 − 1247	581 × 64	6.664 ÷ 0.98
2	8928 + 5397	10395 − 13657	735 × 44	4144 ÷ 37
3	4578 + 3566	27534 − 11846	23 × 76	23596 ÷ 68
4	8546 + 5773	7814 − 1937	397 × 35	11515 ÷ 47
5	3696 + 1276	57631 − 14768	34 × 87	16068 ÷ 78
6	23.27 + 594.9	93.12 − 148.73	93 × 0.24	5.472 ÷ 57
7	749.6 + 4737.9	574.21 − 18.796	7.2 × 98.6	2352 ÷ 24
8	6.759 + 0.2867	5.614 − 10.4935	0.893 × 3.7	403.76 ÷ 0.98
9	926.4 + 75.72	208.3 − 129.26	2.17 × 0.83	66.3 ÷ 6.5
10	38.69 + 629.8	15.94 − 10.798	0.68 × 7.9	343.2 ÷ 22

Spatial working memory

This task was similar to Corsi block task (Corsi, unpublished doctoral dissertation). Non-overlapping dots were sequentially presented in an implicit lattice of 3 × 3 on the computer screen. Each dot was presented for 1 s, and dots were presented with an interval of 1 s. After the last dot was presented and disappeared, a cue would be presented on the screen to ask the participants to click the positions where the dots had appeared in the same sequence as their appearance. The number of dots ranged from 3 to 7. There was no feedback to participants. The average distance between the position where the dot appeared and the position where participants clicked was calculated and treated as an index of spatial working memory.

Word semantic processing

The format of this task was similar to the one used by Siegel and Ryan (1988) and So and Siegel (1997). Materials in the task were adapted from the language examinations used in China in recent years. In the task, a sentence was presented in the center of the computer screen with a word missing. Participants needed to select one of two candidate words presented beneath the sentence by pressing a left or a right key. The stimulus remained on the screen until the participants responded. The formal test included 120 trials and was limited to 5 min.

For each of the time-limited tasks (i.e., mental rotation, Raven's Progressive Matrices, and word semantic processing), we calculated scores using Guilford formula (Guilford proposed a correction formula "$S = R - W/(n - 1)$" (S: the adjusted number of items that the participants can actually perform without the aid of chance. R: the number of correct responses, W: the number of incorrect responses. n: the number of alternative responses to each item; Guilford, 1936). For the spatial working memory task, as mentioned earlier, the average distance between the position where the dot appeared and the position where participants clicked was calculated. We then subtracted the average distance from 200 to create a score for spatial working memory. For the approximate arithmetic task, we used the formula "$100 - |(PR - EA)/(PR + EA)| \times 100$" to calculate accuracy in approximate arithmetic. PR refers to participant's response and EA the exact answer. Using this formula, accuracy scores in approximate arithmetic would have the theoretical range from 0 to 100.

Data Analysis

Because our sample came from 20 classes, it was necessary to first investigate whether the nested data needed to be analyzed with multilevel models. We used the unconditional means model to compute the intraclass correlation coefficients (ICC) (Peugh and Enders, 2005). The ICC was 0.12 for approximate arithmetic, suggesting significant variability at the between-classroom level. Therefore, we conducted multilevel models by using the MIXED procedure in SPSS for all data analyses. The following equations were used:

$$\text{Level 1}: \text{Score}_{ij} = \beta_{0j} + \beta_{1j}\left(\text{Age}_{ij}\right) + \beta_{2j}\left(\text{Gender}_{ij}\right) + \beta_{3j}\left(\text{Covariates}_{ij}\right) + \gamma_{ij}$$

Where Score_{ij} was the score of approximate arithmetic for participant i in class j, and β_{0j} was the mean score for class j. β_{1j}, β_{2j}, and β_{3j} were the slopes of age, gender and covariates (i.e., scores of various tests) predicting the score within class j. γ_{ij} was the random component of the score for participant i in class j.

$$\text{Level 2}: \quad \beta_{0j} = \gamma_{00} + \gamma_{01}\, Region_{ij} + \mu_{0j}$$

$$\beta_{1j} = \gamma_{10}$$

$$\beta_{2j} = \gamma_{20}$$

$$\beta_{3j} = \gamma_{30}$$

Where β_{0j} was the mean score for class j, γ_{00} was the grand mean score across all classes, γ_{01} was the slope of level-2 variable region predicting the mean score for class j, and μ_{0j} was the random component of the mean score for class j. β_{1j}, β_{2j}, and β_{3j}, were the slopes of age, gender and covariates predicting the mean score for class j.

Combined:

$$Score_{ij} = \gamma_{00} + \gamma_{01}(Region) + \gamma_{10}(Age) + \gamma_{20}(Gender) + \gamma_{30}(Covariates) + \mu_{0j} + \gamma_{ij}$$

Results and discussion

Of the 19840 answers (496 children × 40 trials), 210 (1.1%) were correct exact answers. **Table 2** shows the mean scores and standard deviations of all tasks. **Table 3** shows the inter-task correlations. All correlations were significant.

According to multilevel model analysis, boys outperformed girls in approximate arithmetic and mental rotation, whereas girls outperformed boys in word semantic processing and Raven's Progressive Matrices. There was no gender difference in spatial working memory (**Table 2**).

The analysis showed no differences between older and younger children for all tasks [$b = -1.13$, $t(330) = -0.54$, $p = 0.586$ for symbolic approximate arithmetic; $b = 0.57$, $t(168) = 0.60$, $p = 0.551$ for mental rotation; $b = -0.94$, $t(222) = -1.21$, $p = 0.227$ for word semantic processing; $b = 1.17$, $t(249) = 0.47$, $p = 0.638$ for spatial working memory; $b = 0.95$, $t(216) = 1.51$, $p = 0.133$ for Raven's Progressive Matrices]. In the multilevel model (when classroom effect was considered), no region differences were found for all tasks [$b = -5.49$, $t(18) = -1.61$, $p = 0.125$ for symbolic approximate arithmetic; $b = 0.96$, $t(16) = 0.81$, $p = 0.429$ for mental rotation; $b = -1.42$, $t(21) = -1.41$, $p = 0.172$ for word semantic processing; $b = -4.73$, $t(20) = -1.38$, $p = 0.181$ for spatial working memory; $b = 1.10$, $t(15) = 1.25$, $p = 0.229$ for Raven's Progressive Matrices]. None of the interactions involving gender and approximate arithmetic were significant [$b = 0.12$, $t(477) = 0.03$, $p = 0.979$ for gender × region; $b = 5.26$, $t(479) = 1.06$, $p = 0.288$ for gender × age; $b = -5.37$, $t(476) = -0.079$, $p = 0.431$ for gender × region × age].

Multilevel model analysis showed that after controlling for mental rotation, gender difference in approximate arithmetic disappeared (**Table 4** and **Figure 1**). After controlling for any one of the other measures, however, gender difference

TABLE 2 | Means, standard deviations, and gender differences for all tasks (Experiment 1).

Task	Younger children (ages 11–12)				Older children (13–15)				Tests of gender difference (multilevel model)	
	Beijing		Liuzhou		Beijing		Liuzhou			
	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls	*b*	*t*
Approximate arithmetic	62.2 (20.1)	55.7 (17.6)	53.3 (23.8)	51.0 (17.9)	62.6 (15.2)	60.4 (13.3)	55.3 (22.8)	54.1 (16.4)	− 3.59	t (479.57) = − 2.22*
Mental rotation	21.3 (8.4)	18.3 (9.7)	23.3 (8.0)	19.7 (9.1)	21.9 (9.2)	20.2 (10.7)	23.0 (8.4)	18.9 (8.1)	− 3.48	t (481.51) = − 4.36***
Word semantic processing	27.8 (7.4)	31.3 (7.9)	27.6 (7.9)	29.3 (7.2)	29.1 (7.1)	33.2 (6.4)	27.3 (7.5)	31.2 (6.4)	3.33	t (483.42) = 5.21***
Spatial working memory	153.5 (20.5)	154.3 (15.8)	151.2 (24.3)	149.8 (22.3)	158.2 (12.4)	152.1 (19.2)	148.5 (27.7)	149.1 (28.4)	1.49	t (482.46) = 0.74
Raven's Progressive Matrices	19.9 (7.1)	19.8 (6.2)	20.2 (7.6)	21.7 (5.9)	18.8 (6.2)	20.9 (5.9)	19.7 (4.7)	21.3 (4.5)	1.10	t (479.32) = 2.14*

$^{*}p < 0.05$; $^{***}p < 0.001$; Gender was coded to 0 for boys and 1 for girls.

TABLE 3 | Correlations among all tasks (Experiment 1).

Tasks	1	2	3	4
1 Approximate arithmetic	–			
2 Mental rotation	0.16**	–		
3 Word semantic processing	0.21***	0.12**	–	
4 Spatial working memory	0.31***	0.20***	0.16***	–
5 Raven's Progressive Matrices	0.14**	0.20***	0.12**	0.13**

$^{**}p < 0.01$; $^{***}p < 0.001$.

TABLE 4 | Results from multilevel modeling showing gender differences in approximate arithmetic (Experiment 1).

Covariate	Approximate arithmetic		
	b	*SE* × *b*	*t*
None	–3.59	1.61	$t(479.57) = -2.22^{*}$
Mental rotation	–2.73	1.64	$t(481.02) = -1.66$
Word semantic processing	–5.02	1.64	$t(477.95) = -3.06^{**}$
Spatial working memory	–3.21	1.57	$t(479.47) = -2.05^{*}$
Raven's Progressive Matrices	–4.02	1.61	$t(478.10) = -2.50^{*}$

$^{*}p < 0.05$; $^{**}p < 0.01$; Gender was coded as 0 for boys and 1 for girls. SE: standard error.

in approximate arithmetic still remained (**Table 4**). Even after controlling for all the other measures simultaneously, gender difference in approximate arithmetic remained (**Figure 1**), $b = -4.74$, $t(476.27) = -2.97$, $p = 0.003$.

We further examined whether mental rotation could explain the gender differences in other tasks. The results showed that these gender differences could not be explained by mental rotation: including gender difference in word semantic processing, $b = 3.76$, $t(485.73) = 5.82$, $p < 0.0001$; and in Raven's Progressive Matrices: $b = 1.57$, $t(482.95) = 3.05$, $p = 0.002$.

To further examine whether gender differences were consistent across the four arithmetic operations (i.e., addition, subtraction, multiplication, and division), we re-conducted the multilevel model analysis, with arithmetic operation as a within-subject variable and gender, age, and region as between-subject variables. Results showed that gender, age, and region had significant main effects, $b = -2.80$, $t(1883) = -2.62$, $p = 0.009$ for gender, $b = 2.70$, $t(1883) = 2.41$, $p = 0.016$ for age, and $b = 6.65$, $t(1883) = 6.03$, $p < 0.001$ for region. No significant interaction effects were found among the variables, $b = 0.11$, $t(1883) = 0.10$, $p = 0.920$. That is, boys outperformed girls for each operation (**Figure 2**). Controlling for scores on the mental rotation task, gender difference in approximate arithmetic was no longer significant, $b = -1.71$, $t(1871) = -1.59$, $p = 0.113$.

The current investigation focused on children from primary and secondary schools in two regions of China. As expected, boys performed better than girls on approximate arithmetic. When we controlled for the three-dimensional mental rotation task, gender difference in approximate arithmetic disappeared. However, after controlling for the other cognitive tasks, gender difference in approximate arithmetic remained.

To our knowledge, little research has been conducted to explore the development of gender difference in arithmetic. Thus, the second experiment was conducted to investigate whether

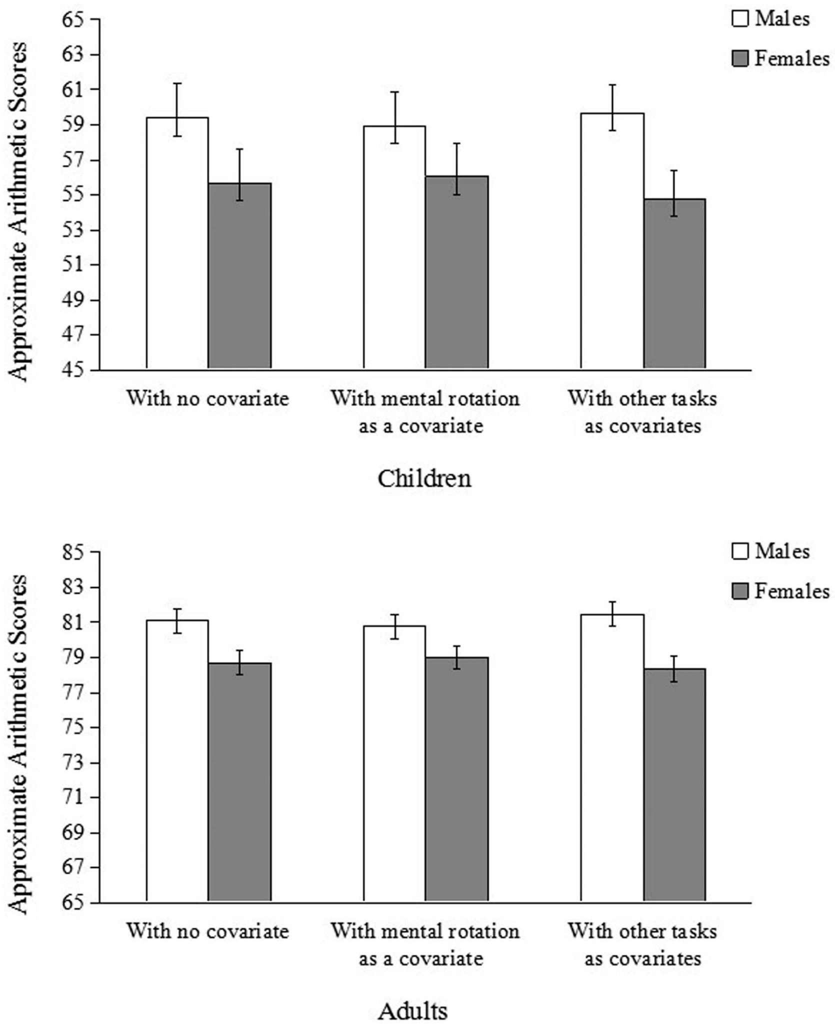


FIGURE 1 | Average scores in approximate arithmetic of children in Experiment 1 (top) and adults in Experiment 2 (bottom). The bars on the left show the means without controlling for covariate; the bars in the middle show the adjusted means after controlling for performance on the mental rotation task only; and the bars on the right show the adjusted means after controlling for performance on all other tasks except mental rotation task. Error bars indicate standard errors.

the gender differences in approximate arithmetic would exist in adults, and whether the same cognitive mechanisms would explain such gender differences.

EXPERIMENT 2

Materials and Methods

Participants

The adult sample of 554 college students (250 males and 304 females, 18.0–21.9 years old) was recruited from Harbin Normal University and Southwest University. It included 292 students majoring in sciences such as chemistry, computer science, biology, mathematics, and physics, and the others majoring in arts and humanities such as Chinese literature, education, history, and political science. All participants were native Chinese speakers and had normal or corrected-to-normal eyesight. They gave written consent form after procedure was fully explained. They received 30 RMB (about US$ 4.8) as a compensation for their time.

Procedure and Tasks

The procedure and tasks were the same as in Experiment 1.

Data Analysis

Similar multilevel models as in Experiment 1 were used in the current data analysis. The main equation was as follows:

$$Score_{ij} = \gamma_{00} + \gamma_{01}(Major) + \gamma_{10}(Gender) + \gamma_{20}(Covariates) + \mu_{0j} + \gamma_{ij}$$

Results and Discussion

Ten participants (seven males and three females) were deleted as outliers because their approximate arithmetic scores were 3

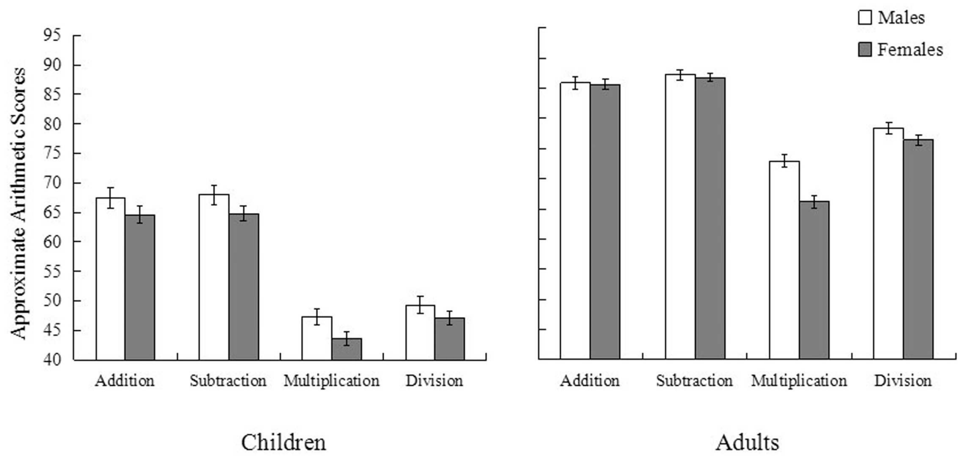


FIGURE 2 | Mean scores of approximate arithmetic (addition, subtraction, multiplication, and division) of children in Experiment 1 (left) and adults in Experiment 2 (right). Error bars indicate standard errors.

SD above or below the group mean. Of the remaining 21760 responses (544 participants × 40 trials), 1481 responses (6.8%) were exact answers. **Table 5** shows the mean scores and standard deviations of all tasks. **Table 6** shows the inter-task correlations. All correlations were significant.

Males outperformed females in approximate arithmetic and mental rotation, whereas females outperformed males in word semantic processing. There was no gender difference in spatial working memory and Raven's Progressive Matrices. Science students were superior to arts students in approximate arithmetic, $b = 2.43$, $t(551) = 2.55$, $p = 0.011$. No difference across majors was found for other tasks: Raven's Progressive Matrices, $b = 0.52$, $t(6.48) = 0.59$, $p = 0.577$; spatial working memory, $b = 2.40$, $t(4.51) = 1.21$, $p = 0.286$; word semantic processing, $b = -0.86$, $t(6.36) = -0.63$, $p = 0.550$. The interaction between gender and major was not significant [$b = -0.70$, $t(550) = -0.37$, $p = 0.715$].

Results showed that after controlling for mental rotation, gender difference in approximate arithmetic disappeared (**Table 7** and **Figure 1**). But after controlling for other tasks, gender difference in approximate arithmetic remained (**Table 7** and **Figure 1**). We further examined whether mental rotation could explain gender differences in performance on other tasks. The results showed that gender differences in word semantic processing could not be explained by mental rotation, $b = -3.32$, $t(549.87) = -5.62$, $p < 0.001$.

To examine whether other cognitive tasks except for mental rotation could explain gender difference in approximate arithmetic, we controlled for spatial working memory, word semantic processing, and Raven' Progressive Matrices simultaneously. Gender difference remained, $b = 2.81$, $t(548) = 2.98$, $p = 0.003$.

To further examine whether gender differences were consistent across the four arithmetic operations (i.e., addition, subtraction, multiplication, and division), we conducted repeated measure ANOVA with gender and students' major as between-subject variables. Results showed that gender [$b = 3.01$, $t(2006) = 2.19$, $p = 0.029$] and major [$b = 4.02$, $t(2006) = 2.86$, $p = 0.004$] had significant main effects but no significant interaction [$b = 0.72$, $t(2006) = 1.15$, $p = 0.250$]. Males outperformed females, and science students outperformed arts and humanities students on each operation. Results showed that after controlling for scores on the mental rotation task, gender differences in approximate arithmetic disappeared [$b = 1.08$, $t(2008) = 1.51$, $p = 0.132$].

In Experiment 2, we found similar results as those found with children in Experiment 1. Males performed better than females in approximate arithmetic. Controlling for the mental

TABLE 5 | Means, standard deviations, and gender differences for all tasks (Experiment 2).

Tasks	Arts		Science		Gender difference
	Males	Females	Males	Females	*F*
Approximate arithmetic	79.9 (12.8)	77.5 (10.2)	81.9 (12.0)	80.2 (9.7)	– 2.11*
Mental rotation	27.4 (8.0)	24.5 (8.4)	28.9 (9.6)	26.3 (7.9)	– 3.71***
Word semantic processing	36.2 (8.6)	40.6 (6.4)	36.0 (6.5)	38.3 (6.3)	4.95***
Spatial working memory	149.5 (27.5)	153.8 (18.7)	154.1 (22.6)	154.5 (20.2)	1.16
Raven's Progressive Matrices	23.1 (7.4)	23.3 (7.0)	22.8 (6.6)	23.8 (5.7)	0.94

*$p < 0.05$; ***$p < 0.001$.

TABLE 6 | Correlations among all tasks (Experiment 2).

Tasks		1	2	3	4
1	Approximate arithmetic	–			
2	Mental rotation	0.17***	–		
3	Word semantic processing	0.10*	0.12**	–	
4	Spatial working memory	0.18***	0.22***	0.13**	–
5	Raven's Progressive Matrices	0.22***	0.25***	0.24***	0.26***

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

TABLE 7 | Results from multilevel modeling showing gender differences in approximate arithmetic (Experiment 2).

Covariate	Approximate arithmetic		
	b	*SE* × *b*	*t*
None	–2.01	0.95	$t(551) = -2.11$*
Mental rotation	–1.50	0.96	$t(550) = -1.57$
Word semantic processing	–2.78	0.97	$t(550) = -2.87$**
Spatial working memory	–2.22	0.94	$t(550) = -2.37$*
Raven's Progressive Matrices	–2.26	0.93	$t(550) = -2.43$*

*$p < 0.05$; **$p < 0.01$; Gender was coded as 0 for boys and 1 for girls.

rotation task, gender difference disappeared; but controlling for the other cognitive tasks, males still had an advantage over females.

DISCUSSION

The goal of the current study was to examine gender differences in approximate arithmetic. Our results showed that males performed better in approximate arithmetic than did females, and this gender difference disappeared after controlling for spatial ability.

Cognitive Mechanism of Approximate Arithmetic

Approximate arithmetic has a high correlation with spatial ability. Behavioral studies showed that participants represented numerical magnitude on the mental number line in the symbolic and non-symbolic approximate arithmetic tasks (McCrink and Wynn, 2004; Knops et al., 2009) and that the mental number line has a spatial property (Dehaene et al., 1993). Neuroimaging studies have shown that approximate arithmetic and spatial processing share a similar brain basis, typically involving the parietal cortex (Dehaene et al., 1999; Stanescu-Cosson et al., 2000; Lemer et al., 2003). Compared to the non-mathematician control group, mathematicians excelled in approximate arithmetic (Dowker, 1992; Dowker et al., 1996) and their parietal cortex (a brain region involved in spatial processing, (Corbetta et al., 1998; Kosslyn et al., 1998; Gitelman et al., 1999; Zacks et al., 1999) showed greater gray matter density (Aydin et al., 2007).

Approximate arithmetic relies on spatial ability, but not on language ability. In a study of language and approximate arithmetic (Spelke and Tsivkin, 2001), bilingual students were trained to perform exact and approximate arithmetic problems in two languages. Results showed that, for exact arithmetic, the language used for training mattered, but for approximate arithmetic, the language used for training did not matter. A recent study also found that children with language impairment had lower accuracy in exact arithmetic, but they had similar performance in approximate arithmetic as compared to the normal children (Nys et al., 2013). From a developmental perspective, approximate arithmetic precedes exact arithmetic because the latter relies on number symbols as language processing. For example, preschool children can perform approximate arithmetic but not exact arithmetic with the same numbers (Gilmore et al., 2007). Similarly, Amazonian indigenes can perform approximate arithmetic, but not exact arithmetic, due to their lack of a formal language-based number system (Pica et al., 2004).

Gender Difference in Spatial Ability

Many studies have shown that males outperform females on spatial ability tasks, especially the mental rotation tasks (Voyer et al., 1995). Gender difference in spatial ability emerges as early as about 3–5 months of age (Moore and Johnson, 2008; Quinn and Liben, 2008) and is evident to the age of 95 years (De Frias et al., 2006; Tran and Formann, 2008). Moreover, based on data from more than 200,000 subjects from 53 nations, Lippa et al. (2010) showed that males performed better than females on visuospatial tasks.

Neuroimaging studies have showed that males have a larger parietal lobule (Frederikse et al., 1999), which could explain males' superiority in spatial ability (Koscik et al., 2009). The right parietal cortex is involved in visuospatial processing during arithmetic tasks (see Arsalidou and Taylor, 2011, for a meta-analysis). For example, when the right parietal cortex was suppressed, participants could not perform spatial tasks (Bjoertomt et al., 2002; Rosenthal et al., 2009). Interestingly, when males perform the spatial tasks, their bilateral hemispheres are involved, whereas females tend to rely on their right hemisphere (Gur et al., 2000; Clements et al., 2006). Taken together, it is plausible that males' larger parietal cortex (especially in the right hemisphere, Caviness et al., 1996; Baibakov and Fedorov, 2010) accounts for their better performance on spatial tasks (Moore and Johnson, 2008; Quinn and Liben, 2008).

In sum, our study showed consistent gender differences in approximate arithmetic favoring males across age groups and identified gender differences in spatial ability as a potential cognitive mechanism. These results have important implications for later development of mathematical cognition. Future research should pay more attention to the understudied approximate arithmetic, which may be important for advanced mathematics.

AUTHOR CONTRIBUTIONS

WW: designed the experiment, collected and analyzed the data and drafted the manuscript; CC: revised the manuscript; XZ: designed the experiment, revised the manuscript.

ACKNOWLEDGMENTS

This research was supported by the National Key Basic Research Program of China (No. 2014CB846100), by three grants from the Natural Science Foundation of China (Nos. 31271187, 31221003 and 31500902) and by grant from Ministry of Education of the PRC (No. mjzxyb1412).

REFERENCES

Arsalidou, M., and Taylor, M. J. (2011). Is 2+2=4? Meta-analyses of brain areas needed for numbers and calculations. *Neuroimage* 54, 2382–2393. doi: 10.1016/j.neuroimage.2010.10.009

Aydin, K., Ucar, A., Oguz, K. K., Okur, O. O., Agayev, A., Unal, Z., et al. (2007). Increased gray matter density in the parietal cortex of mathematicians: a voxel-based morphometry study. *Am. J. Neuroradiol.* 28, 1859–1864. doi: 10.3174/ajnr.A0696

Baibakov, S. E., and Fedorov, V. P. (2010). Morphometric characteristics of the brain in children aged one year (magnetic resonance tomography data). *Neurosci. Behav. Physiol.* 40, 69–72. doi: 10.1007/s11055-009-9224-5

Bjoertomt, O., Cowey, A., and Walsh, V. (2002). Spatial neglect in near and far space investigated by repetitive transcranial magnetic stimulation. *Brain* 125, 2012–2022. doi: 10.1093/brain/awf211

Caviness, V. S. Jr., Kennedy, D. N., Richelme, C., Rademacher, J., and Filipek, P. A. (1996). The human brain age 7-11 years: a volumetric analysis based on magnetic resonance images. *Cereb. Cortex* 6, 726–736. doi: 10.1093/cercor/6.5.726

Ceci, S. J., Williams, W. M., and Barnett, S. M. (2009). Women's underrepresentation in science: sociocultural and biological considerations. *Psychol. Bull.* 135:218. doi: 10.1037/a0014412

Clements, A. M., Rimrodt, S. L., Abel, J. R., Blankner, J. G., Mostofsky, S. H., Pekar, J. J., et al. (2006). Sex differences in cerebral laterality of language and visuospatial processing. *Brain Lang.* 98, 150–158. doi: 10.1016/j.bandl.2006.04.007

Corbetta, M., Akbudak, E., Conturo, T. E., Snyder, A. Z., Ollinger, J. M., Drury, H. A., et al. (1998). A common network of functional areas for attention and eye movements. *Neuron* 21, 761–773. doi: 10.1016/S0896-6273(00)80593-0

De Frias, C. M., Nilsson, L.-G., and Herlitz, A. (2006). Sex differences in cognition are stable over a 10-year period in adulthood and old age. *Aging Neuropsychol. Cogn.* 13, 574–587. doi: 10.1080/13825580600678418

Dehaene, S., Bossini, S., and Giraux, P. (1993). The mental representation of parity and number magnitude. *J. Exp. Psychol.* 122, 371–396. doi: 10.1037/0096-3445.122.3.371

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., and Tsivkin, S. (1999). Sources of mathematical thinking: behavioral and brain-imaging evidence. *Science* 284, 970–974. doi: 10.1126/science.284.5416.970

Dowker, A. (1992). Computational estimation strategies of professional mathematicicans. *J. Res. Math. Educ.* 23, 45–55. doi: 10.2307/749163

Dowker, A., Flood, A., Griffiths, H., Harriss, L., and Hook, L. (1996). Estimation strategies of four groups. *Math. Cogn.* 2, 113–135. doi: 10.1080/135467996387499

Else-Quest, N. M., Hyde, J. S., and Linn, M. C. (2010). Cross-national patterns of gender differences in mathematics: a meta-analysis. *Psychol. Bull.* 136:103. doi: 10.1037/a0018053

Frederikse, M. E., Lu, A., Aylward, E., Barta, P., and Pearlson, G. (1999). Sex differences in the inferior parietal lobule. *Cereb. Cortex* 9, 896–901. doi: 10.1093/cercor/9.8.896

Gilmore, C. K., McCarthy, S. E., and Spelke, E. S. (2007). Symbolic arithmetic knowledge without instruction. *Nature* 447, 589–591. doi: 10.1038/nature05850

Gitelman, D. R., Nobre, A. C., Parrish, T. B., LaBar, K. S., Kim, Y. H., Meyer, J. R., et al. (1999). A large-scale distributed network for covert spatial attention Further anatomical delineation based on stringent behavioural and cognitive controls. *Brain* 122, 1093–1106. doi: 10.1093/brain/122.6.1093

Guilford, J. P. (1936). The determination of item difficulty when chance success is a factor. *Psychometrika* 1, 259–264. doi: 10.1007/BF02287877

Guiso, L., Ferdinando, M., Paola, S., and Zingales, L. (2008). Culture, gender, and math. *Science* 320, 1164–1165. doi: 10.1126/science.1154094

Gur, R. C., Alsop, D., Glahn, D., Petty, R., Swanson, C. L., Maldjian, J. A., et al. (2000). An fMRI study of sex differences in regional activation to a verbal and a spatial task. *Brain Lang.* 74, 157–170. doi: 10.1006/brln.2000.2325

Halpern, D. F., Benbow, C. P., Geary, D. C., Gur, R. C., Hyde, J. S., and Gernsbacher, M. A. (2007). The science of sex differences in science and mathematics. *Psychol. Sci. Public Interest* 8, 1–51. doi: 10.1111/j.1529-1006.2007.00032.x

Hyde, J. S., Lindberg, S. M., Linn, M. C., Ellis, A. B., and Williams, C. C. (2008). Gender similarities characterize math performance. *Science* 321, 494–495. doi: 10.1126/science.1160364

Hyde, J. S., and Linn, M. C. (2006). Gender similarities in mathematics and science. *Science* 314, 599–600. doi: 10.1126/science.1132154

Knops, A., Viarouge, A., and Dehaene, S. (2009). Dynamic representations underlying symbolic and nonsymbolic calculation: evidence from the operational momentum effect. *Attent. Percept. Psychophys.* 71, 803–821. doi: 10.3758/APP.71.4.803

Koscik, T., O'Leary, D., Moser, D. J., Andreasen, N. C., and Nopoulos, P. (2009). Sex differences in parietal lobe morphology: relationship to mental rotation performance. *Brain Cogn.* 69, 451–459. doi: 10.1016/j.bandc.2008.09.004

Kosslyn, S. M., DiGirolamo, G. J., Thompson, W. L., and Alpert, N. M. (1998). Mental rotation of objects versus hands: neural mechanisms revealed by positron emission tomography. *Psychophysiology* 35, 151–161. doi: 10.1111/1469-8986.3520151

Kovas, Y. H., Claire, M. A., Petrill, S. A., and Plomin, R. (2007). Mathematical ability of 10-Year-old boys and girls genetic and environmental etiology of typical and low performance. *J. Learn. Disabil.* 40, 554–567. doi: 10.1177/00222194070400060601

Lemer, C. D., Stanislas, S. E., and Cohen, L. (2003). Approximate quantities and exact number words: dissociable systems. *Neuropsychologia* 41, 1942–1958. doi: 10.1016/S0028-3932(03)00123-4

Levine, D. R. (1982). Strategy use and estimation ability of college students. *J. Res. Math. Educ.* 13, 350–359. doi: 10.2307/749010

Linn, M. C., and Hyde, J. S. (1989). Gender, mathematics, and science. *Educ. Res.* 18, 17–27. doi: 10.3102/0013189X018008017

Lippa, R. A., Collaer, M. L., and Peters, M. (2010). Sex differences in mental rotation and line angle judgments are positively associated with gender equality and economic development across 53 nations. *Arch. Sex. Behav.* 39, 990–997. doi: 10.1007/s10508-008-9460-8

McCrink, K., and Wynn, K. (2004). Large-number addition and subtraction by 9-month-old infants. *Psychol. Sci.* 15, 776–781. doi: 10.1111/j.0956-7976.2004.00755.x

Moore, D. S., and Johnson, S. P. (2008). Mental rotation in human infants a sex difference. *Psychol. Sci.* 19, 1063–1066. doi: 10.1111/j.1467-9280.2008.02200.x

Nosek, B. A., Smyth, F. L., Sriram, N., Lindner, N. M., Devos, T., Ayala, A., et al. (2009). National differences in gender–science stereotypes predict national sex differences in science and math achievement. *Proc. Natl. Acad. Sci. U.S.A.* 106, 10593–10597. doi: 10.1073/pnas.0809921106

Nys, J., Content, A., and Leybaert, J. (2013). Impact of language abilities on exact and approxiamte number skills development: evidence from children with specific language impairment. *J. Speech Lang. Hear Res.* 56, 956–970. doi: 10.1044/1092-4388(2012/10-0229)

Peugh, J. L., and Enders, C. K. (2005). Using the SPSS mixed procedure to fit cross-sectional and longitudinal multilevel models. *Educ. Psychol. Measur.* 65:717. doi: 10.1177/0013164405278558

Pica, P., Lemer, C., Izard, V., and Dehaene, S. (2004). Exact and approximate arithmetic in an Amazonian indigene group. *Science* 306, 499–503. doi: 10.1126/science.1102085

Quinn, P. C., and Liben, L. S. (2008). A sex difference in mental rotation in young infants. *Psychol. Sci.* 19, 1067–1070. doi: 10.1111/j.1467-9280.2008.02201.x

Raven, J. (1998). *Manual for Raven's Progressive Matrices and Vocabulary Scales*. Oxford: Oxford Psychologists Press.

Rosenthal, C. R., Roche-Kelly, E. E., Husain, M., and Kennard, C. (2009). Response-dependent contributions of human primary motor cortex and angular gyrus to manual and perceptual sequence learning. *J. Neurosci.* 29, 15115–15125. doi: 10.1523/JNEUROSCI.2603-09.2009

Rubenstein, R. N. (1985). Computational estimation and related mathematical skills. *J. Res. Math. Educ.* 16, 106–119. doi: 10.2307/748368

Shen, H. (2013). Inequality quantified: mind the gender gap. *Nature* 495, 22–24. doi: 10.1038/495022a

Shepard, R. N., and Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science* 171, 701–703. doi: 10.1126/science.171.3972.701

Siegel, L. S., and Ryan, E. B. (1988). Development of grammatical-sensitivity, phonological, and short-term memory skills in normally achieving and learning disabled children. *Dev. Psychol.* 24, 28–37. doi: 10.1037/0012-1649.24.1.28

So, D., and Siegel, L. S. (1997). Learning to read Chinese: semantic, syntactic, phonological and working memory skills in normally achieving and poor Chinese readers. *Read. Writ.* 9, 1–21. doi: 10.1023/A:1007963513853

Spelke, E. S. (2005). Sex differences in intrinsic aptitude for mathematics and science? A critical review. *Am. Psychol. Am. Psychol.* 60, 950–958. doi: 10.1037/0003-066X.60.9.950

Spelke, E. S., and Tsivkin, S. (2001). Language and number: a bilingual training study. *Cognition* 78, 45–88. doi: 10.1016/S0010-0277(00)00108-6

Stanescu-Cosson, R., Pinel, P., van De Moortele, P. F., Le Bihan, D., Cohen, L., and Dehaene, S. (2000). Understanding dissociations in dyscalculia A brain imaging study of the impact of number size on the cerebral networks for exact and approximate calculation. *Brain* 123, 2240–2255. doi: 10.1093/brain/123.11.2240

Tran, U. S., and Formann, A. K. (2008). Piaget's water-level tasks: performance across the lifespan with emphasis on the elderly. *Pers. Individ. Differ.* 45, 232–237. doi: 10.1016/j.paid.2008.04.004

Voyer, D., Voyer, S., and Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: a meta-analysis and consideration of critical variables. *Psychol. Bull.* 117, 250–270. doi: 10.1037/0033-2909.117.2.250

Wei, W., Lu, H., Zhao, H., Chen, C., Dong, Q., and Zhou, X. (2012). Gender differences in children's arithmetic performance are accounted for by gender differences in language abilities. *Psychol. Sci.* 23, 320–330. doi: 10.1177/0956797611427168

Zacks, J., Rypma, B., Gabrieli, J. D., Tversky, B., and Glover, G. H. (1999). Imagined transformations of bodies: an fMRI investigation. *Neuropsychologia* 37, 1029–1040. doi: 10.1016/S0028-3932(99)00012-3

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

frontiers in Psychology

ORIGINAL RESEARCH
published: 17 June 2016
doi: 10.3389/fpsyg.2016.00892

Neural Correlates of Math Gains Vary Depending on Parental Socioeconomic Status (SES)

Özlem Ece Demir-Lira[1,2]*, Jérôme Prado[3] and James R. Booth[1,4]

[1] Department of Communication Sciences and Disorders, Northwestern University, Evanston, IL, USA, [2] Department of Psychology, University of Chicago, Chicago, IL, USA, [3] Institut des Sciences Cognitives Marc Jeannerod, UMR 5304, Centre National de la Recherche Scientifique – Université de Lyon, Bron, France, [4] Department of Communication Sciences and Disorders, The University of Texas at Austin, Austin, TX, USA

We used functional magnetic resonance imaging (fMRI) to examine the neural predictors of math development, and asked whether these predictors vary as a function of parental socioeconomic status (SES) in children ranging in age from 8 to 13 years. We independently localized brain regions subserving verbal versus spatial processing in order to characterize relations between activation in these regions during an arithmetic task and long-term change in math skill (up to 3 years). Neural predictors of math gains encompassed brain regions subserving both verbal and spatial processing, but the relation between relative reliance on these regions and math skill growth varied depending on parental SES. Activity in an area of the left inferior frontal gyrus (IFG) identified by the verbal localizer was related to greater growth in math skill at the higher end of the SES continuum, but lesser improvements at the lower end. Activity in an area of the right superior parietal cortex identified by the spatial localizer was related to greater growth in math skill at the lower end of the SES continuum, but lesser improvements at the higher end. Results highlight early neural mechanisms as possible neuromarkers of long-term arithmetic learning and suggest that neural predictors of math gains vary with parental SES.

Keywords: socioeconomic status, arithmetic, subtraction, fMRI, longitudinal, children

OPEN ACCESS

Edited by:
Bert De Smedt, Katholieke Universiteit Leuven, Belgium

Reviewed by:
Gavin Price, The University of Western Ontario, Canada
Tanya Marie Evans, Stanford University, USA

****Correspondence:***
Özlem Ece Demir-Lira
ece@uchicago.edu

Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *12 February 2016*
Accepted: *30 May 2016*
Published: *17 June 2016*

Citation:
Demir-Lira ÖE, Prado J and Booth JR (2016) Neural Correlates of Math Gains Vary Depending on Parental Socioeconomic Status (SES). Front. Psychol. 7:892. doi: 10.3389/fpsyg.2016.00892

INTRODUCTION

Children from disadvantaged backgrounds as a group fall behind their peers in math achievement and math skill growth starting from the early grades (Pungello et al., 1996; Cheadle, 2008; National Center for Education Statistics, 2011). However, some of the children from disadvantaged backgrounds exhibit developmental trajectories that are similar to their peers from more advantaged backgrounds. Whether these children recruit the same neural systems as their peers or recruit alternative systems is not known. In the present study, we used functional magnetic resonance imaging (fMRI) to examine the neural predictors of long-term change in children's math skill, and asked whether these predictors vary as a function of parental socioeconomic status (SES). Identifying early predictors of math skill growth in children from varying backgrounds might aid our understanding of the reasons behind individual differences in math skill growth. Increased understanding of the mechanisms behind these individual differences in turn might have implications for decreasing the achievement gap.

Mathematics is built upon earlier developing, existing verbal and spatial skills (Dehaene et al., 1999). In solving arithmetical problems, adults and children rely upon a wide network of brain regions, including regions that underlie verbal representations and processing, such as left lateral temporal cortex and inferior frontal cortex, and upon brain regions that underlie spatial representations and processing, such as right intra-parietal sulcus (IPS), precuneus, and posterior superior parietal cortex (Lee, 2000; Dehaene et al., 2003; Schmithorst and Brown, 2004; Andres et al., 2011; Prado et al., 2011; Menon, 2013). In the context of arithmetic processing, activation in verbal networks have been linked to retrieval of arithmetic facts and executive control (Prado et al., 2011), whereas activation in spatial networks have been linked to modality independent representations and procedural manipulation of numerical magnitude (De Smedt et al., 2011).

Although studies have found these regions to be engaged in most participants, activity within this network may vary as a function of task and children's concurrent math skill (Zago et al., 2001; Grabner et al., 2007; Rosenberg-Lee et al., 2009; Cho et al., 2011; De Smedt et al., 2011). For example, De Smedt et al. (2011) showed that 10- to 12-year-old children with lower math skill activated the right intraparietal sulcus to a greater extent than children with higher skill for small addition and subtraction problems. The results were interpreted to suggest that low skill children might use procedural strategies (and rely on spatial neural representations), whereas higher skill children might retrieve arithmetical information from memory (and rely on verbal neural representations).

How the neural differences relate to growth in arithmetic skills is unclear. Some studies have shown that structural and intrinsic functional connectivity predicts math gains (Evans et al., 2015; Jolles et al., 2015). For example, a recent study reported that short-term arithmetic skill gains (8 weeks) after an intervention could be predicted by (1) gray matter volume in the hippocampus and (2) functional connectivity between hippocampus and dorsolateral and ventrolateral prefrontal cortices (as well as basal ganglia), highlighting the role of the hippocampus and memory in the development of arithmetic skills (Supekar et al., 2013). In a longitudinal study, improvement in arithmetic retrieval fluency over a 1-year period was related to hippocampus-neocortical connectivity (Qin et al., 2014). Here, for the first time, we examine the task-based functional neural predictors of long-term change in math skill, i.e., up to 3 years. Importantly, our main focus is on if the neural predictors of math skill growth vary along the SES gradient.

SES-related differences in mathematics are larger on verbal aspects of mathematics, such as verbally presented number combinations, than on spatial aspects, such as non-verbal calculations with disks (Jordan and Levine, 2009). SES-related differences in children's verbal skills are well described and appear to be more robust than differences in spatial skills in other domains as well (Hart and Risley, 1995; Noble et al., 2007). In a recent neuroimaging study, we showed that the neural underpinnings of arithmetic processing vary as a function of SES and children's concurrent math skill level (Demir et al., 2015). Reliance on brain regions that support verbal representations (i.e., middle temporal gyrus, MTG) was related to concurrent math skill to a greater extent for higher than lower SES children. On the contrary, reliance on brain regions that support spatial representations (i.e., IPS) were related to concurrent math skill to a greater extent for lower than higher SES children. Importantly, these differences were observed in a sample where a normative range of parental SES was represented. These results suggest that depending on their parental SES, children might develop adaptations and recruit alternative neural networks to perform at par with their peers.

This previous study left open the question of whether the neural networks that predict growth prospectively vary as function of SES and whether these are the same networks that are concurrently predictive of skill? In the present study, we asked how children's early reliance on verbal and spatial neural systems during elementary arithmetic predicts math skill change, and importantly whether the neural systems that predict change vary as a function of SES. To address these questions, we measured brain activity of 8- to 13-year-old children during a single-digit subtraction task, as well as during verbal and spatial localizer tasks. We administered a standardized behavioral measure of math skill before scanning and up to 3 years later (Woodcock et al., 2001). We measured parental SES with parental education and occupation information. We specifically tested if in line with our previous findings, reliance on verbal neural systems would predict math skill growth for higher SES children, whereas reliance on spatial neural systems would predict math skill growth for lower SES children.

We used functional localizer tasks to identify the reliance on brain systems underlying verbal and spatial mechanisms during subtraction. We used a word rhyming task as our verbal localizer and a non-symbolic, dot comparison task as our spatial localizer. Previous literature showed that this word rhyming task taps into verbal representations and successfully localizes verbal neural systems in left temporo-parietal and inferior frontal cortices (Booth, 2010; Prado et al., 2011, 2014). Previous literature showed that this dot comparison task taps into spatio-numerical representations and successfully localizes regions in right intraparietal sulcus, superior parietal lobule and precuneus (Prado et al., 2011, 2014). Importantly, performance on tasks similar to our verbal and spatial localizer tasks relate to mathematical skill, suggesting an overlap between the neural basis of our localizers and mathematical performance (Siegel and Linder, 1984; Hecht et al., 2001; Halberda et al., 2008; Simmons et al., 2008; Krajewski and Schneider, 2009; Piazza et al., 2010).

MATERIALS AND METHODS

Participants

Forty-one children were recruited from schools in the greater Chicago area to participate in the study[1]. All children (1) were native English speakers, (2) were free of past or present neurological or psychiatric disorders, (3) had no history of

[1]Fifteen of the children included in the current study overlapped with the previous Demir et al. (2015) study examining concurrent relations between math skill and parental SES and neural basis of arithmetic performance.

reading, oral language, or attention deficits, and (4) scored higher than 80 standard score on full scale IQ as measured by Wechsler Abbreviated Scale of Intelligence (WASI; Weschler, 1999). Data from eight participants were excluded because of excessive movement in the scanner (see criteria below, $n = 6$), low behavioral accuracy in the scanner (i.e., lower than 40% in the arithmetic and localizer tasks) and/or response bias in the scanner (i.e., false alarm to misses ratio greater than 2 and false alarm rate greater than 50%, $n = 2$). The remaining 33 participants (20 females) were included in the analyses. At the beginning of the study (T1) children were from 8 to 13 years of age (mean age = 10.9, $SD = 1.5$, range = 8–13.8). At the second visit (T2), children were from 11 to 16 years of age (mean age = 13.4, $SD = 1.5$, range = 10.6–16.1). Written consent was obtained from the children and their parents/guardians. All experimental procedures were approved by the Institutional Review Board at Northwestern University.

Standardized Measures

Children were administered standardized measures to assess their intellectual and mathematical abilities on entering the study (T1) and after a follow-up period of 2.5 years ($SD = 0.16$, range = 2.2–2.8) (T2). We measured IQ by the Verbal (Vocabulary, Similarities) and Performance (Block Design, Matrix Reasoning) subtests of the WASI (Weschler, 1999). Mathematical skill was assessed by the Math Fluency subtest of the Woodcock-Johnson III Tests of Achievement (WJ-III, Woodcock et al., 2001). The Math Fluency subtest requires children to solve as many simple addition, subtraction, and multiplication problems as possible within a 3-min period. The difference in raw score between T1 and T2 was 21 points ($SD = 14.2$). **Table 1** summarizes children's performance on standardized tests at T1 and T2.

Socioeconomic Status

Parental SES information was collected on entering the study (T1). A widely-used measure of SES, the Hollingshead Index, based on primary caregiver education and occupation was used as our measure of child SES (Hollingshead, 1975; Adams and Weakliem, 2011). The education level of the primary caregivers was measured categorically with values ranging between 1 (less than 7th grade) to 7 (graduate degree). The average Hollingshead education score for our sample was 6 ($SD = 0.8$), with a range from 4.5 to 7 years, corresponding to a college or associates degree. The occupation level of the primary caregivers was measured categorically with values ranging between 1 (farm laborer, menial service worker, student, housewife) and 9 (higher executive, large business owner, major professional). The average Hollingshead occupation score was 6 ($SD = 2.3$), with a range from 1 to 9, corresponding to technician, semi-professional or small business owner. Following Hollingshead, SES was calculated using the formula (Occupation × 7) + (Education × 4), ($M = 50.9$, $SD = 14.3$). For 24 children both mother and father were primary caregivers, whereas for nine children mother was the primary caregiver. For children with dual caregivers, average education and highest occupation level was used. For the remaining, the education and occupation information of the primary caregiver was used. Average primary caregiver education and occupation were highly correlated with each other, $r = 0.74$, $p < 0.04$.

TABLE 1 | Means and SDs for behavioral measures.

	T1		T2	
	Mean	*SD*	Mean	*SD*
IQ (Standardized)	118.1	13.8	120.7	14.1
Math fluency (Standardized)	97.1	15.0	94.1	13.9
Math fluency (Raw)	65.8	24.7	85.7	25.2
Subtraction accuracy	83.3%	17.3%	–	–
Subtraction RT	1172	295	–	–
Verbal localizer accuracy	85.5%	11.0%	–	–
Verbal localizer RT	1280	214	–	–
Spatial localizer accuracy	87.6%	11.9%	–	–
Spatial localizer RT	1051	204	–	–

Arithmetic Task

Children were administered a single-digit subtraction task in the scanner on entering the study (T1). In each trial of the subtraction task, children were asked to evaluate whether the answer to a single-digit subtraction problem was true or false (**Figure 1A**). Twenty-four number pairs were used, covering the full range of single-digit subtraction problems (with the exceptions below). Each pair was repeated twice with a true answer (e.g., 5 – 3 = 2) and once with a false answer. Thus, children were presented with 72 problems in the main experiment and 24 problems in the practice session. False answers were created by subtracting 1 from the correct answer (e.g., 5 – 3 = 1) or by adding 1 or 2 to the correct answer (e.g., 5 – 3 = 4). Problems with 0 or 1 as the second operand (e.g., 5 – 0), tie problems where the first and second operand are identical (e.g., 5 – 5), problems where the correct answer correspond to the second term (e.g., 6 – 3) and problems where the first operand is smaller than the second (e.g., 3 – 5) were not used.

Localizer Tasks

Children were administered two localizer tasks in the scanner on entering the study (T1). We used a word rhyming task to localize verbal neural systems. In each trial of the verbal localizer, two words were sequentially presented. Children were asked to evaluate whether the two words rhymed or not (**Figure 1B**). All words were monosyllabic English words with varying orthographic and phonological similarity (e.g., dime – lime, pint – mint, grade – laid, press – list). Similarity was manipulated so that responses could not be based on spelling alone. Fouty-eight word pairs were used in the main experiment (24 similar, 24 not similar) and 48 word pairs were used in the practice session. We used a non-symbolic, dot comparison task to localize brain regions that subserve spatial representations. In each trial of the spatial localizer, two dot arrays were sequentially presented (**Figure 1C**). Children were asked to decide which of the two dot arrays were composed of a larger number of dots. Arrays of 12, 24, and 36 dots were used with varying single dot sizes and cumulative surface area. Seventy-two pairs of dot arrays

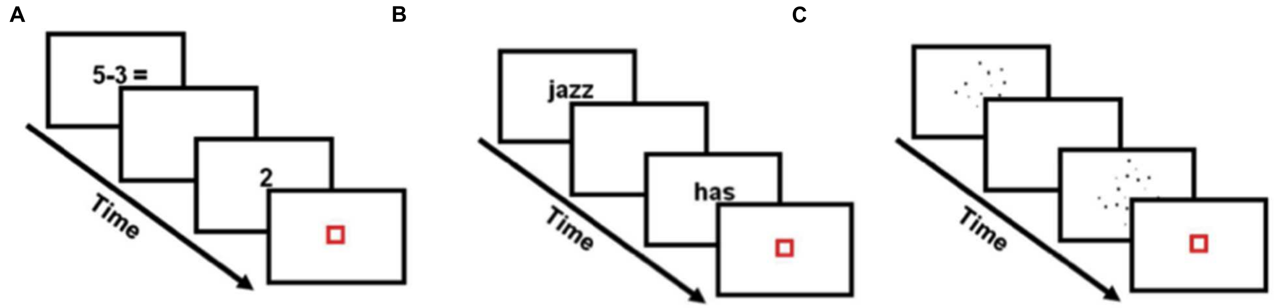


FIGURE 1 | Experimental tasks. (A) In the arithmetic problems, participants were asked to evaluate subtraction problems. Localizer tasks were used to identify the Regions of Interest. **(B)** In the verbal localizer task, participants decided if two words rhymed or not. **(C)** In the spatial localizer task, participants decided which dot array included a larger number of dots.

were used in the main experiment and 36 pairs were used in the practice session. **Table 1** summarizes children's performance on subtraction and localizer tasks.

Experimental Procedure

At T1, after informed consent was obtained and standardized tests were administered, children participated in a practice session. During the practice session, children learned to minimize their head movement (with feedback from an infrared tracking device), and practiced all three tasks in a mock fMRI scanner. The actual fMRI scanning session took place within one week of the practice session. In the fMRI scanner, subtraction and spatial localizer tasks were divided into two runs of about 4 min each. The verbal localizer task was administered in a single run lasting about 7 min. The order of tasks was counterbalanced across participants. Behavioral responses were recorded using an MR-compatible keypad placed below the right hand. Visual stimuli were generated using E-prime software (Psychology Software Tools Inc., 2012), and projected onto a translucent screen. Children viewed the screen through a mirror attached to the head coil.

Stimulus timing was identical in all tasks. A trial started with the presentation of a first stimulus (subtraction, dot array or word depending on the task) for 800 ms, followed by a blank screen for 200 ms. A second stimulus (subtraction, dot array or word depending on the task) was presented for 800 ms, followed by a red fixation square presented for 200 ms. Participants were asked to make a response during an interval ranging from 2,800 ms to 3,600 ms. Twenty-four null trials were included in the subtraction and spatial localizer tasks. Twelve null trials were used for the verbal localizer task. In the null trials, a blue square was presented for the same duration as the experimental conditions and children were asked to press a button when the square turned red. Each run ended with 22 s of passive visual fixation. Fixation periods (between trials and at the end of the run) constituted the baseline. The timing and order of trial presentation within each run was optimized for estimation efficiency using Optseq2[2] (Dale, 1999).

[2]http://surfer.nmr.mgh.harvard.edu/optseq/

fMRI Data Acquisition

Images were collected using a Siemens 3T TIM Trio MRI scanner (Siemens Healthcare, Erlangen, Germany) at Northwestern University's Center for Translational Imaging (CTI). The fMRI blood oxygenation level-dependent (BOLD) signal was measured with a susceptibility weighted single-shot echo planar imaging (EPI) sequence. The following parameters were used: TE = 20 ms, flip angle = 80°, matrix size = 128 × 120, field of view = 220 mm × 206.25 mm, slice thickness = 3 mm (0.48 mm gap), number of slices = 32, TR = 2,000 ms. Before functional image acquisition, a high resolution T1-weighted 3D structural image was acquired for each subject (TR = 1,570 ms, TE = 3.36 ms, matrix size = 256 × 256, field of view = 240 mm, slice thickness = 1 mm, number of slices = 160).

Behavioral Data Analyses

The math change score was calculated by subtracting children's raw score on the Math Fluency subtest at T1 from their score at T2 and dividing this change score by the age difference between T2 and T1[3]. This measure reflected the rate of change in math score between T1 and T2. In order to examine if any of the behavioral measures collected at T1 predicted math change score, math change score was correlated with IQ, Math Fluency score (raw and standardized score), subtraction accuracy and RT, and age at T1. Correlations with parental SES were also calculated.

fMRI Data Analyses

Data analyses were performed using SPM8 (Statistical Parametric Mapping[4]). The first six images of each run were discarded, functional images were corrected for slice acquisition delays, realigned to the first image of the first run to correct for head movements, and spatially smoothed with a Gaussian filter equal to about twice the voxel size (4 mm × 4 mm × 8 mm full width at half maximum). ArtRepair software was used to suppress residual fluctuations due to large head motion and to identify

[3]We used raw scores rather than standardized scores because we were interested in the rate of growth in absolute arithmetic knowledge, rather than relative to peers. Standardized and raw change scores were significantly correlated with each other, $r = 0.72$, $p < 0.001$. Results remain unchanged using standardized scores.

[4]www.fil.ion.ucl.ac.uk/spm

volumes with significant artifact and outliers relative to the global mean signal (4% from the global mean). Volumes showing rapid scan-to-scan movements of greater than 1.5 mm were excluded via interpolation of the two nearest non-repaired volumes. Interpolated volumes were partially deweighted when first-level models were calculated on the repaired images (Mazaika et al., 2009). All participants had less than 5% of the total number of volumes replaced in a single run. Average translation and rotation movements were small (x-plane: $M = 0.06$ mm; y-plane: $M = 0.08$ mm, z-plane: $M = 0.27$ mm, pitch: $M = 0.27°$, roll: $M = 0.12°$, yaw: $M = 0.09°$). Functional volumes were co-registered with the segmented anatomical image and normalized to the standard T1 Montreal Neurological Institute (MNI) template volume (normalized voxel size, 2 mm × 2 mm × 4 mm).

First Level Analyses

Event-related statistical analyses were performed according to the General Linear Model. Activation was modeled as epochs with onsets time-locked to the presentation of the first stimulus (operands) and ending at the offset of the second stimulus (answer). For the arithmetic tasks, all responses were included in the model. However, only responses in problems with a true answer were considered of interest in the analyses to avoid inhibitory processes associated with rejecting invalid trials. All epochs were convolved with a canonical hemodynamic response function. The time series data were high-pass filtered (1/128 Hz), and serial correlations were corrected using an autoregressive AR(1) model. Effect sizes were estimated using linear statistical contrasts and subsequently entered into second level analyses.

Second Level Analyses

In order to evaluate the relations between SES, rate of math score change and neural bases of arithmetic, second level voxel-wise regression models were created. In each analysis, SES, math change score, as well as the interaction between SES and math change score constituted the regressors of interest. Additionally, we included as regressor of no interest full scale IQ at T1. Our specific question was about interactive relations of math change score and parental SES to the neural basis of arithmetic. We identified brain regions that showed an increase or a decrease in activity during the evaluation of subtraction problems with respect to the interaction term across subjects. All analyses were repeated with measures of performance (accuracy) on the arithmetic task and T1 math score as regressors of no interest and the results reported below remained unchanged, as described below. We specifically focused on the interaction between math change score and SES because of the nature of our specific question and also in order to reduce our Type 1 error. Analyses examining main effects of math change score and SES on the neural basis of arithmetic are provided in Supplementary Materials.

ROI Definition

The relations of SES and rate of math change score to the neural basis of subtraction were examined within verbal and spatial ROIs. Verbal ROIs were identified using the verbal localizer contrast (contrast of [words versus null trials] across all subjects). Spatial ROIs were identified using the spatial localizer contrast (contrast of [dots versus null trials]). The resulting statistical maps were thresholded for significance using a voxelwise threshold of $p < 0.01$ (uncorrected) and a clusterwise threshold of $p < 0.05$ (FWE corrected for multiple comparisons). To ensure the specificity of the localizer activation (i.e., no overlap between localizers), each contrast was exclusively masked by the voxels in which the other localizer contrast was positive (exclusive mask thresholded at $p < 0.05$ uncorrected).

The verbal localizer contrast was associated with enhanced activity in the left inferior/middle temporal, inferior/middle frontal, fusiform, and precentral gyri (**Figure 2A** and **Table 2**). These clusters constitute the verbal localizer mask. The spatial localizer contrast was associated with enhanced activity in multiple clusters spanning right inferior/superior parietal lobule, precuneus, cuneus, posterior cingulate, lingual gyrus, postcentral gyrus, insula, putamen and left anterior cingulate (**Figure 2B** and **Table 2**). These clusters constituted the spatial localizer mask. The localizers enabled us to independently identify brain regions that subserve verbal versus spatial processes.

ROI Analyses

Statistical significance within each of these localizer masks was defined using Monte Carlo simulations (using AFNI's AlphaSim program[5]). In order to reach corrected level threshold (alpha = 0.05) within the verbal ROIs, the clusters needed to contain 75 voxels with a height threshold of 0.05. Within the spatial ROIs, clusters needed to contain 85 voxels with a height threshold of 0.05. Statistical maps were used to estimate smoothness. Throughout the paper, we consider a cluster significant if $p < 0.05$ and a trend if $p < 0.1$.

Whole Brain Analyses

To investigate non-predicted effects in regions outside verbal or spatial ROIs, we also report results of whole-brain analyses conducted outside the ROIs reported above. The statistical maps were thresholded for significance using a voxelwise threshold of $p < 0.01$ (uncorrected) and a clusterwise threshold of $p < 0.05$ (FWE corrected for multiple comparisons).

RESULTS

Behavioral Performance and Relations to Math Change Score

Table 3 summarizes correlations between behavioral measures at T1 (e.g., IQ, math score), math change score and SES. None of the behavioral measures significantly predicted change in math scores. We included IQ as a covariate in our analyses, but results remained unchanged using other covariates as described below. SES did not significantly relate to any of the measures at T1 or to change in math score. In a series of regression analyses, we examined whether math score change was related to the interaction of SES with any of the behavioral measures. We included SES, behavioral measures and their interaction as

[5] http://afni.nimh.nih.gov/

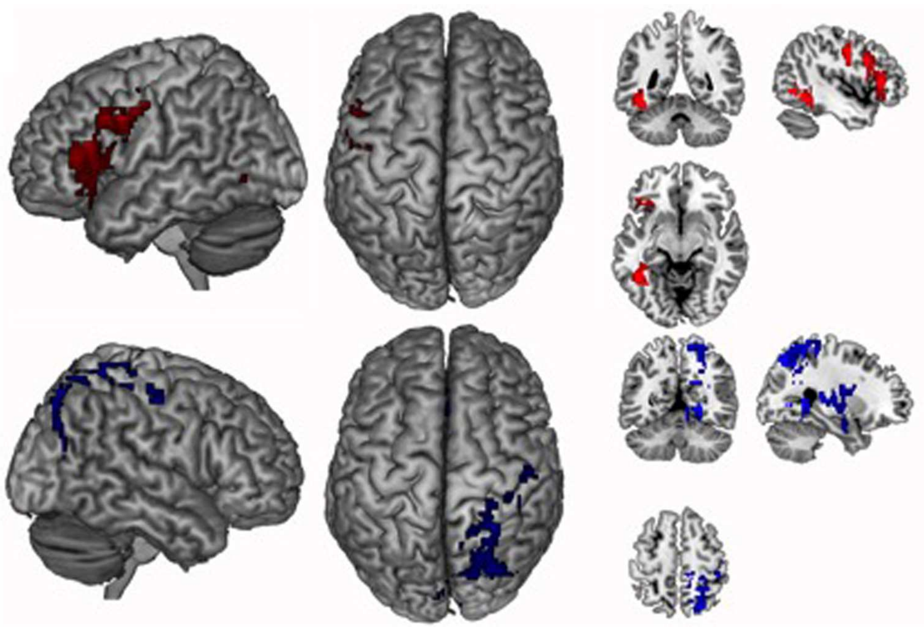


FIGURE 2 | Brain networks identified by the localizer tasks. (A) The verbal localizer task was associated with enhanced activity in a network that included left inferior/middle temporal, inferior/middle frontal, fusiform and precentral gyri. **(B)** The spatial localizer task was associated with enhanced activity in a network that included right inferior/superior parietal lobule, precuneus, cuneus, posterior cingulate, lingual gyrus, postcentral gyrus, insula, putamen and left anterior cingulate. Activations are overlaid on a 3D rendering and on coronal, sagittal, and axial slices of the MNI-normalized anatomical brain.

independent variables and math change score as the dependent variable. None of the interaction terms predicted math score change.

Overall Activation in Verbal and Spatial ROIs during the Subtraction Task

We first examined overall activation in the verbal and spatial ROIs during the subtraction task, using the contrast of [subtraction trials– baseline] submitted to a one-sample t-test across all participants. In verbal ROIs, subtraction problems showed significant activation in left IFG (peak coordinate: $x = -52$, $y = 8$, $z = 38$, BA $= 9$, $z = 4.21$, $k = 324$ voxels) and in left MTG (peak coordinate: $x = -44$, $y = -60$, $z = -6$, BA $= 21$, $z = 3.71$, $k = 178$ voxels). In spatial ROIs, subtraction problems showed activation in right culmen/lingual gyrus (peak coordinate: $x = 10$, $y = -62$, $z = -14$, BA $= 19$, $z = 5.52$, $k = 109$ voxels), and although not significant, subtraction problems also showed activation in precuneus (peak coordinate: $x = 26$, $y = -46$, $z = -46$, BA $= 7$, $z = 3.12$, $k = 51$ voxels).

Relation between Change in Math Score and Neural Activity during the Subtraction Task is Moderated by Parental SES

We then examined whether SES moderates the relation of rate of math score change to the neural basis of subtraction problems. We identified the brain regions within our verbal or spatial ROIs where activity during the evaluation subtraction problems was

TABLE 2 | Peak activated voxels in the localizer tasks.

Anatomical location	~BA	MNI coordinates			*Z*-score	Size
		X	Y	Z		
L. inferior/middle temporal gyrus/fusiform gyrus	19/37/39	−44	−60	−6	5.51	292
L. inferior/middle frontal gyrus/precentral gyrus	6/45/46	−50	−6	38	4.62	916
Spatial localizer						
R. cuneus/posterior cingulate/lingual gyrus	17/18/30	14	−78	6	4.75	520
R. superior parietal lobule/precuneus/postcentral gyrus	5/7/31	28	−48	62	4.50	806
R. inferior parietal lobule/insula/putamen	13/40	42	−24	26	5.32	997
L. anterior cingulate	32	−12	26	30	4.25	350

L, left; R, right; ~BA, approximate Brodmann area for the peak coordinate; MNI, Montreal Neurological Institute; Size, number of 2 mm × 2 mm × 4 mm voxels.

TABLE 3 | Correlations between SES, behavioral measures at T1, and change in math fluency.

T1	Change in math fluency	SES
SES	0.01	–
Change in math fluency	–	0.01
Age	−0.18	−0.23
WASI IQ (Standardized)	0.22	0.13
WJ math fluency (Standardized)	−0.06	0.10
WJ math fluency (Raw)	−0.24	0.24
Subtraction accuracy	−0.06	0.09
Subtraction RT	−0.09	0.23
Verbal localizer accuracy	0.12	0.24
Verbal localizer RT	−0.09	0.11
Spatial localizer accuracy	0.09	−0.10
Spatial localizer RT	0.08	−0.06

None of these correlations were significant.

associated with the interaction between SES and math change score (when the effects of IQ were controlled).

Verbal ROIs

We found a significant interaction (SES × change) in a cluster in left IFG (peak coordinate: $x = -48$, $y = 8$, $z = 34$, BA = 9, $z = 3.18$, $k = 79$ voxels; **Figure 3A**)[6]. For visualization purposes only, we divided the children into two groups based on median SES (lower than or at the median constituting lower SES, and higher than the median constituting higher SES). We then extracted the adjusted eigen variate from the significant cluster and plotted it against math change score for the two SES groups. This plot showed that for higher SES, change is positively associated with activity during subtraction in left IFG, but the relation is negative for lower SES (**Figure 3B**).

Finally, the interaction identified with continuous variables was confirmed with follow-up analyses comparing relations between change score and activation for higher versus lower SES children. For these analyses, we divided the children into two groups based on median SES (lower than or at the median constituting lower SES, and higher than the median constituting higher SES). We conducted a full factorial design including SES as a binary variable (higher, lower), change as continuous variable, as well as an interaction term between the binary SES variable and change. IQ was included as a continuous covariate. The interaction term enabled us to directly compare the association between change and brain activity in higher versus lower SES. We first identified areas in verbal ROIs where brain activity was associated with change to a greater extent for higher than lower SES children. This direct comparison revealed that a cluster in left IFG was significantly and more strongly related to change in higher SES children than lower SES children (peak coordinate: $x = -50$, $y = 8$, $z = 34$, BA = 9, $z = 3.56$, $k = 187$ voxels). This cluster overlaps with the cluster identified by the analyses using the continuous variables. The reverse contrast did not reveal any significant activation – there were no significant clusters in verbal ROIs where activation was related to change more strongly for lower than higher SES children.

Spatial ROIs

We found a marginally significant interaction in a cluster in right PSPL/Pr, (peak coordinate: $x = 20$, $y = -66$, $z = 54$, BA = 7, $z = 2.52$, $p = 0.06$, $k = 83$ voxels; **Figure 4A**)[7]. For visualization purposes only, we divided the children into two groups based on median SES. We then extracted the adjusted eigenvariate from the significant cluster and plotted it against math change score for the two SES groups. This plot showed that for lower SES children, change is positively associated with activity during subtraction in right PSPL/Pr, but the relation between change and activation in this area is negative for higher SES children (**Figure 4B**).

In order to confirm the interaction identified with continuous variables, we then divided the children into two groups based on median SES (lower than or at the median constituting lower SES, and higher than the median constituting higher SES). We conducted a full factorial design including SES as a binary variable (higher, lower), change as continuous variable, as well as an interaction term between the binary SES variable and change. IQ was included as a continuous covariate. The interaction term enabled us to directly compare the association between change and brain activity in higher versus lower SES. We identified areas in spatial ROIs where brain activity was associated with change to a greater extent for lower than higher SES children in spatial ROIs. This direct comparison revealed that a cluster in right PSPL/Pr was significantly and more strongly related to change in lower SES children than higher SES children (peak coordinate: $x = 20$, $y = -66$, $z = 54$, BA = 7, $z = 2.96$, $k = 95$ voxels). This cluster overlaps with the cluster identified by the analyses using the continuous variables. The reverse contrast also revealed a significant activation in the spatial ROIs– a cluster in inferior parietal, specifically extending from postcentral gyrus to insula where activation was related to change more strongly for higher SES than lower SES children (peak coordinate in the insula: $x = 30$, $y = -30$, $z = 18$, BA = 13, $z = 2.70$, $k = 250$ voxels).

Whole Brain Analyses

Outside the ROIs, the interaction term (SES × change) was significantly and positively related to activation in two clusters. Activity in these clusters was related to greater growth in math skill at the higher end of the SES continuum, but lesser improvements at the lower end. The two clusters included one spanning right supramarginal, superior temporal and extending into inferior parietal gyri (peak coordinate, $x = 42$, $y = -44$, $z = 22$, BA = 13/22/40, $z = 3.81$, $k = 438$ voxels) and another in right inferior frontal, middle frontal, and extending into precentral gyri (peak coordinate, $x = 46$, $y = 10$, $z = 30$, BA = 6/9, $z = 3.58$, $k = 278$ voxels). The latter peak was within 5 mm of the peak noted above identified within the verbal ROIs in the left hemisphere. There were no areas that were negatively and significantly related to the interaction term outside the ROIs.

[6]The pattern of results for the interaction term in the verbal ROI remained unchanged when controlling for accuracy on task ($z = 3.23$, $k = 82$) and math score at T1 ($z = 3.32$, $k = 71$).

[7]The pattern on results for the interaction term in the spatial ROI remained unchanged when controlling for accuracy on task ($z = 3.23$, $k = 66$) and math score at T1 ($z = 2.61$, $k = 92$).

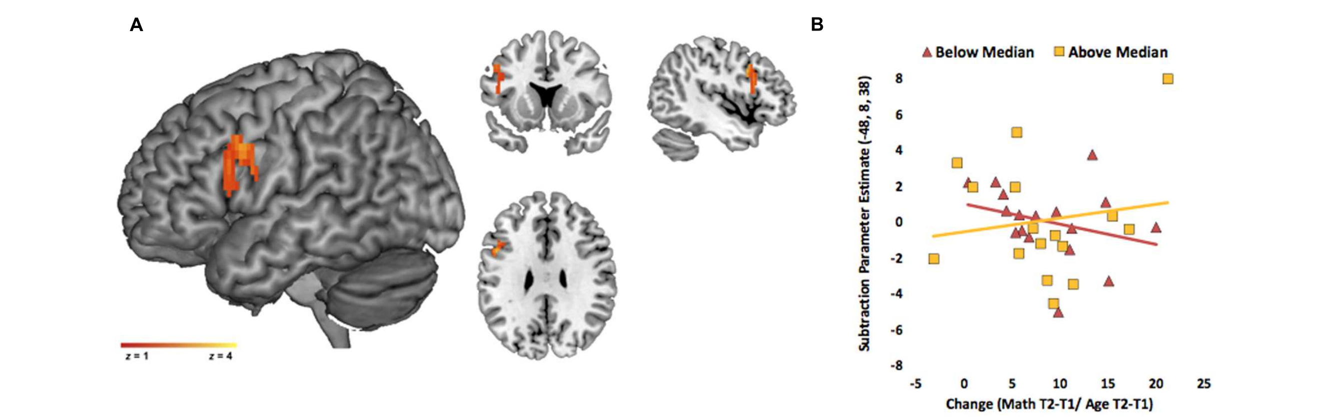


FIGURE 3 | Interaction between SES and math score change in the verbal ROI for subtraction problems. (A) Activity in left inferior frontal gyrus (IFG) showed a SES and change interaction. Activation is overlaid on a 3D rendering and on coronal, sagittal, and axial slices of MNI-normalized anatomical brain. **(B)** Average brain activity (adjusted eigenvariates) was extracted from the significant cluster in left IFG and plotted against change scores for visualization purposes only. Relation was visualized for children above the median SES and below the median SES.

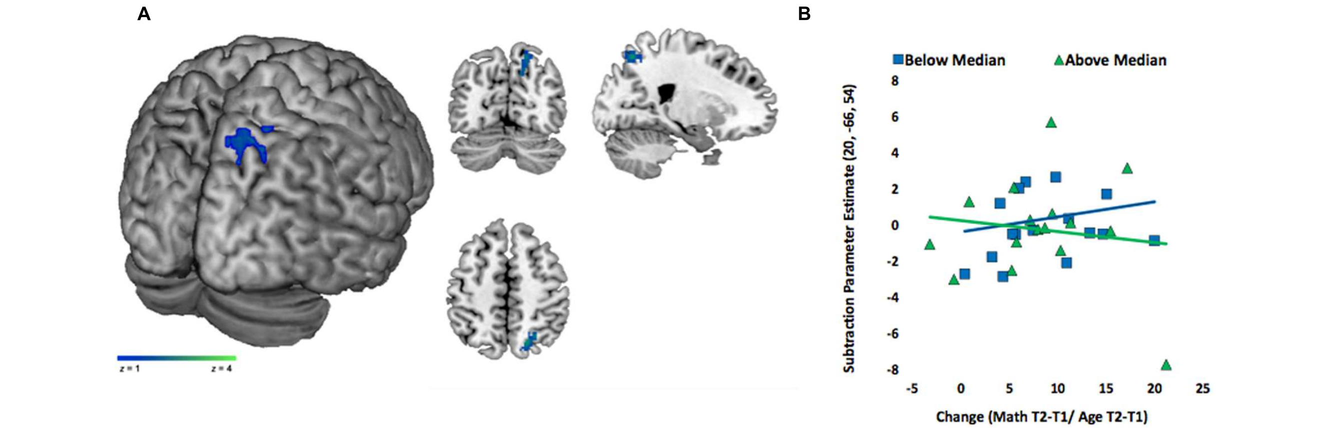


FIGURE 4 | Interaction between SES and math score change in the spatial ROI for subtraction problems. (A) Activity in right superior parietal sulcus/precuneus (PSPL/Pr) showed a SES and change interaction. Activation is overlaid on a 3D rendering and on coronal, sagittal, and axial slices of MNI-normalized anatomical brain. **(B)** Average brain activity (adjusted eigenvariates) was extracted from the significant cluster (3 mm around the peak) in right PSPL/Pr, and plotted against change scores for visualization purposes only. Relation was visualized for children above the median SES and below the median SES.

DISCUSSION

Children differ widely in their math skill growth, and parental SES is one of the strongest predictors of these individual differences. To our knowledge, nothing is known about how early neural predictors of later math skill growth vary for children at different SES levels. In the current study, we independently identified brain regions that subserve verbal and spatial neural systems using localizer tasks. We asked how early reliance on these regions relate to growth in math skill over a 3-year period and whether the neural predictors vary as a function of parental SES. Results showed that early neural predictors of math skill gains encompassed brain regions underlying verbal processing, such as left inferior frontal and middle temporal gyri, as well as visuo-spatial processing, such as right culmen/lingual gyrus and precuneus. In addition, neural predictors of math gains varied depending on parental SES.

Activity in an area of the left inferior frontal gyrus (IFG) identified by the verbal localizer was related to greater growth in math skill at the higher end of the SES continuum, but lesser improvements at the lower end. We showed that early reliance on verbal neural systems, specifically left IFG, predicted rate of change in math skill to a greater extent for children at the higher end of the SES continuum than the lower end. Left IFG is consistently activated in arithmetic tasks, and considered to be involved the manipulation of verbal representations of arithmetic rules and facts hosted in left middle temporal cortex (Kucian et al., 2008; Rosenberg-Lee et al., 2009). Left IFG is also implicated in executive control, which is strongly associated with both SES and arithmetic skill (Bull and Scerif, 2001; Badre and Wagner, 2007; Hackman and Farah, 2009).

During development higher SES children might have learned to better manipulate verbal representations in general and verbal representations of numerical quantities more specifically (for example between Arabic numbers and their meanings) as compared to lower SES children. Differential relations of SES and math skill growth in left IFG might reflect more robust manipulation of such verbal representations by higher SES with higher skill growth children compared to children from lower SES backgrounds. This might aid higher SES children when learning arithmetic problems, e.g., in forming associations between problems and answers or acquiring arithmetic rules and procedures, more than lower SES children. Whole brain analyses revealed right-lateralized activation in right supramarginal/superior temporal and inferior/middle frontal areas to be more strongly associated with math skill change at the higher end of the SES continuum as compared to the lower end. A bilateral fronto-temporal network including these regions has been argued to underlie verbal processing of arithmetic problems, specifically of verbal retrieval or verbalization (Zarnhofer et al., 2012). Thus, whole-brain analyses add support to the interpretation that reliance on verbal representations might predict growth in math skill in higher SES to a greater extent than lower SES children.

In a previous paper, we showed that, at higher levels of SES, higher math skill was associated with concurrent reliance on left MTG, but not IFG (Demir et al., 2015). Left temporo-parietal cortices are thought to support verbal representations, such as representations of the associations between arithmetic problems and their solutions (Booth et al., 2002; Fiebach et al., 2002; Blumenfeld et al., 2006; Prado et al., 2011). Combined with the current findings, these results suggest that concurrent math skill might be related to the representational systems themselves hosted in middle temporal regions, whereas acquiring new math knowledge might be associated with 'higher-level' regions manipulating these representations, such inferior frontal regions.

Early parental input might explain why reliance on verbal neural systems predicts growth in math skill to a greater extent for higher than lower SES children. Children differ widely from each other along the SES continuum in their exposure to verbal input in general and verbal input about mathematics specifically, but SES differences in exposure to spatial stimulation are less consistent (Saxe et al., 1987; Hart and Risley, 1995; Blevins-Knabe and Musun-Miller, 1996; Hoff, 2003; Ehrlich, 2007; Levine et al., 2010; Gunderson and Levine, 2011; Levine et al., 2012). The quantity of parental number talk during naturalistic parent–child interactions during preschool years is higher in higher SES families (Gunderson and Levine, 2011). Parental verbal input strongly relates to preschool numerosity outcomes, more strongly than numerosity-related activities (Gunderson and Levine, 2011; Anders et al., 2012). Previous neuroimaging studies suggest that the neural basis of verbal processing, specifically left IFG, is more specialized in higher SES children, confirming our findings regarding left IFG predicting greater change for higher SES children than lower SES children (Pakulak et al., 2005; Raizada et al., 2008; Hackman and Farah, 2009).

Activity in an area of the right superior parietal cortex identified by the spatial localizer was related to greater growth in math skill at the lower end of the SES continuum, but lesser improvements at the higher end. Early reliance on spatial neural systems, specifically right superior parietal cortex/precuneus (PSPL/Pr), predicted rate of change in math skill to a greater extent for lower than higher SES children. The right PSPL/Pr is considered to be involved in spatial and attentional processes and, in the context of arithmetic, in the spatial manipulation of numerical magnitudes, hosted in right intraparietal sulcus (Dehaene et al., 2003; Ischebeck et al., 2006; Metcalfe et al., 2013; Prado et al., 2014; Berteletti et al., 2015). We argue that differential relations of SES and math skill growth in right PSPL/Pr might reflect more robust manipulation of spatial representations of numbers by children with lower SES with higher skill growth. In the absence of the rich verbal input that higher SES children receive, lower SES children might rely on spatial strategies in learning arithmetic to a greater extent than higher SES children. It should be noted that the interaction effect we observed might also be due to higher SES children showing a negative relation to change in right PSPL/Pr – children who use spatial strategies despite being exposed to rich input might exhibit shallower growth over time.

Indeed, SES-related differences in mathematical cognition tend to be larger on verbal aspects of math as compared to spatial aspects (Jordan and Levine, 2009). Interventions aiming to improve mathematical cognition in low SES children are also reported to improve performance on verbal aspects of math, e.g., comparison of number words, but not non-symbolic, spatial aspects, e.g., comparison of magnitudes, suggesting greater room for growth in verbal systems (Wilson et al., 2009). Extending our findings to the domain of reading, Gullick et al. (in press) recently similarly reported that the relation of reading skill to white matter depends on SES. For lower SES children, higher reading skill was correlated with white matter in right hemisphere visuo-spatial tracts, suggesting that lower SES children may rely more on visuo-spatial orthographic processing strategies for reading success. Thus, lower SES children might find rely on visuo-spatial neural systems to a greater extent than higher SES children across different academic tasks.

Prior literature suggested that SES-related differences in mathematics are larger on verbal aspects of mathematics than on spatial aspects (Jordan and Levine, 2009). In general, SES-related differences in children's verbal skills are well described and appear to be more robust than differences in spatial skills (Hart and Risley, 1995; Noble et al., 2007). Our findings add to the existing literature suggesting that the nature of SES differences might be better described as interacting with children's skill and highlight differential relationships between SES and verbal versus spatial neural systems, rather than an overall effect of SES on verbal systems. In sum, depending on parental SES, children might develop adaptations and recruit alternative neural networks to varying degrees to perform at par with their peers.

In a previous study (Demir et al., 2015), we showed the activation in right IPS to relate to concurrent math skill for children at the lower end of the SES continuum. The IPS has been argued to house spatial representations important for arithmetic processing (Dehaene et al., 2003). These results combined with current findings support our argument regarding the distinction between neural systems that support representations themselves for concurrent performance versus manipulation of these representations for learning. Indeed, longitudinal behavioral studies with children showed that working memory is a strong predictor of mathematical skill growth over and above the contributions of domain-specific quantitative, calculation or reading skill, short-term memory and phonological processing skill (Bull et al., 2008; Swanson et al., 2008; Welsh et al., 2010; Metcalfe et al., 2013). Similarly, a recent neuroimaging study found that activation in parietal lobule during a visuo-spatial working memory task predicts math skill growth over a 2-year period (Dumontheil and Klingberg, 2011).

Our results showed that growth in math skill was significantly predicted by neural, but not behavioral measures included in the study, e.g., IQ, early math skill and age. Although null results are hard to interpret, these results are in line recent neuroimaging studies in math and reading development that showed predictive power of neural differences over and above behavioral differences (Hoeft et al., 2007, 2011; McNorgan et al., 2011; Supekar et al., 2013). Neuroimaging measures might serve as sensitive measures of individual differences in underlying neural mechanisms not fully captured by current behavioral standardized tests. This highlights the possibility of using early neural markers to predict future math performance.

The current study raises various questions to be addressed by future research. First, the current study specifically focused on subtraction problems. Prior studies have shown that subtraction problems activate both verbal and visuo-spatial neural systems, and thus subtraction problems might be more appropriate to examine the differential reliance of SES on verbal versus spatial neural systems (Siegler, 1988; De Smedt et al., 2011). However, future studies should examine SES relations to the neural basis of other operations, specifically those that primarily rely on verbal representations, such as multiplication (Lee and Kang, 2002; Prado et al., 2013). Second, our study did not include children at lowest end of the SES continuum. This enabled us to examine SES-related differences within the normative range of SES, in the absence of other confounding factors, such as nutritional differences, differences in sleep patterns or stress. In our study children's behavioral performance on single-digit arithmetic problems did not vary according to SES, which also allowed us to examine SES-related differences without confounding neural effects with differences due to accuracy or motivation. Future studies should examine SES-related differences in neural predictors of growth in more complex mathematical tasks where SES discrepancies are particularly wide, such as math word problems and on a wider SES continuum (Abedi and Lord, 1998; Jordan and Levine, 2009). Third, SES is a broad measure encompassing multiple characteristics including parental education, occupation, income, perceived social status, and is associated with parental cognitive stimulation, access to education, high-quality neighborhoods, and reduced stress among others (Brooks-Gunn and Duncan, 1997; Bradley and Corwyn, 2002; Hackman and Farah, 2009; Duncan and Magnuson, 2012). We used widely used indicators of SES that strongly relate to academic outcomes and we controlled for effects of IQ to gain more specificity about SES effects. Future studies should provide further specificity regarding the relations of different components of SES and neural basis of arithmetic development. Finally, it is important highlight that neural predictors of math growth encompassed brain regions that underlie both verbal and spatial processing. It was the relative degree to which activity in an area was related to math gains that varied along the SES continuum. Future longitudinal studies should focus on when do the differences along the SES gradient emerge and develop over time.

In summary, we, for the first time, highlight how neural systems that may be early neural predictors of long-term mathematical learning vary as a function of SES. Reducing the achievement gap necessitates a nuanced understanding of children's differences early on. Although many intervening steps still need to be taken, targeted interventions that build upon early neural indicators might effectively address the challenges of children from differing backgrounds.

AUTHOR CONTRIBUTIONS

JB directed the larger study in which the present sub-study is embedded. OD-L, JP, and JB substantially contributed to the sub-study conceptualization and design of the work. JB and JP developed the experimental paradigm. OD-L and JP oversaw data collection. OD-L conducted the data processing, data analysis, and interpretation with input from JP and JB. OD-L drafted the manuscript, and all authors provided critical revisions. All authors approved the final version of the manuscript for submission. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

FUNDING

This research was supported by HD059177 from the National Institute of Child Health and Human Development to JB.

ACKNOWLEDGMENTS

We thank John V. Binzak and Rachna Mutreja for their assistance in data collection. We would like to thank all participating children and their parents.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2016.00892

REFERENCES

Abedi, J., and Lord, C. (1998). The language factor in mathematics tests. *Appl. Meas. Educ.* 14, 219–234. doi: 10.1207/S15324818AME1403_2

Adams, J., and Weakliem, D. L. (2011). August B. Hollingshead's "Four factor index of social status": from unpublished paper to citation classic. *Yale J. Sociol.* 8, 11–20.

Anders, Y., Rossbach, H.-G., Weinert, S., Ebert, S., Kuger, S., Lehrl, S., et al. (2012). Home and preschool learning environments and their relations to the development of early numeracy skills. *Early Child. Res. Q.* 27, 231–244. doi: 10.1016/j.ecresq.2011.08.003

Andres, M., Pelgrims, B., Michaux, N., Olivier, E., and Pesenti, M. (2011). Role of distinct parietal areas in arithmetic: an fMRI-guided TMS study. *Neuroimage* 54, 3048–3056. doi: 10.1016/j.neuroimage.2010.11.009

Badre, D., and Wagner, A. D. (2007). Left ventrolateral prefrontal cortex and the cognitive control of memory. *Neuropsychologia* 45, 2883–2901. doi: 10.1016/j.neuropsychologia.2007.06.015

Berteletti, I., Man, G., and Booth, J. R. (2015). How number line estimation skills relate to neural activations in single digit subtraction problems. *Neuroimage* 107, 198–206. doi: 10.1016/j.neuroimage.2014.12.011

Blevins-Knabe, B., and Musun-Miller, L. (1996). Number use at home by children and their parents and its relationship to early mathematical performance. *Early Dev. Parent.* 5, 35–45. doi: 10.1002/(SICI)1099-0917(199603)5:1<35::AID-EDP113>3.0.CO;2-0

Blumenfeld, H. K., Booth, J. R., and Burman, D. D. (2006). Differential prefrontal-temporal neural correlates of semantic processing in children. *Brain Lang.* 99, 226–235. doi: 10.1016/j.bandl.2005.07.004

Booth, J. R. (2010). "Development and language," in *Encyclopaedia of Behavioral Neuroscience*, eds G. Koob, M. Le Moal, and R. F. Thompson (Oxford: Academic Press), 387–395.

Booth, J. R., Burman, D. D., Meyer, J. R., Gitelman, D. R., Parrish, T. B., and Mesulam, M. M. (2002). Modality independence of word comprehension. *Hum. Brain Mapp.* 16, 251–261. doi: 10.1002/hbm.10054

Bradley, R. H., and Corwyn, R. F. (2002). Socioeconomic development and child development. *Annu. Rev. Psychol.* 53, 371–399. doi: 10.1146/annurev.psych.53.100901.135233

Brooks-Gunn, J., and Duncan, G. J. (1997). The effects of poverty on children. *Future Child.* 7, 55–71. doi: 10.2307/1602387

Bull, R., Espy, K. A., and Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: longitudinal predictors of mathematical achievement at age 7 years. *Dev. Neuropsychol.* 33, 205–228. doi: 10.1080/87565640801982312

Bull, R., and Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching, and working memory. *Dev. Neuropsychol.* 19, 273–293. doi: 10.1207/S15326942DN1903_3

Cheadle, J. E. (2008). Educational investment, family context , and children's math and reading growth from kindergarten through the third grade. *Sociol. Educ.* 81, 1–31. doi: 10.1177/003804070808100101

Cho, S., Ryali, S., Geary, D. C., and Menon, V. (2011). How does a child solve 7 + 8? Decoding brain activity patterns associated with counting and retrieval strategies. *Dev. Sci.* 14, 989–1001. doi: 10.1111/j.1467-7687.2011.01055.x

Dale, A. M. (1999). Optimal experimental design for event-related fMRI. *Hum. Brain Mapp.* 8, 109–114.

De Smedt, B., Holloway, I. D., and Ansari, D. (2011). Effects of problem size and arithmetic operation on brain activation during calculation in children with varying levels of arithmetical fluency. *Neuroimage* 57, 771–781. doi: 10.1016/j.neuroimage.2010.12.037

Dehaene, S., Piazza, M., Pinel, P., and Cohen, L. (2003). Three parietal circuits for number processing. *Cogn. Neuropsychol.* 20, 487–506. doi: 10.1080/02643290244000239

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., and Tsivkin, S. (1999) Sources of mathematical thinking: behavioral and brain-imaging evidence. *Science* 284, 970–974. doi: 10.1126/science.284.5416.970

Demir, ÖE., Prado, J., and Booth, J. R. (2015). Parental socioeconomic status and the neural basis of arithmetic: differential relations to verbal and visuo-spatial representations. *Dev. Sci.* 18, 799–814. doi: 10.1111/desc.12268

Dumontheil, I., and Klingberg, T. (2011). Brain activity during a visuospatial working memory task predicts arithmetical performance 2 years later. *Cereb. Cortex* 22, 1078–1085. doi: 10.1093/cercor/bhr175

Duncan, G. J., and Magnuson, K. (2012). Socioeconomic status and cognitive functioning: moving from correlation to causation. *Wiley Interdiscip. Rev. Cogn. Sci.* 3, 377–386. doi: 10.1002/wcs.1176

Ehrlich, S. (2007). *The Preschool Achievement Gap: Are Variations in Teacher Input Associated with Differences in Number Knowledge*? Ph.D. dissertation, University of Chicago, Chicago, IL.

Evans, T. M., Kochalka, J., Ngoon, T. J., Wu, S. S., Qin, S., Battista, C., et al. (2015). Brain structural integrity and intrinsic functional connectivity forecast 6 year longitudinal growth in children's numerical abilities. *J. Neurosci.* 35, 11743–11750. doi: 10.1523/JNEUROSCI.0216-15.2015

Fiebach, C. J., Friederici, A. D., Müller, K., and von Cramon, D. Y. (2002). fMRI evidence for dual routes to the mental lexicon in visual word recognition. *J. Cogn. Neurosci.* 14, 11–23. doi: 10.1162/089892902317205285

Grabner, R. H., Ansari, D., Reishofer, G., Stern, E., Ebner, F., and Neuper, C. (2007). Individual differences in mathematical competence predict parietal brain activation during mental calculation. *Neuroimage* 38, 346–356. doi: 10.1016/j.neuroimage.2007.07.041

Gullick, M., Demir, ÖE., and Booth, J. R. (in press). Socio-economic status predicts divergent reading skill-fractional (anisotropy)relationships in visuospatial tracts. *Dev. Sci.*

Gunderson, E. A., and Levine, S. C. (2011). Some types of parent number talk count more than others: relations between parents' input and children's cardinal-number knowledge. *Dev. Sci.* 14, 1021–1032. doi: 10.1111/j.1467-7687.2011.01050.x

Hackman, D. A., and Farah, M. J. (2009). Socioeconomic status and the developing brain. *Trends Cogn. Sci.* 13, 65–73. doi: 10.1016/j.tics.2008.11.003

Halberda, J., Mazzocco, M. M., and Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature* 455, 665–668. doi: 10.1038/nature07246

Hart, B., and Risley, T. R. (1995). *Meaningful Differences in the Everyday Experience of Young American Children*. Baltimore, MD: Paul H Brookes Publishing Co.

Hecht, S. A., Torgesen, J. K., Wagner, R. K., and Rashotte, C. A. (2001). The relations between phonological processing abilities and emerging individual differences in mathematical computation skills: a longitudinal study from second to fifth grades. *J. Exp. Child Psychol.* 79, 192–227. doi: 10.1006/jecp.2000.2586

Hoeft, F., McCandliss, B. D., Black, J. M., Gantman, A., Zakerani, N., Hulme, C., et al. (2011). Neural systems predicting long-term outcome in dyslexia. *Proc. Natl. Acad. Sci. U.S.A.* 108, 361–366. doi: 10.1073/pnas.1008950108

Hoeft, F., Ueno, T., Reiss, A. L., Meyler, A., Whitfield-Gabrieli, S., Glover, G. H., et al. (2007). Prediction of children's reading skills using behavioral, functional, and structural neuroimaging measures. *Behav. Neurosci.* 121, 602–613. doi: 10.1037/0735-7044.121.3.602

Hoff, E. (2003). The specificity of environmental influence: socioeconomic status affects early vocabulary development via maternal speech. *Child Dev.* 74, 1368–1378. doi: 10.1111/1467-8624.00612

Hollingshead, A. B. (1975). *Four Factor Index of Social Status*. New Haven, CT: Yale University.

Ischebeck, A., Zamarian, L., Siedentopf, C., Koppelstätter, F., Benke, T., Felber, S., et al. (2006). How specifically do we learn? Imaging the learning of multiplication and subtraction. *Neuroimage* 30, 1365–1375.

Jolles, D., Wassermann, D., Chokhani, R., Richardson, J., Tenison, C., Bammer, R., et al. (2015). Plasticity of left perisylvian white-matter tracts is associated with individual differences in math learning. *Brain Struct. Funct.* 221, 1337–1351. doi: 10.1007/s00429-014-0975-6

Jordan, N. C., and Levine, S. C. (2009). Socioeconomic variation, number competence, and mathematics learning difficulties in young children. *Dev. Disabil. Res. Rev.* 15, 60–68. doi: 10.1002/ddrr.46

Krajewski, K., and Schneider, W. (2009). Exploring the impact of phonological awareness, visual–spatial working memory, and preschool quantity–number competencies on mathematics achievement in elementary school: findings from a 3-year longitudinal study. *J. Exp. Child Psychol.* 103, 516–531. doi: 10.1016/j.jecp.2009.03.009

Kucian, K., von Aster, M., Loenneker, T., Dietrich, T., and Martin, E. (2008). Development of neural networks for exact and approximate calculation: a FMRI study. *Dev. Neuropsychol.* 33, 447–473. doi: 10.1080/87565640802101474

Lee, K.-M. (2000). Cortical areas differentially involved in multiplication and subtraction: a functional magnetic resonance imaging study and correlation with a case of selective acalculia. *Ann. Neurol.* 48, 657–661. doi: 10.1002/1531-8249(200010)48:4<657::AID-ANA13>3.0.CO;2-K

Lee, K.-M., and Kang, S.-Y. (2002). Arithmetic operation and working memory: differential suppression in dual tasks. *Cognition* 83, B63–B68. doi: 10.1016/S0010-0277(02)00010-0

Levine, S. C., Ratliff, K. R., Huttenlocher, J., and Cannon, J. (2012). Early puzzle play: a predictor of preschoolers' spatial transformation skill. *Dev. Psychol.* 48, 530–542. doi: 10.1037/a0025913

Levine, S. C., Suriyakham, L. W., Rowe, M. L., Huttenlocher, J., and Gunderson, E. A. (2010). What counts in the development of young children's number knowledge? *Dev. Psychol.* 46, 1309–1319. doi: 10.1037/a0019671

Mazaika, P., Hoeft, F., Glover, G., and Reiss, A. (2009). "Methods and software for fMRI analysis for clinical subjects," in *Proceedings of the Presentation at the 15th Annual Meeting of the Organization for Human Brain Mapping*, San Francisco, CA, 18–23.

McNorgan, C., Alvarez, A., Bhullar, A., Gayda, J., and Booth, J. R. (2011). Prediction of reading skill several years later depends on age and brain region: implications for developmental models of reading. *J. Neurosci.* 31, 9641–9648. doi: 10.1523/JNEUROSCI.0334-11.2011

Menon, V. (2013). "Arithmetic in child and adult brain," in *Handbook of Mathematical Cognition*, eds R. C. Kadosh and A. Dowker (Oxford: Oxford University Press).

Metcalfe, A. W., Ashkenazi, S., Rosenberg-Lee, M., and Menon, V. (2013). Fractionating the neural correlates of individual working memory components underlying arithmetic problem solving skills in children. *Dev. Cogn. Neurosci.* 6, 162–175. doi: 10.1016/j.dcn.2013.10.001

National Center for Education Statistics (2011). *The Nation's Report Card: Mathematics 2011*. Washington, DC: National Center for Education Statistics.

Noble, K. G., McCandliss, B. D., and Farah, M. J. (2007). Socioeconomic gradients predict individual differences in neurocognitive abilities. *Dev. Sci.* 10, 464–480. doi: 10.1111/j.1467-7687.2007.00600.x

Pakulak, E., Sanders, L., Paulsen, D. J., and Neville, H. (2005). "Semantic and syntactic processing in children from different familial socio-economic status as indexed by ERPS," in *Poster Presented at the 12th Annual Cognitive Neuroscience Society Meeting*, New York, NY.

Psychology Software Tools Inc. (2012). *E-Prime 2.0 [Computer Software]*. Available at: http://www.pstnet.com.

Piazza, M., Facoetti, A., Trussardi, A. N., Berteletti, I., Conte, S., Lucangeli, D., et al. (2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition* 116, 33–41. doi: 10.1016/j.cognition.2010.03.012

Prado, J., Lu, J., Liu, L., Dong, Q., Zhou, X., and Booth, J. R. (2013). The neural bases of the multiplication problem-size effect across countries. *Front. Hum. Neurosci.* 7:189. doi: 10.3389/fnhum.2013.00189

Prado, J., Mutreja, R., and Booth, J. R. (2014). Developmental dissociation in the neural responses to simple multiplication and subtraction problems. *Dev. Sci.* 17, 537–552. doi: 10.1111/desc.12140

Prado, J., Mutreja, R., Zhang, H., Mehta, R., Desroches, A. S., Minas, J. E., et al. (2011). Distinct representations of subtraction and multiplication in the neural systems for numerosity and language. *Hum. Brain Mapp.* 32, 1932–1947. doi: 10.1002/hbm.21159

Pungello, E. P., Kupersmidt, J. B., Burchinal, M. R., and Patterson, C. J. (1996). Environmental risk factors and children's achievement from middle childhood to early adolescence. *Dev. Psychol.* 32, 755–767. doi: 10.1037/a0019816

Qin, S., Cho, S., Chen, T., Rosenberg-Lee, M., Geary, D. C., and Menon, V. (2014). Hippocampal-neocortical functional reorganization underlies children's cognitive development. *Nat. Neurosci.* 17, 1263–1269. doi: 10.1038/nn.3788

Raizada, R. D. S., Richards, T. L., Meltzoff, A., and Kuhl, P. K. (2008). Socioeconomic status predicts hemispheric specialisation of the left inferior frontal gyrus in young children. *Neuroimage* 40, 1392–1401. doi: 10.1016/j.neuroimage.2008.01.021

Rosenberg-Lee, M., Lovett, M. C., and Anderson, J. R. (2009). Neural correlates of arithmetic calculation strategies. *Cogn. Affect. Behav. Neurosci.* 9, 270–285. doi: 10.3758/CABN.9.3.270

Saxe, G. B., Guberman, S. R., Gearhart, M., Gelman, R., Massey, M., and Rogoff, B. (1987). Social processes in early number development. *Monogr. Soc. Res. Child Dev.* 52:i+iii–v+vii–viii+1+3–17+19+21–33+35–53+55+57–99+101–162. doi: 10.2307/1166071

Schmithorst, V. J., and Brown, R. D. (2004). Empirical validation of the triple-code model of numerical processing for complex math operations using functional MRI and group independent component analysis of the mental addition and subtraction of fractions. *Neuroimage* 22, 1414–1420. doi: 10.1016/j.neuroimage.2004.03.021

Siegel, L. S., and Linder, B. A. (1984). Short-term memory processes in children with reading and arithmetic learning disabilities. *Dev. Psychol.* 20, 200. doi: 10.1080/13803395.2015.1066759

Siegler, R. S. (1988). Strategy choice procedures and the development of multiplication skill. *J. Exp. Psychol. Gen.* 117, 258–275. doi: 10.1037/0096-3445.117.3.258

Simmons, F., Singleton, C., and Horne, J. (2008). Phonological awareness and visual-spatial sketchpad functioning predict early arithmetic attainment: evidence from a longitudinal study. *Eur. J. Cogn. Psychol.* 20, 711–722. doi: 10.1080/09541440701614922

Supekar, K., Swigart, A. G., Tenison, C., Jolles, D. D., Rosenberg-Lee, M., and Fuchs, L. (2013). Neural predictors of individual differences in response to math tutoring in primary-grade school children. *Proc. Natl. Acad. Sci. U.S.A.* 110, 8230–8235. doi: 10.1073/pnas.1222154110

Swanson, H. L., Jerman, O., and Zheng, X. (2008). Growth in working memory and mathematical problem solving in children at risk and not at risk for serious math difficulties. *J. Educ. Psychol.* 100, 343–379. doi: 10.1037/0022-0663.100.2.343

Welsh, J. A., Nix, R. L., Blair, C., Bierman, K. L., and Nelson, K. E. (2010). The development of cognitive skills and gains in academic school readiness for children from low-income families. *J. Educ. Psychol.* 102, 43–53. doi: 10.1037/a0016738

Weschler, D. (1999). *Weschler Abbreviated Scale of Intelligence*. New York, NY: The Psychological Corporation.

Wilson, A. J., Dehaene, S., Dubois, O., and Fayol, M. (2009). Effects of an adaptive game intervention on accessing number sense in kindergarten children. *Mind Brain Educ.* 3, 224–234. doi: 10.1111/j.1751-228X.2009.01075.x

Woodcock, R. W., McGrew, K. S., and Mather, N. (2001). *Woodcock-Johnson III Tests of Achievement*. Itasca: Riverside Publishing.

Zago, L., Pesenti, M., Mellet, E., Crivello, F., Mazoyer, B., and Tzourio-Mazoyer, N. (2001). Neural correlates of simple and complex mental calculation. *Neuroimage* 13, 314–327. doi: 10.1006/nimg.2000.0697

Zarnhofer, S., Braunstein, V., Ebner, F., Koschutnig, K., Neuper, C., Reishofer, G., et al. (2012). The influence of verbalization on the pattern of cortical activation during mental arithmetic. *Behav. Brain Funct.* 8:1. doi: 10.1186/1744-9081-8-13

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

frontiers in Psychology

PERSPECTIVE
published: 15 September 2016
doi: 10.3389/fpsyg.2016.01318

CrossMark

An Extension of the Procedural Deficit Hypothesis from Developmental Language Disorders to Mathematical Disability

Tanya M. Evans[1] and Michael T. Ullman[2]**

[1] Department of Psychiatry and Behavioral Sciences, Stanford University School of Medicine, Stanford, CA, USA, [2] Brain and Language Laboratory, Department of Neuroscience, Georgetown University, Washington, DC, USA

Mathematical disability (MD) is a neurodevelopmental disorder affecting math abilities. Here, we propose a new explanatory account of MD, the procedural deficit hypothesis (PDH), which may further our understanding of the disorder. According to the PDH of MD, abnormalities of brain structures subserving the procedural memory system can lead to difficulties with math skills learned in this system, as well as problems with other functions that depend on these brain structures. This brain-based account is motivated in part by the high comorbidity between MD and language disorders such as dyslexia that may be explained by the PDH, and in part by the likelihood that learning automatized math skills should depend on procedural memory. Here, we first lay out the PDH of MD, and present specific predictions. We then examine the existing literature for each prediction, while pointing out weaknesses and gaps to be addressed by future research. Although we do not claim that the PDH is likely to fully explain MD, we do suggest that the hypothesis could have substantial explanatory power, and that it provides a useful theoretical framework that may advance our understanding of the disorder.

Keywords: procedural deficit hypothesis, math disability, dyscalculia, math, dyslexia, specific language impairment, procedural memory, intraparietal sulcus

OPEN ACCESS

Edited by:
Bert De Smedt, KU Leuven, Belgium

Reviewed by:
Dana Ganor-Stern, Achva Academic College, Israel
Jérôme Prado, Centre National de la Recherche Scientifique, France

Correspondence:
Tanya M. Evans
evanst@stanford.edu
Michael T. Ullman
michael@georgetown.edu

Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *08 February 2016*
Accepted: *18 August 2016*
Published: *15 September 2016*

Citation:
Evans TM and Ullman MT (2016) An Extension of the Procedural Deficit Hypothesis from Developmental Language Disorders to Mathematical Disability. Front. Psychol. 7:1318. doi: 10.3389/fpsyg.2016.01318

INTRODUCTION

Children show marked individual differences in their mathematical abilities (Geary, 1994). Mathematical disability (MD), which includes developmental dyscalculia, is a neurodevelopmental disorder in which math abilities are lower than expected given the individual's age, where the difficulties are not better accounted for by intellectual disability, other developmental disorders, or neurological or motor disorders (American Psychiatric Association, 2013). MD affects 7–10% of school-age children worldwide (Gross-Tsur et al., 1996; Shalev et al., 2000), and can persist as functional innumeracy into adolescence and adulthood (Geary et al., 2013). Whereas the development of math skills in typically developing (TD) children is characterized by improvements in math performance and more efficient problem-solving strategies (Butterworth, 2005), children with MD continue to rely on immature strategies, and make more calculation errors than their TD peers (Geary et al., 1992).

Mathematical disability is highly comorbid with dyslexia (Lewis et al., 1994; Wilson et al., 2015), and may be comorbid with specific language impairment (SLI) as well (Fazio, 1999; Donlan, 2003;

Archibald et al., 2013). It has been suggested that the neurobiological basis for this overlap between MD and dyslexia could be either (1) Additive (from independent neural insults) or (2) Domain general (due to the dysfunction of mechanisms that underlie both domains, in particular of either verbal or non-verbal mechanisms) (Ashkenazi et al., 2013a). Here, we propose a domain-general framework whereby aberrations of procedural memory circuitry may provide explanatory value for these cross-domain impairments.

Previous research suggests that certain neurodevelopmental disorders, in particular those affecting reading and language, may be at least partly explained by the procedural deficit hypothesis (PDH; Ullman, 2004; Ullman and Pierpont, 2005; Nicolson and Fawcett, 2007; Lum et al., 2013, 2014; Ullman et al., accepted). Under this view, dyslexia and SLI may be partly or even largely accounted for by abnormalities of brain structures underlying procedural memory, a system that is critical for learning automatized skills (see the section "The Procedural Deficit Hypothesis of Mathematical Disability" for more on the system). These abnormalities are posited to help explain the observed reading and language difficulties, as well as accompanying impairments of other functions that depend on these brain structures (Ullman, 2004; Ullman and Pierpont, 2005). For example, according to the PDH of SLI, the frontal/basal-ganglia abnormalities in the disorder can explain the observed deficits of procedural memory (e.g., of sequence learning), grammar (which appears to rely on procedural memory; Ullman, 2004, 2016), and other functions (e.g., working memory) that depend on these brain structures (Ullman and Pierpont, 2005; Lum et al., 2014; Ullman et al., accepted).

Here, we propose that this brain-based framework may also apply to MD. The extension of the PDH to MD is primarily motivated by the following factors. First, since MD is comorbid with dyslexia and possibly SLI, these disorders may share causal mechanisms. Second, it seems likely that procedural memory underlies certain aspects of math, particularly automatized math skills, which should thus show deficits following aberrations to this system. Third and more generally, an explanatory account involving learning processes seems reasonable, since math (like reading and language) has to be largely if not entirely learned; moreover, learning difficulties might be expected in a developmental 'learning disorder' (American Psychiatric Association, 2013). Finally, like developmental disorders of reading and language, MD is neurodevelopmental in origin, and thus a brain-based account could have substantial explanatory power (Ullman and Pierpont, 2005).

We therefore posit that, like dyslexia and SLI, MD can be at least partly explained by abnormalities of brain structures underlying the procedural memory system – though we emphasize that we do not suggest that all aspects of MD are explained by this hypothesis. Importantly, the PDH of MD makes quite specific predictions, and thus the hypothesis can be directly tested. In this paper, we first provide an overview of the PDH of MD and lay out its main predictions. Next, for each prediction, we briefly examine existing evidence and empirical gaps. Since this is a new hypothesis, little evidence exists thus far. Thus, the goal of this paper is primarily to guide future research to examine the validity and utility of this novel perspective.

THE PROCEDURAL DEFICIT HYPOTHESIS OF MATHEMATICAL DISABILITY

The PDH posits that MD is at least partly explained by abnormalities of brain structures underlying procedural memory. According to the PDH, these abnormalities, which may be caused by a variety of etiologies, should result in problems with various functions that depend on the affected structures, including procedural memory itself (Ullman and Pierpont, 2005; Ullman et al., accepted).

Procedural memory is relatively well understood, from both animal and human studies (for more details on the system and its functions, including the development of automaticity, see Ullman, 2004, 2016; Doyon et al., 2009; Ashby et al., 2010). (Note the term "procedural" is generally used differently in the math literature, where "procedure" is often used interchangeably with "strategy"; also see the section "Difficulties with Aspects of Math that Depend on Procedural Memory"). The procedural memory brain system underlies the implicit learning and processing of a wide range of perceptual-motor and cognitive skills across domains, including motor skills, navigation, sequences, rules, and categories. (Here, procedural memory refers to a particular brain system, rather than implicit memory more generally, which is how some researchers use the term). This system may be specialized for learning to predict, such as the next item in a sequence or the output of a rule. Learning in procedural memory requires practice, and thus typically takes time. However, what is eventually learned seems to be processed rapidly and automatically. The process of automatization is still not well understood. However, typically an initial stage of rapid improvement in performance is followed by a gradual decrease in the learning rate and a trend toward an asymptote, together with the emergence of automaticity (Korman et al., 2003; Hauptmann et al., 2005).

Procedural memory depends on a network of interconnected frontal, parietal, basal ganglia, cerebellar, and other brain structures (Ullman, 2004, 2016; Doyon et al., 2009; Ashby et al., 2010). Each structure contributes somewhat different functions. For example, the basal ganglia (especially the caudate nucleus) seem to play a critical role in learning and consolidating new skills, particular during early stages, whereas neocortical regions, including frontal areas [especially (pre)motor and related cortex, including BA 6 and BA 44], may be more important for processing skills after they have been automatized. Parietal cortex (especially the intraparietal sulcus and adjacent supramarginal gyrus) also plays a role (Ullman, 2004), perhaps in part as a repository of stored skills (Heilman et al., 1997). Indeed, parietal cortex, including the intraparietal sulcus, seems to play a role in automatization, for both math (Grabner et al., 2009, 2013) and motor skills (Sakai et al., 1998; Hikosaka et al., 2002).

The PDH of MD makes a number of predictions. Here we lay out the five main ones. First, MD should be associated with abnormalities of brain structures underlying procedural memory. Because this is a neuroanatomical hypothesis, it makes no claims as to what etiologies or types of neuropathology should lead to these abnormalities. Indeed, at least in SLI, numerous genetic and environmental factors appear to lead to the basal ganglia abnormalities that may underlie the disorder (Ullman and Pierpont, 2005; Ullman et al., accepted). In principle, any of the brain structures subserving procedural memory could be affected in MD. Thus, the PDH focuses on brain networks, or circuitry, rather than on a specific structure (Ullman and Pierpont, 2005). Given that the various brain structures have different functions, the types of procedural memory dysfunctions in MD should depend on which structure(s) are affected (Ullman and Pierpont, 2005). For example, basal ganglia abnormalities should lead to different types of procedural memory dysfunction than parietal abnormalities. However, MD explained by the PDH is only likely if the abnormalities affect those portions of the structures that actually underlie procedural memory. For example, not all parts of parietal cortex or the basal ganglia play roles in procedural memory, and thus abnormalities of these structures will not necessarily lead to procedural memory deficits (Ullman and Pierpont, 2005). Although it remains to be seen which portions are critical for procedural memory, some patterns are already emerging (e.g., within the basal ganglia, the caudate nucleus seems crucial; see above).

Second, abnormalities of neural substrates that subserve procedural memory could of course lead to dysfunctions of procedural memory itself, such as in the automatization of skills that rely on this system (Ullman and Pierpont, 2005). Such abnormalities may therefore cause impairments of math skills that depend on procedural memory, including their automatization. Since the different brain structures of procedural memory have different functional roles, the nature of the math impairments should depend on which brain structures are affected.

Third, these abnormalities may also be expected to lead to broader impairments of procedural memory, beyond math skills. Even if procedural memory circuits turn out to be subspecialized for different types of procedures, such as for math or grammar (for which there is no clear evidence at this point; Ullman et al., 2014), neurobiological abnormalities seem unlikely to be restricted to this subcircuitry alone, leading to a probability of at least somewhat broader problems with procedural memory (Ullman and Pierpont, 2005). Of course if no such subspecialization for math or certain math skills exists, abnormalities of procedural memory circuitry should also result in broader procedural memory impairments. Thus, MD individuals whose math difficulties are at least partly explained by the PDH may show impairments of other skills that seem to depend on this system, such as perceptual-motor skills, navigation, sequences, rules, categories, grammar, and reading.

Fourth, the posited neurobiological abnormalities may affect non-procedural functions as well, since the abnormalities may also extend beyond portions of the circuitry that subserve procedural memory (Ullman and Pierpont, 2005). For example, the frontal/basal ganglia structures affected in SLI also subserve non-procedural functions such as working memory and temporal processing, which may explain the deficits of these functions in the disorder (Ullman and Pierpont, 2005). Thus, individuals with MD may also have difficulties with apparently non-procedural functions such as working memory, attention, inhibitory control, and temporal processing, all of which depend on brain structures underlying procedural memory (Ullman, 2004; Ullman and Pierpont, 2005).

Fifth, the posited impairments of procedural and non-procedural functions such as of grammar, reading, motor skills, and attention could result in comorbidities between MD and disorders of these domains, such as SLI, dyslexia, developmental coordination disorder (DCD), and ADHD, at least where these disorders are due to abnormalities of brain structures that underlie procedural memory (Ullman, 2004; Ullman and Pierpont, 2005). The presence of particular comorbidities may be explained in part by the particular procedural and non-procedural (sub)circuits that are affected.

To avoid confusion about the nature of the PDH, we emphasize that while mathematical difficulties are predicted to result from procedural memory deficits, they can also be caused by other factors. These could arise either from abnormalities of brain structures that underlie other functions in addition to procedural memory, or from abnormalities of other (completely non-procedural) brain structures (since etiologies that affect procedural memory brain structures could also affect other structures; Ullman and Pierpont, 2005). In either case, non-procedural impairments could lead to math difficulties in various ways. For example, it has been suggested that MD may be explained by impairments of working memory, attention, or inhibitory control (see next paragraph), all of which may result from the neural abnormalities posited by the PDH. Additionally, since verbal abilities may be important for aspects of math (Dehaene and Cohen, 1995; Prado et al., 2011; Evans et al., 2014), any language deficits from abnormalities to non-procedural (or procedural) circuitry could also lead to mathematical difficulties. In sum, the posited existence of individuals whose math difficulties are explained by procedural impairments in no way precludes math deficits explained by non-procedural functions, even in the same, let alone other, individuals.

We summarize the five main predictions of the PDH of MD in **Table 1**, where they are compared with analogous predictions from other accounts of MD (Szucs et al., 2013), in particular the magnitude representation (core numerosity) deficit hypothesis (Piazza et al., 2007, 2010; Rousselle and Noël, 2007; Butterworth, 2010), the spatial working memory deficit hypothesis (Geary, 2004; Rotzer et al., 2009), the attention deficit hypothesis (Ashkenazi et al., 2009; Ashkenazi and Henik, 2010; Hannula et al., 2010; Henik et al., 2011), and the inhibitory control deficit hypothesis (Espy et al., 2004). As can be seen in the Table, although some of the predictions of the PDH are also made by other accounts, the full set of predictions

TABLE 1 | Predictions of the procedural deficit hypothesis (PDH) compared to other accounts of mathematical disability (MD).

	Procedural deficit hypothesis	Magnitude representation deficit hypothesis	Spatial working memory deficit hypothesis	Attention deficit hypothesis	Inhibitory control deficit hypothesis
Prediction 1: Abnormalities of brain structures underlying procedural memory	Yes	Yes (intraparietal sulcus)	Yes? (not clearly specified)	Yes? (not clearly specified)	Yes? (not clearly specified)
Prediction 2: Difficulties with aspects of math that depend on procedural memory	Yes	None of these four hypotheses specifically predict difficulties with those aspects of math posited to depend on procedural memory.			
Prediction 3: Difficulties with procedural memory in other domains	Yes	None of these four hypotheses predict difficulties with procedural memory in other domains.			
Prediction 4: Difficulties with non-procedural functions that rely on brain structures subserving procedural memory	Yes	Yes (magnitude representation)	Yes (spatial working memory)	Yes (attention)	Yes (inhibitory control)
Prediction 5: Comorbidity with other developmental disorders that may be explained by the PDH	Yes	No	No	Possibly ADHD	Possibly ADHD

allows them to be distinguished. Moreover, we underscore that whereas most other accounts explain MD largely in terms of processing deficits related to particular functions, the PDH posits the dysfunction of a *brain system*, which is moreover involved in *learning*. Thus, while each competing account can explain a particular non-mathematical deficit (e.g., the working memory deficit hypothesis can account for working memory problems, and resulting math difficulties), as we have seen above the PDH can explain a wide range of deficits, since it is a brain-based rather than functional account. Note that even the magnitude representation deficit hypothesis, which is also neuroanatomically grounded (see **Table 1**), differs in spirit from the PDH, in that it focuses on a single brain structure and a single function, rather than the system-wide approach taken by the PDH, which moreover specifically makes the broader claim that any other functions that depend on these brain structures should also be impaired. Finally, given that math must be learned, and MD is a developmental disorder, moreover one that is characterized as a 'learning disorder' (American Psychiatric Association, 2013), a learning account may prove to have important explanatory power.

EVIDENCE, GAPS, AND FUTURE RESEARCH

Here, we present evidence to date for each of the five main predictions of the PDH of MD, and identify gaps and future areas of research.

Abnormalities of Brain Structures Underlying Procedural Memory

Math disability explained by the PDH should be accompanied by abnormalities in one or more brain structures that underlie procedural memory. A number of these brain structures have already been implicated in MD, even though these abnormalities have thus far not been interpreted from the perspective of the PDH.

Perhaps the most consistently implicated procedural memory brain structure in MD to date is parietal cortex, in particular the intraparietal sulcus, with both structural (Molko et al., 2003; Rotzer et al., 2008; Rykhlevskaia et al., 2009) and functional (Ashkenazi et al., 2012; Rosenberg-Lee et al., 2015) abnormalities localized to this region. Aberrant activity in children with MD has also been found in inferior parietal cortex, in particular the supramarginal gyrus (Ashkenazi et al., 2012). Given the role of the intraparietal sulcus and inferior parietal cortex in procedural memory (see the section "The Procedural Deficit Hypothesis of Mathematical Disability"), dysfunction of these regions in MD could lead to procedural memory difficulties, consistent with the PDH.

Other portions of the procedural memory network have also been implicated in MD. Inferior and other frontal abnormalities, including of BA 6 and 44, have been found in children with developmental dyscalculia (Rotzer et al., 2008; Ashkenazi et al., 2012; Rosenberg-Lee et al., 2015). Additionally, abnormal activity during calculation has been observed in the basal ganglia, specifically in the caudate nucleus, both in children with developmental dyscalculia and those with Turner Syndrome, which is also associated with math impairments (Molko et al., 2003). Interestingly, basal ganglia lesions have also been associated with acquired acalculia (Delazer et al., 2004; Roşca, 2009). We are not aware of any abnormalities of cerebellar structures associated with MD.

Difficulties with Aspects of Math That Depend on Procedural Memory

The PDH of MD posits that MD is explained at least in part by the dysfunction of aspects of math that depend on procedural memory. Although research linking MD to this memory system is still sparse, some evidence suggests that certain aspects of math, including some that seem automatized and are characteristically impaired in MD, depend on this system. As discussed above, procedural memory underlies a wide range of functions, including sequences, rules, and categories, and thus various aspects of math could depend on it.

Several aspects of math learning can be linked to procedural memory, most notably arithmetic (e.g., addition or subtraction). The achievement of arithmetic fluency involves children initially using effortful "procedural" strategies (e.g., counting strategies for addition), but eventually automatizing these processes (Siegler, 1996). Although this is often characterized as a shift from effortful strategies to the retrieval of math facts (e.g., "$2 + 3 = 5$"), it has alternatively been suggested, consistent with learning in procedural memory, that "procedural" strategies simply become automatized, accounting for observed increases in speed (Baroody, 1983, 1984; Fayol and Thevenot, 2012; Barrouillet and Thevenot, 2013; Prado et al., 2014; Thevenot et al., 2016; Uittenhove et al., 2016). It has been additionally suggested that this proceduralization of arithmetic computations is analogous to the proceduralization of computations in grammar (Baroody, 1983), which in fact have been closely linked to the procedural memory system (Ullman, 2004, 2015, 2016). At the brain level, the circuitry involved in procedural memory (Ullman, 2004, 2016) overlaps considerably with the network subserving arithmetic processing [which includes the intraparietal sulcus, inferior parietal cortex, ventrolateral prefrontal cortex (especially BA 44 for automatized processing; Maruyama et al., 2012; Jeon and Friederici, 2015), and the basal ganglia, as well as the medial temporal lobe and other structures; Menon, 2014], underscoring a possible dependence of arithmetic on the procedural memory system (see the section "Future Directions and Conclusion" for discussion of the medial temporal lobes and declarative memory). Finally, consistent with the predictions of the PDH, children with MD have particular problems with arithmetic, especially with its automatization (Geary, 2004). Although these problems have often been characterized as retrieval deficits (Price and Ansari, 2013), they may also be consistent with difficulties automatizing computations in procedural memory.

Other aspects of math skills that are impaired in children with MD might also involve procedural memory. For example, the count sequence, which eventually becomes highly automatized, is difficult to master for children with MD (Geary, 2004). Similarly, magnitude representation seems to be at least partly implicit and learned, depends on the intraparietal sulcus, and is problematic in MD (Price and Ansari, 2013). Future research seems warranted to examine these and other math skills whose dysfunction in MD may be explained by the PDH – in particular math skills that show behavioral and/or neural signatures of procedural memory, such as being implicit, automatized, or reliant on procedural memory brain structures (Ullman, 2016).

As mentioned above, given the varied functional roles of the brain structures that constitute the procedural memory system, abnormalities of the different structures may result in somewhat different specific deficits, though all could lead to impaired automatization. For example, abnormalities of the caudate nucleus could result in problems with early stages of learning math skills, thus potentially precluding their later automatization, whereas neocortical abnormalities, such as of BA 44, may lead to problems processing automatized routines. We believe that future research should be able to identify which brain abnormalities lead to what types of impairments in automatized math skills in MD.

Difficulties with Procedural Memory in Other Domains

As discussed above, the posited procedural memory dysfunction in MD likely extends beyond the domain of math. In principle, procedural memory impairments could be found in any domain, with the exact manifestation depending on which portions of procedural memory structures are impacted, and which aspects of procedural memory they support. Thus, like the PDH of SLI (Ullman and Pierpont, 2005), the PDH of MD predicts that procedural memory deficits may be found across a range of tasks. These could include, for example, motor skill learning (e.g., in the rotary pursuit task), sequence learning (e.g., in serial reaction time tasks), probabilistic learning (e.g., in weather prediction tasks), or artificial grammar learning; see Ullman and Pierpont (2005) and Ullman (2016). The exact pattern of procedural memory deficits could reveal the nature of the posited procedural memory impairments in MD. For example, recent evidence suggests that the procedural memory deficits in SLI may particularly affect the acquisition of sequences, perhaps especially their consolidation, consistent with the associated grammatical impairments (Hedenius et al., 2011; Hsu and Bishop, 2014; Lum et al., 2014). We are not aware of any published studies examining procedural learning or consolidation in MD, leaving an important gap for future studies to address. Interestingly, however, MD has been linked to motor skill deficits (Rosenberg, 1989), consistent with procedural memory impairments.

Difficulties with Non-procedural Functions That Rely on Brain Structures Subserving Procedural Memory

Since the brain structures underlying procedural memory also subserve other, non-procedural, functions, abnormalities of these structures may additionally result in deficits of these functions – with the nature and extent of the deficits depending on which portions of which structures are affected, and what functions they subserve (see the section "The Procedural Deficit Hypothesis of Mathematical Disability"). In the in-depth examination of the PDH of SLI presented by Ullman and Pierpont (2005), a number of such functions were examined. Consistent with extending the PDH to MD, some of these, as well as others, have also been found to be impaired in this disorder, including working memory (Ashkenazi et al., 2013b), attention (Ashkenazi and Henik, 2010; Henik et al., 2011), inhibitory control (Espy et al., 2004), and temporal processing (Vicario et al., 2012). Future research should examine the extent to which non-procedural functions that depend on procedural memory brain structures implicated in MD are affected in the disorder.

Comorbidity with Other Developmental Disorders That May be Explained by the PDH

The PDH predicts that the posited MD deficits of procedural and non-procedural functions such as of reading, grammar, motor skills, and attention may result in comorbidities between MD and disorders affecting these functions, where these disorders are explained by abnormalities of brain structures underlying procedural memory. Here, we lay out these and related predictions (going beyond the basic claims that partially motivated the PDH of MD), briefly review the literature, and point out gaps in the research.

As discussed above, MD is highly comorbid with dyslexia (Wilson et al., 2015). Nearly two-thirds of children with math difficulties also have reading difficulties (Lewis et al., 1994). Conversely, about one-third of children with reading problems also have math problems (Lewis et al., 1994). Even children with dyslexia with math scores in the normal range show subtle deficits in arithmetic performance (Simmons and Singleton, 2008), and utilize immature strategies for arithmetic problems (Boets and De Smedt, 2010). The PDH predicts common brain abnormalities between MD and dyslexia, and possibly shared etiologies as well. Indeed, like MD, dyslexia is associated with abnormalities of inferior parietal regions (including the intraparietal sulcus), inferior frontal regions (including BA 44 and BA 6), and the basal ganglia (in particular the caudate nucleus) (Eckert et al., 2003, 2005; Richlan, 2012). Further, candidate susceptibility genes for dyslexia (e.g., ROBO1) also appear to contribute to math difficulties (Mascheretti et al., 2014).

Evidence also suggests comorbidity of MD and SLI. Individuals with MD may show indications of SLI (Archibald et al., 2013), while conversely, and better studied, individuals with SLI show various math impairments (Fazio, 1994, 1996, 1999; Arvedson, 2002; Donlan, 2003; Cowan et al., 2005; Donlan et al., 2007). As expected by the PDH, SLI, like MD, is associated with abnormalities of procedural memory brain structures, in particular the basal ganglia (especially the caudate nucleus) and inferior frontal structures (including BA 44 and BA 6), as well as (though more weakly) inferior parietal abnormalities (Ullman and Pierpont, 2005; Ullman et al., accepted). However, to date less research has examined MD comorbidity with SLI than with dyslexia, leaving an important gap for future research.

The PDH also predicts that individuals with dyslexia or SLI should tend to show particular difficulties in aspects of math that depend on procedural memory. Indeed, problems with arithmetic have been found in both dyslexia (Simmons and Singleton, 2008; Boets and De Smedt, 2010) and SLI (Fazio, 1996; Donlan et al., 2007). Additionally, difficulties with the count sequence have been found both in dyslexia (Ackerman et al., 1990; Gobel and Snowling, 2010) and SLI (Fazio, 1994, 1996).

The nature and extent of the comorbidities between MD and either dyslexia or SLI should depend on which procedural memory structures underlie each disorder. For example, if MD is caused primarily by procedural memory dysfunction from parietal abnormalities (see above), whereas SLI is characterized mainly by frontal/basal-ganglia insults (Ullman and Pierpont, 2005; Ullman et al., accepted), the likelihood of their comorbidity will be lower than between disorders with abnormalities in the same procedural memory structures. Interestingly, dyslexia, like MD, is strongly associated with parietal abnormalities (in particular of the left inferior parietal lobe; Richlan, 2012), perhaps helping explain the high comorbidity between these two disorders.

Other disorders may also be expected to be comorbid with MD. In brief, any neurodevelopmental disorder involving abnormalities of brain structures underlying procedural memory could be comorbid with MD, with the likelihood of comorbidity depending to what extent the same (portions of) structures are affected in both disorders. Indeed, at least DCD and ADHD are promising candidates, since both are associated with abnormalities of procedural memory structures (Krain and Castellanos, 2006; Kashiwagi and Tamai, 2013; Peters et al., 2013; Sidlauskaite et al., 2015), and both have been linked to math difficulties (Kaufmann and Nuerk, 2008; Gomez et al., 2015).

FUTURE DIRECTIONS AND CONCLUSION

In sum, the PDH provides a set of clear testable predictions for MD. Importantly, our theoretical and empirical understanding of the PDH in language disorders promises to facilitate the investigation of the PDH in MD, even beyond the predictions laid out above. For example, previous work in language disorders suggests that consolidation problems of procedural memory (Hedenius et al., 2011) may also be important in MD. Moreover, the hippocampus-based declarative memory system, which appears to remain relatively spared in SLI and dyslexia (Ullman and Pullman, 2015), may also be important in MD: not only because in language disorders it plays compensatory roles for procedural memory-based impairments (Ullman and Pullman, 2015), but also because it seems to underlie aspects of learning math facts (Cho et al., 2012; Qin et al., 2014). Indeed, such a role for declarative memory is expected, given its importance in learning idiosyncratic information such as facts (Ullman, 2016). More generally, the roles of both declarative and procedural memory in math warrant further investigation, both in MD and TD children, since math, like language, must be largely if not entirely learned, and these are arguably the most important learning and memory systems in the brain (Ullman, 2004, 2016). That is, just as the PDH may be extended from language disorders to MD, the declarative/procedural (DP) model of language (Ullman, 2004, 2016) may be extended to an analogous DP model of math. Finally, research on language disorders suggests that understanding the roles of procedural and declarative memory may lead to important diagnostic and therapeutic advances in MD (Ullman and Pierpont, 2005; Ullman and Pullman, 2015).

Although we emphasize that we are not claiming that all MD is explained by the PDH, we suggest that the hypothesis may offer a substantial amount of explanatory power, and that it provides a useful theoretical framework that may advance our understanding of the disorder.

AUTHOR CONTRIBUTIONS

TE and MU contributed equally in conceiving of and writing the manuscript.

ACKNOWLEDGMENT

We thank Ian Lyons for his valuable input.

REFERENCES

Ackerman, P. T., Dykman, R. A., and Gardner, M. Y. (1990). Counting rate, naming rate, phonological sensitivity and memory span: major factors in dyslexia. *J. Learn. Disabil.* 23, 325–327. doi: 10.1177/002221949002300514

American Psychiatric Association (2013). *Diagnostic and Statistical Manual of Mental Disorders*, 5th Edn. Washington, DC: American Psychiatric Association.

Archibald, L. M. D., Oram Cardy, J., Joanisse, M. F., and Ansari, D. (2013). Language, reading, and math learning profiles in an epidemiological sample of school age children. *PLoS ONE* 8:e77463. doi: 10.1371/journal.pone.0077463

Arvedson, P. J. (2002). Young children with specific language impairment and their numerical cognition. *J. Speech Lang. Hear. Res.* 45, 970–982. doi: 10.1044/1092-4388(2002/079)

Ashby, F. G., Turner, B. O., and Horvitz, J. C. (2010). Cortical and basal ganglia contributions to habit learning and automaticity. *Trends Cogn. Sci.* 14, 208–215. doi: 10.1016/j.tics.2010.02.001

Ashkenazi, S., Black, J. M., Abrams, D. A., Hoeft, F., and Menon, V. (2013a). Neurobiological underpinnings of math and reading learning disabilities. *J. Learn. Disabil.* 46, 549–569. doi: 10.1177/0022219413483174

Ashkenazi, S., and Henik, A. (2010). Attentional networks in developmental dyscalculia. *Behav. Brain Funct.* 6:2. doi: 10.1186/1744-9081-6-2

Ashkenazi, S., Rosenberg-Lee, M., Metcalfe, A. W. S., Swigart, A. G., and Menon, V. (2013b). Visual-spatial working memory is an important source of domain-general vulnerability in the development of arithmetic cognition. *Neuropsychologia* 51, 2305–2317. doi: 10.1016/j.neuropsychologia.2013.06.031

Ashkenazi, S., Rosenberg-Lee, M., Tenison, C., and Menon, V. (2012). Weak task-related modulation and stimulus representations during arithmetic problem solving in children with developmental dyscalculia. *Dev. Cogn. Neurosci.* 2(Suppl. 1), S152–S166. doi: 10.1016/j.dcn.2011.09.006

Ashkenazi, S., Rubinsten, O., and Henik, A. (2009). Attention, automaticity, and developmental dyscalculia. *Neuropsychology* 23, 535–540. doi: 10.1037/a0015347

Baroody, A. J. (1983). The development of procedural knowledge: an alternative explanation for chronometric trends of mental arithmetic. *Dev. Rev.* 3, 225–230. doi: 10.1016/0273-2297(83)90031-X

Baroody, A. J. (1984). A reexamination of mental arithmetic models and data: a reply to Ashcraft. *Dev. Rev.* 4, 148–156. doi: 10.1016/0273-2297(84)90004-2

Barrouillet, P., and Thevenot, C. (2013). On the problem-size effect in small additions: can we really discard any counting-based account? *Cognition* 128, 35–44. doi: 10.1016/j.cognition.2013.02.018

Boets, B., and De Smedt, B. (2010). Single-digit arithmetic in children with dyslexia. *Dyslexia* 16, 183–191. doi: 10.1002/dys.403

Butterworth, B. (2005). The development of arithmetical abilities. *J. Child Psychol. Psychiatry* 46, 3–18. doi: 10.1111/j.1469-7610.2004.00374.x

Butterworth, B. (2010). Foundational numerical capacities and the origins of dyscalculia. *Trends Cogn. Sci.* 14, 534–541. doi: 10.1016/j.tics.2010.09.007

Cho, S., Metcalfe, A. W. S., Young, C. B., Ryali, S., Geary, D.C., and Menon, V. (2012). Hippocampal-prefrontal engagement and dynamic causal interactions in the maturation of children's fact retrieval. *J. Cogn. Neurosci.* 24, 1849–1866. doi: 10.1162/jocn_a_00246

Cowan, R., Donlan, C., Newton, E. J., and Llyod, D. (2005). Number skills and knowledge in children with specific language impairment. *J. Educ. Psychol.* 97, 732–744. doi: 10.1037/0022-0663.97.4.732

Dehaene, S., and Cohen, L. (1995). Towards an anatomical and functional model of number processing. *Math. Cogn.* 1, 83–120.

Delazer, M., Domahs, F., Lochy, A., Karner, E., Benke, T., and Poewe, W. (2004). Number processing and basal ganglia dysfunction: a single case study. *Neuropsychologia* 42, 1050–1062. doi: 10.1016/j.neuropsychologia.2003.12.009

Donlan, C. (2003). "The early numeracy of children with specific language impairments," in *The Development of Arithmetic Concepts and Skills: Constructive Adaptive Expertise*, eds A. Baroody and A. Dowker (Abingdon: Taylor & Francis), 337–358.

Donlan, C., Cowan, R., Newton, E. J., and Lloyd, D. (2007). The role of language in mathematical development: evidence from children with specific language impairments. *Cognition* 103, 23–33. doi: 10.1016/j.cognition.2006.02.007

Doyon, J., Bellec, P., Amsel, R., Penhune, V., Monchi, O., Carrier, J., et al. (2009). Contributions of the basal ganglia and functionally related brain structures to motor learning. *Behav. Brain Res.* 199, 61–75. doi: 10.1016/j.bbr.2008.11.012

Eckert, M. A., Leonard, C. M., Richards, T. L., Aylward, E. H., Thomson, J., and Berninger, V. W. (2003). Anatomical correlates of dyslexia: frontal and cerebellar findings. *Brain* 126, 482–494. doi: 10.1093/brain/awg026

Eckert, M. A., Leonard, C. M., Wilke, M., Eckert, M., Richards, T., Richards, A., et al. (2005). Anatomical signatures of dyslexia in children: unique information from manual and voxel based morphometry brain measure. *Cortex* 42, 304–315. doi: 10.1016/S0010-9452(08)70268-5

Espy, K. A., McDiarmid, M. M., Cwik, M. F., Stalets, M. M., Hamby, A., and Senn, T. E. (2004). The contribution of executive functions to emergent mathematic skills in preschool children. *Dev. Neuropsychol.* 26, 465–486. doi: 10.1207/s15326942dn2601_6

Evans, T. M., Flowers, D. L., Napoliello, E. M., Olulade, O. A., and Eden, G. F. (2014). The functional anatomy of single-digit arithmetic in children with developmental dyslexia. *Neuroimage* 101, 644–652. doi: 10.1016/j.neuroimage.2014.07.028

Fayol, M., and Thevenot, C. (2012). The use of procedural knowledge in simple addition and subtraction problems. *Cognition* 123, 392–403. doi: 10.1016/j.cognition.2012.02.008

Fazio, B. B. (1994). The counting abilities of children with specific language impairment: a comparison of oral and gestural tasks. *J. Speech Lang. Hear. Res.* 37, 358–368. doi: 10.1044/jshr.3702.358

Fazio, B. B. (1996). Mathematical abilities of children with specific language impairment: a 2-year follow-up. *J. Speech Lang. Hear. Res.* 39, 839–849. doi: 10.1044/jshr.3904.839

Fazio, B. B. (1999). Arithmetic calculation, short-term memory, and language performance in children with specific language impairment: a 5-year follow-up. *J. Speech Lang. Hear. Res.* 42, 420–431. doi: 10.1044/jslhr.4202.420

Geary, D. C. (1994). *Children's Mathematical Development: Research and Practical Applications*. Washington, DC: American Psychological Association.

Geary, D. C. (2004). Mathematics and learning disabilities. *J. Learn. Disabil.* 37, 4–15. doi: 10.1177/00222194040370010201

Geary, D. C., Bow-Thomas, C. C., and Yao, Y. (1992). Counting knowledge and skill in cognitive addition: a comparison of normal and mathematically disabled children. *J. Exp. Child Psychol.* 54, 372–391. doi: 10.1016/0022-0965(92)90026-3

Geary, D. C., Hoard, M. K., Nugent, L., and Bailey, D. H. (2013). Adolescents' functional numeracy is predicted by their school entry number system knowledge. *PLoS ONE* 8:e54651. doi: 10.1371/journal.pone.0054651

Gobel, S. M., and Snowling, M. J. (2010). Number-processing skills in adults with dyslexia. *Q. J. Exp. Psychol.* 63, 1361–1373. doi: 10.1080/17470210903359206

Gomez, A., Piazza, M., Jobert, A., Dehaene-Lambertz, G., Dehaene, S., and Huron, C. (2015). Mathematical difficulties in developmental coordination disorder: symbolic and nonsymbolic number processing. *Res. Dev. Disabil.* 4, 167–178. doi: 10.1016/j.ridd.2015.06.011

Grabner, R. H., Ansari, D., Koschutnig, K., Reishofer, G., and Ebner, F. (2013). The function of the left angular gyrus in mental arithmetic: evidence from the associative confusion effect. *Hum. Brain Mapp.* 34, 1013–1024. doi: 10.1002/hbm.21489

Grabner, R. H., Ansari, D., Koschutnig, K., Reishofer, G., Ebner, F., and Neuper, C. (2009). To retrieve or to calculate? Left angular gyrus mediates the retrieval of arithmetic facts during problem solving. *Neuropsychologia* 47, 604–608. doi: 10.1016/j.neuropsychologia.2008.10.013

Gross-Tsur, V., Manor, O., and Shalev, R. S. (1996). Developmental dyscalculia: prevalence and demographic features. *Dev. Med. Child Neurol.* 38, 25–33. doi: 10.1111/j.1469-8749.1996.tb15029.x

Hannula, M. M., Lepola, J., and Lehtinen, E. (2010). Spontaneous focusing on numerosity as a domain-specific predictor of arithmetical skills. *J. Exp. Child Psychol.* 107, 394–406. doi: 10.1016/j.jecp.2010.06.004

Hauptmann, B., Reinhart, E., Brandt, S. A., and Karni, A. (2005). The predictive value of the leveling off of within-session performance for procedural memory consolidation. *Cogn. Brain Res.* 24, 181–189. doi: 10.1016/j.cogbrainres.2005.01.012

Hedenius, M., Persson, J., Tremblay, A., Adi-Japha, E., Veríssimo, J., Dye, C. D., et al. (2011). Grammar predicts procedural learning and consolidation deficits in children with specific language impairment. *Res. Dev. Disabil.* 32, 2362–2375. doi: 10.1016/j.ridd.2011.07.026

Heilman, K. M., Watson, R. T., and Rothi, L. G. (1997). "Disorders of skilled movements: limb apraxia," in *Behavioral Neurology and Neuropsychology*, eds T. E. Feinberg and M. I. Farah (New York, NY: McGraw-Hill), 227–235.

Henik, A., Rubinsten, O., and Ashkenazi, S. (2011). The "where" and "what" in developmental dyscalculia. *Clin. Neuropsychol.* 25, 989–1008. doi: 10.1080/13854046.2011.599820

Hikosaka, O., Nakamura, K., Sakai, K., and Nakahara, H. (2002). Central mechanisms of motor skill learning. *Curr. Opin. Neurobiol.* 12, 217–222. doi: 10.1016/S0959-4388(02)00307-0

Hsu, H. J., and Bishop, D. V. (2014). Sequence-specific procedural learning deficits in children with specific language impairment. *Dev. Sci.* 17, 352–365. doi: 10.1111/desc.12125

Jeon, H. A., and Friederici, A. D. (2015). Degree of automaticity and the prefrontal cortex. *Trends Cogn. Sci.* 19, 244–250. doi: 10.1016/j.tics.2015.03.003

Kashiwagi, M., and Tamai, H. (2013). "Brain mapping of developmental coordination disorder," in *Functional Brain Mapping and the Endeavor to Understand the Working Brain*, eds F. Signorelli and D. Chirchiglia (Rijeka: Intech).

Kaufmann, L., and Nuerk, H. C. (2008). Basic number processing deficits in ADHD: a broad examination of elementary and complex number processing skills in 9- to 12-year-old children with ADHD-C. *Dev. Sci.* 11, 692–699. doi: 10.1111/j.1467-7687.2008.00718.x

Korman, M., Raz, N., Flash, T., and Karni, A. (2003). Multiple shifts in the representation of a motor sequence during the acquisition of skilled performance. *Proc. Natl. Acad. Sci. U.S.A.* 100, 12492–12497. doi: 10.1073/pnas.2035019100

Krain, A. L., and Castellanos, F. X. (2006). Brain development and ADHD. *Clin. Psychol. Rev.* 26, 433–444. doi: 10.1016/j.cpr.2006.01.005

Lewis, C., Hitch, G. J., and Walker, P. (1994). The prevalence of specific arithmetic difficulties and specific reading difficulties in 9- to 10-year-old boys and girls. *J. Child Psychol. Psychiatry* 35, 283–292. doi: 10.1111/j.1469-7610.1994.tb01162.x

Lum, J. A. G., Conti-Ramsden, G., Morgan, A. T., and Ullman, M. T. (2014). Procedural learning deficits in specific language impairment (SLI): a meta-analysis of serial reaction time task performance. *Cortex* 51, 1–10. doi: 10.1016/j.cortex.2013.10.011

Lum, J. A. G., Ullman, M. T., and Conti-Ramsden, G. (2013). Procedural learning is impaired in dyslexia: evidence from a meta-analysis of serial reaction time studies. *Res. Dev. Disabil.* 34, 3460–3476. doi: 10.1016/j.ridd.2013.07.017

Maruyama, M., Pallier, C., Jobert, A., Sigman, M., and Dehaene, S. (2012). The cortical representation of simple mathematical expressions. *Neuroimage* 61, 1444–1460. doi: 10.1016/j.neuroimage.2012.04.020

Mascheretti, S., Riva, V., Giorda, R., Beri, S., Lanzoni, L. F. E., Cellino, M. R., et al. (2014). KIAA0319 and ROBO1: evidence on association with reading and pleiotropic effects on language and mathematics abilities in developmental dyslexia. *J. Hum. Genet.* 59, 189–197. doi: 10.1038/jhg.2013.141

Menon, V. (2014). "Arithmetic in child and adult brain," in *Handbook of Mathematical Cognition*, eds R. Cohen Kadosh and A. Dowker (Oxford: Oxford University Press).

Molko, N., Cachia, A., Rivière, D., Mangin, J. F., Bruandet, M., Le Bihan, D., et al. (2003). Functional and structural alterations of the intraparietal sulcus in a developmental dyscalculia of genetic origin. *Neuron* 40, 847–858. doi: 10.1016/S0896-6273(03)00670-6

Nicolson, R. I., and Fawcett, A. J. (2007). Procedural learning difficulties: reuniting the developmental disorders? *Trends Neurosci.* 30, 135–141. doi: 10.1016/j.tins.2007.02.003

Peters, L. H. J., Maathuis, C. G. B., and Hadders-Algra, M. (2013). Neural correlates of developmental coordination disorder. *Dev. Med. Child Neurol.* 55(Suppl. 4), 59–64. doi: 10.1111/dmcn.12309

Piazza, M., Facoetti, A., Trussardi, A. N., Berteletti, I., Conte, S., Lucangeli, D., et al. (2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition* 116, 33–41. doi: 10.1016/j.cognition.2010.03.012

Piazza, M., Pinel, P., Le Bihan, D., and Dehaene, S. (2007). A magnitude code common to numerosities and number symbols in human intraparietal cortex. *Neuron* 53, 293–305. doi: 10.1016/j.neuron.2006.11.022

Prado, J., Mutreja, R., and Booth, J. R. (2014). Developmental dissociation in the neural responses to simple multiplication and subtraction problems. *Dev. Sci.* 17, 537–552. doi: 10.1111/desc.12140

Prado, J., Mutreja, R., Zhang, H., Mehta, R., Desroches, A. S., Minas, J. E., et al. (2011). Distinct representations of subtraction and multiplication in the neural systems for numerosity and language. *Hum. Brain Mapp.* 32, 1932–1947. doi: 10.1002/hbm.21159

Price, G. R., and Ansari, D. (2013). Developmental dyscalculia. *Handb. Clin. Neurol.* 111, 241–244. doi: 10.1016/B978-0-444-52891-9.00025-7

Qin, S., Cho, S., Chen, T., Rosenberg-Lee, M., Geary, D. C., and Menon, V. (2014). Hippocampal-neocortical functional reorganization underlies children's cognitive development. *Nat. Neurosci.* 17, 1263–1269. doi: 10.1038/nn.3788

Richlan, F. (2012). Developmental dyslexia: dysfunction of a left hemisphere reading network. *Front. Hum. Neurosci.* 6:120. doi: 10.3389/fnhum.2012.00120

Roşca, E. C. (2009). Arithmetic procedural knowledge: a cortico-subcortical circuit. *Brain Res.* 1302, 148–156. doi: 10.1016/j.brainres.2009.09.033

Rosenberg, P. B. (1989). Perceptual-motor and attentional correlates of developmental dyscalculia. *Ann. Neurol.* 26, 216–220. doi: 10.1002/ana.410260206

Rosenberg-Lee, M., Ashkenazi, S., Chen, T., Young, C. B., Geary, D. C., and Menon, V. (2015). Brain hyper-connectivity and operation-specific deficits during arithmetic problem solving in children with developmental dyscalculia. *Dev. Sci.* 18, 351–372. doi: 10.1111/desc.12216

Rotzer, S., Kucian, K., Martin, E., von Aster, M., Klaver, P., and Loenneker, T. (2008). Optimized voxel-based morphometry in children with developmental dyscalculia. *Neuroimage* 39, 417–422. doi: 10.1016/j.neuroimage.2007.08.045

Rotzer, S., Loenneker, T., Kucian, K., Martin, E., Klaver, P., and von Aster, M. (2009). Dysfunctional neural network of spatial working memory contributes to developmental dyscalculia. *Neuropsychologia* 47, 2859–2865. doi: 10.1016/j.neuropsychologia.2009.06.009

Rousselle, L., and Noël, M.-P. (2007). Basic numerical skills in children with mathematics learning disabilities: a comparison of symbolic vs non-symbolic number magnitude processing. *Cognition* 102, 361–395. doi: 10.1016/j.cognition.2006.01.005

Rykhlevskaia, E., Uddin, L. Q., Kondos, L., and Menon, V. (2009). Neuroanatomical correlates of developmental dyscalculia: combined evidence from morphometry and tractography. *Front. Hum. Neurosci.* 3:51. doi: 10.3389/neuro.09.051.2009

Sakai, K., Hikosaka, O., Miyauchi, S., Takino, R., Sasaki, Y., and Putz, B. (1998). Transition of brain activation from frontal to parietal areas in visuomotor sequence learning. *J. Neurosci.* 18, 1827–1840.

Shalev, R. S., Auerbach, J., Manor, O., and Gross-Tsur, V. (2000). Developmental dyscalculia: prevalence and prognosis. *Eur. Child Adolesc. Psychiatry* 9(Suppl. 2), II58–II64. doi: 10.1007/s007870070009

Sidlauskaite, J., Caeyenberghs, K., Sonuga-Barke, E., Roeyers, H., and Wiersema, J. R. (2015). Whole-brain structural topology in adult attention-deficit/hyperactivity disorder: preserved global – disturbed local network organization. *Neuroimage Clin.* 9, 506–512. doi: 10.1016/j.nicl.2015.10.001

Siegler, R. S. (1996). *Emerging Minds: The Process of Change in Children's Thinking*. New York, NY: Oxford University Press.

Simmons, F. R., and Singleton, C. (2008). Do weak phonological representations impact on arithmetic development? A review of research into arithmetic and dyslexia. *Dyslexia* 14, 77–94. doi: 10.1002/dys.341

Szucs, D., Devine, A., Soltesz, F., Nobes, A., and Gabriel, F. (2013). Developmental dyscalculia is related to visuo-spatial memory and inhibition impairment. *Cortex* 49, 2674–2688. doi: 10.1016/j.cortex.2013.06.007

Thevenot, C., Barrouillet, P., Castel, C., and Uittenhove, K. (2016). Ten-year-old children strategies in mental addition: a counting model account. *Cognition* 146, 48–57. doi: 10.1016/j.cognition.2015.09.003

Uittenhove, K., Thevenot, C., and Barrouillet, P. (2016). Fast automated counting procedures in addition problem solving: when are they used and why are they mistaken for retrieval? *Cognition* 146, 289–303. doi: 10.1016/j.cognition.2015.10.008

Ullman, M. (2016). "The declarative/procedural model: a neurobiological model of language learning, knowledge, and use," in *Neurobiology of Language*, eds G. Hickok and S. A. Small (Amsterdam: Elsevier), 953–968.

Ullman, M. T. (2004). Contributions of memory circuits to language: the declarative/procedural model. *Cognition* 92, 231–270. doi: 10.1016/j.cognition.2003.10.008

Ullman, M. T. (2015). "The declarative/procedural model: a neurobiologically-motivated theory of first and second language," in *Theories in Second Language Acquisition*, eds B. VanPatten and J. Williams (London: Routledge), 135–158.

Ullman, M. T., Lum, J. A., and Conti-Ramsden, G. (2014). "Domain specificity in language development," in *Encyclopedia of Language Development*, eds P. Brooks and V. Kempe (Los Angeles, CA: Sage Publications).

Ullman, M. T., and Pierpont, E. I. (2005). Specific language impairment is not specific to language: the procedural deficit hypothesis. *Cortex* 41, 399–433. doi: 10.1016/S0010-9452(08)70276-4

Ullman, M. T., and Pullman, M. Y. (2015). A compensatory role for declarative memory in neurodevelopmental disorders. *Neurosci. Biobehav. Rev*. 51, 205–222. doi: 10.1016/j.neubiorev.2015.01.008

Ullman, M. T., Pullman, M., Lovelett, J. T., Pierpont, E. I, and Turkeltaub, P. E. (accepted). The neuroanatomy of specific language impairment. *Annu. Rev. Psychol.*

Vicario, C. M., Rappo, G., Pepi, A., Pavan, A., and Martino, D. (2012). Temporal abnormalities in children with developmental dyscalculia. *Dev. Neuropsychol.* 37, 636–652. doi: 10.1080/87565641.2012.702827

Wilson, A. J., Andrewes, S. G., Struthers, H., Rowe, V. M., Bogdanovic, R., and Waldie, K. E. (2015). Dyscalculia and dyslexia in adults: cognitive bases of comorbidity. *Learn. Individ. Differ.* 37, 118–132. doi: 10.1016/j.lindif.2014.11.017

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

frontiers in Psychology

ORIGINAL RESEARCH
published: 10 June 2016
doi: 10.3389/fpsyg.2016.00803

Shared and Unique Risk Factors Underlying Mathematical Disability and Reading and Spelling Disability

Esther M. Slot[1], Sietske van Viersen[2], Elise H. de Bree[2] and Evelyn H. Kroesbergen[3]*

[1] Department of Education, Faculty of Social and Behavioral Sciences, Utrecht University, Utrecht, Netherlands, [2] Research Institute of Child Development and Education, University of Amsterdam, Amsterdam, Netherlands, [3] Department of Special Education, Utrecht University, Utrecht, Netherlands

High comorbidity rates have been reported between mathematical learning disabilities (MD) and reading and spelling disabilities (RSD). Research has identified skills related to math, such as number sense (NS) and visuospatial working memory (visuospatial WM), as well as to literacy, such as phonological awareness (PA), rapid automatized naming (RAN) and verbal short-term memory (Verbal STM). In order to explain the high comorbidity rates between MD and RSD, 7–11-year-old children were assessed on a range of cognitive abilities related to literacy (PA, RAN, Verbal STM) and mathematical ability (visuospatial WM, NS). The group of children consisted of typically developing (TD) children ($n = 32$), children with MD ($n = 26$), children with RSD ($n = 29$), and combined MD and RSD ($n = 43$). It was hypothesized that, in line with the multiple deficit view on learning disorders, at least one unique predictor for both MD and RSD and a possible shared cognitive risk factor would be found to account for the comorbidity between the symptom dimensions literacy and math. Secondly, our hypotheses were that (a) a probabilistic multi-factorial risk factor model would provide a better fit to the data than a deterministic single risk factor model and (b) that a shared risk factor model would provide a better fit than the specific multi-factorial model. All our hypotheses were confirmed. NS and visuospatial WM were identified as unique cognitive predictors for MD, whereas PA and RAN were both associated with RSD. Also, a shared risk factor model with PA as a cognitive predictor for both RSD and MD fitted the data best, indicating that MD and RSD might co-occur due to a shared underlying deficit in phonological processing. Possible explanations are discussed in the context of sample selection and composition. This study shows that different cognitive factors play a role in mathematics and literacy, and that a phonological processing deficit might play a role in the occurrence of MD and RSD.

Keywords: reading and spelling disability, mathematical learning disability, comorbidity, multiple deficit model, phonological processing

Edited by:
Bert De Smedt,
KU Leuven, Belgium

Reviewed by:
Karin Landerl,
University of Graz, Austria
Joerg-Tobias Kuhn,
Westfälische Wilhelms-Universität Münster, Germany

****Correspondence:***
Esther M. Slot
e.m.slot@uu.nl

Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *05 February 2016*
Accepted: *12 May 2016*
Published: *10 June 2016*

Citation:
Slot EM, van Viersen S, de Bree EH and Kroesbergen EH (2016) Shared and Unique Risk Factors Underlying Mathematical Disability and Reading and Spelling Disability. Front. Psychol. 7:803. doi: 10.3389/fpsyg.2016.00803

INTRODUCTION

During these last years, there has been a shift from interpreting developmental learning disabilities as being caused by one single underlying deficit to being the result of multiple (interacting) etiological influences (e.g., Pennington, 2006; McGrath et al., 2011; Van Bergen et al., 2014). The single-deficit model, which assumes that learning disabilities arise from one core underlying deficit, is considered to be too deterministic (Pennington, 2006). In contrast, multiple-deficit models assume that several cognitive weaknesses contribute to the development of a specific learning disability, where some cognitive deficits are seen as unique cognitive risk factors and others are shared between disabilities. These shared risk factors may account for a greater than expected co-occurrence between disabilities, i.e., comorbidity. Multiple-deficit models can therefore be a powerful method to study comorbidity between neurodevelopmental disabilities (see e.g., McGrath et al., 2011; Willcutt et al., 2013).

Despite the increasing attention on multiple-deficit models, relatively few studies have examined possible shared cognitive risk factors between mathematical disability (MD) and reading and spelling disability (RSD). Children with MD experience persistent difficulties with numerosity, especially understanding conceptual properties of numbers and acquiring number fact knowledge (Cirino et al., 2007; Geary, 2013). RSD is defined as a persistent difficulty in acquiring basic reading and/or spelling subskills such as word identification and phonological decoding (Vellutino et al., 2004; Rose, 2009). Comorbidity prevalence rates between MD and RSD are substantial, ranging from 11 to 70% (Lewis et al., 1994; Gross-Tsur et al., 1996; Von Aster et al., 2007; Landerl and Moll, 2010; Moll et al., 2014a) rendering the question of whether there are shared risk factors between the two. The present study includes specific as well as shared cognitive predictors for MD and RSD into a multi-factorial risk model in order to test the extent to which we can account for comorbidity between the two symptom dimensions of math and literacy.

For MD, research has indicated that impairments might exist in WM, leading to difficulty with executing calculation procedures and learning arithmetic facts (e.g., Schuchardt et al., 2008; Geary et al., 2009; Raghubar et al., 2010). In addition, a central deficit in the processing of number magnitude information might be related to MD (i.e., number sense, NS; Wilson and Dehaene, 2007; Landerl et al., 2009; Moeller et al., 2012; Kroesbergen and Van Dijk, 2015). However, whether these number processing deficiencies are specific to symbolic magnitudes (i.e., numbers; Rousselle and Noël, 2007) or also involve non-symbolic magnitudes (e.g., dots; Landerl et al., 2009; Moll et al., 2015) is still debated. Furthermore, some studies have found rapid automatized naming (RAN) to be impaired in children with MD (De Weerdt et al., 2013; Willcutt et al., 2013; Donker et al., 2016), but others have not (e.g., Landerl et al., 2009). RAN is considered to be the ability to access and retrieve phonological representations rapidly from long-term memory (Willburger et al., 2008). Recently, Donker et al. (2016) reported that only non-alphanumeric RAN (i.e., RAN colors and pictures) was impaired in children with MD, but not alphanumeric RAN (i.e., RAN of letters and digits). They hypothesize that children with MD might be impaired in a process called *conceptual* processing (i.e., recalling semantic information from memory), required for non-alphanumeric RAN, but less for alphanumeric RAN, which mainly taps print-to-sound translation processes (access-deficit).

A large body of evidence has indicated specific risk factors related to RSD. Phonological awareness (PA), the ability to recognize and manipulate individual speech sounds (phonemes) and combinations of speech sounds, has been found to be significantly related to the development of RSD (Vellutino et al., 2004). In addition, poorer RAN (Willburger et al., 2008) and reduced verbal short term memory (Verbal STM) capacity (Swanson et al., 2009) have been identified as possible risk factors associated with RSD. Note, however, that the contributions of PA, RAN and Verbal STM can differ between orthographies and ages (e.g., De Jong and Van der Leij, 1999, 2003; Georgiou et al., 2008; Smythe et al., 2008; Landerl et al., 2013; Moll et al., 2014b). Furthermore, the risk factors can contribute differently to reading and spelling (e.g., Moll and Landerl, 2009; Georgiou et al., 2012; Moll et al., 2014c). These findings do not always fully endorse the (universal) presence of these risk factors to the same extent (e.g., Pennington et al., 2012).

Despite the fact that MD and RSD co-occur at a greater-than-chance level, a limited number of studies have systematically examined the overlap between RSD and MD (e.g., Landerl et al., 2004, 2009; Willcutt et al., 2013; Moll et al., 2014c; Cirino et al., 2015; Donker et al., 2016; Peterson et al., 2016). These studies identified risk factors specific to MD (i.e., visuospatial WM, NS) and RSD (i.e., PA), as well as potentially shared risk factors (i.e., WM, processing speed, verbal comprehension, phonological processing; Geary et al., 2000; Willburger et al., 2008; Landerl et al., 2009; Willcutt et al., 2013; Donker et al., 2016). However, many of these studies were focused on a specific sample of children (e.g., twins), or a small set of risk factors (e.g., WM). Here, we contribute to this matter by including multiple specific risk factors for both MD (visuospatial WM, NS) and RSD (alphanumeric and non-alphanumeric RAN, PA, Verbal STM) and by further developing the line of inquiry initiated by Geary (1993), Landerl et al. (2009), and Wilson et al. (2015) on the potential role of phonological processing as a shared risk factor for MD and RSD. In order to maximize variation in the symptom dimensions (math, i.e., fact retrieval and complex math skills, and literacy, i.e., spelling and reading) we tested our multi-factorial (comorbidity) model in a broad sample, including typically developing (TD) children as well as children with MD and/or RSD.

The goal of this study was to assess whether the multiple risk model can account for the comorbidity between MD and RSD by studying the contribution of different cognitive skills to math and literacy outcomes. It was hypothesized that in line with the multiple-deficit view we would find at least one unique predictor for both MD and RSD and a possible phonological processing measure that can partly account for the comorbidity between the two symptom dimensions (i.e., RAN or PA). In relation to model testing, we hypothesized that (a) a multi-factorial risk factor model would provide a better fit to the data than a single risk factor model and (b) a shared risk factor model would provide a better fit than a multi-factorial risk factor model. On the basis of findings that there might be differences between alphanumeric and non-alphanumeric RAN in terms of the strength of associations with literacy (van den Bos et al., 2002) and differences in breadth of the RAN-deficit (Donker et al., 2016), RAN was divided into an alphanumeric and non-alphanumeric component, which were added to the model as two distinct predictors. Structural equation modeling (SEM) was applied, as this has been proposed to be an appropriate method for testing multiple-deficit models (e.g., Pennington et al., 2012; Peterson et al., 2016).

MATERIALS AND METHODS

Participants

Participants included 130 7-to-10-year-old Dutch primary school children (37.2% boys), with a mean age of 8;10 years (*SD* = 12 months). All children attended primary schools in the Netherlands (Grade 1 through 5), with the majority (95.5%) in Grades 2, 3, and 4. Recruitment took place through advertisements on special educational needs websites, or contacts with specialized clinical centers and schools. Informed consent was obtained from all participants and their parents before testing. The mean IQ score for the total sample was 102.00 (*SD* = 10.44). Children were included in the sample based on a screening by a clinical expert, following criteria in line with current diagnostic criteria in the Netherlands for MD and RSD. Based on their test scores, dossier information about diagnoses, and received help, children were divided into four groups: a typically developing (TD), reading and/or spelling difficulty (RSD), mathematical difficulty (MD), and a comorbid (RSD+MD) group. Children were considered to have MD if they obtained basic arithmetic scores of 1SD below the mean of the TD children group as well as scored at or below the 25th percentile on a math problem solving test (D/E scores; cf. Janssen et al., 2010). Moreover, MD children should show average scores (standard score $\geq$ 8 or percentile $\geq$ 25) on reading and spelling measures. Children were classified as having RSD if they scored 1SD below the population mean on word or pseudoword reading and/or achieved a score at or below the 10th percentile on a spelling test administered at school (E score) (cf. Kuijpers et al., 2003; Kleijnen et al., 2008), but showed average arithmetic performance (standard score $\geq$ 8 or percentile $\geq$ 25). Children with comorbid difficulties had to meet both the MD and RSD requirements. TD children had to show average reading, spelling, arithmetic, and mathematics performance (standard score $\geq$ 8 or percentile $\geq$ 25). All children had to have an IQ between 80 and 125, and no reported history of sensory impairment, serious emotional or behavioral problems, or developmental disabilities (e.g., ADHD, autism spectrum disorder).

Descriptive statistics for all behavioral and cognitive measures in every group are displayed in **Table 1**. In total, 26 children were included in the MD group, 29 children in the RSD group, 43 children met criteria for both RSD and MD and 32 children were included in the TD control group.

Instruments

Reading

Timed (pseudo)word reading measures were used, taking both word reading accuracy and fluency into account. The Eén Minuut Test (EMT; Brus and Voeten, 1999) consists of a columned list of 116 unrelated (existing) words, increasing in length from one to four syllables. Participants were instructed to fastly read aloud as many words as they could, without making errors. The number of words read correctly in 1 min was computed. The Klepel (Van den Bos et al., 1994) consists of 116 pseudowords, which are similar to the structure of Dutch words (as in EMT) and of increasing complexity. Instruction was identical to the EMT, although the time limit was 2 min. Again, the test score was the amount of pseudowords read correctly in 2 min. Reliabilities were 0.91 for the EMT and 0.92 for the Klepel (Evers et al., 2009–2012).

Spelling

Spelling was assessed using a shortened version of a spelling to dictation task (PI dictee; Geelhoed and Reitsma, 1999), including 42 words (6 sets of 7 words; P. F. de Jong, personal communication, September 2012). The task included regularly spelled words, words containing spelling rules, and irregular words. The test was stopped after children spelled five or more words incorrectly within one set. The internal consistency of the full version varied between 0.90 and 0.93 (Evers et al., 2009–2012).

Math Ability

A speeded arithmetic test, Tempo Toets Rekenen (TTR; De Vos, 1992) was used to measure children's timed arithmetic ability. For each subtest, children were instructed to solve as many problems as they could in 1 min. The first subtest required addition, followed by subtraction, multiplication, and division. Every subtest included 40 problems of increasing complexity. Cronbach's alpha was 0.86 for the addition and subtraction scale and 0.83 for multiplication and division scale.

The national norm-referenced CITO mathematics test was used to measure mathematical problem solving (Janssen et al., 2010). The test has different items for different age groups. Test scores are converted into normed "ability scores," provided by the publisher, that typically increase throughout primary school, allowing a comparison of results throughout the academic career (Janssen et al., 2005). The CITO mathematics test has been shown to be highly reliable; coefficients of different versions range between 0.91 and 0.97 (Janssen et al., 2010).

Intelligence

To assess children's cognitive ability, a short form of the Dutch version of the Wechsler Intelligence Scale for Children NL (WISC-III-NL; Kort et al., 2005) was used, consisting of the verbal subtests Similarities and Vocabulary and the performance subtests Picture Completion and Block Design. The reliability and validity quotients of this short form are all reported to be above 0.83 (Kaufman et al., 1996).

Phonological Awareness

The Dutch Fonemische Analyse Test (FAT; Van den Bos et al., 2009) is a timed computerized test consisting of two subtests: Phoneme Deletion (PD) and Phoneme Manipulation (PM). PD demanded children to repeat a word and delete the initial, middle or last sound (e.g., boek "book" without /b/ is oek). PM required children to switch the first sounds of two given words (e.g., Moeder Gans "Mother Goose" becomes Goeder Mans). Raw accuracy score and online computed reaction times were transformed into the number of correct responses per second. Internal consistency of the total test is reported to be 0.93 (Evers et al., 2009–2012).

TABLE 1 | Descriptive measures for the total sample ($N = 130$) and TD, RSD, MD, and RSD+MD groups.

	TD ($n = 32$)		RSD ($n = 29$)		MD ($n = 26$)		RSD+MD ($n = 43$)	
Measures	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***
Age	103.34^{a}	8.79	104.31^{a}	12.45	106.69^{a}	11.89	113.84^{b}	10.42
Full scale IQ	108.62^{a}	9.53	105.15^{ab}	10.02	99.79^{b}	9.34	96.50^{c}	8.71
Timed reading test	55.16^{a}	10.57	32.58^{b}	13.00	57.17^{a}	14.04	37.79^{b}	12.84
Timed non-word reading	47.13^{a}	13.73	21.42^{b}	10.67	46.45^{a}	14.99	27.72^{b}	11.95
Spelling to dictation	74.44^{a}	21.68	55.88^{b}	22.86	75.82^{a}	20.90	56.16^{b}	18.51
MATH ABILITY								
Addition	18.72^{a}	4.39	16.92^{ab}	5.94	14.45^{b}	4.40	14.79^{ab}	4.26
Subtraction	16.25^{a}	3.91	13.92^{ac}	5.48	10.21^{b}	4.44	10.88^{bc}	4.46
Multiplication	14.76^{a}	5.13	13.86^{ab}	7.21	9.83^{b}	6.07	10.50^{ab}	5.24
Division	8.79^{a}	4.64	7.95^{a}	6.25	4.07^{b}	3.39	4.24^{b}	3.51
Mathematical problem solving	64.57^{a}	19.29	61.73^{a}	24.53	45.38^{b}	25.49	53.41^{ab}	21.87
RAPID NAMING								
Colors	48.19^{a}	9.31	58.23^{bc}	15.01	52.00^{ab}	10.88	55.33^{ac}	12.78
Pictures	51.69^{a}	8.11	61.92^{bc}	15.24	52.48^{ab}	10.86	56.40^{ac}	11.34
Letters	30.00^{a}	6.18	37.65^{bc}	11.23	30.79^{ab}	7.79	35.00^{ac}	10.76
Digits	30.09^{a}	6.68	33.96^{a}	7.65	28.69^{a}	5.40	31.70^{a}	6.17
PHONEME AWARENESS								
Phoneme manipulation	0.08^{a}	0.048	0.031^{b}	0.034	0.048^{ab}	0.043	0.030^{b}	0.025
Phoneme deletion	0.32^{a}	0.131	0.201^{b}	0.153	0.256^{b}	0.123	0.190^{b}	0.094
VERBAL SHORT TERM MEMORY								
Digit Recall	24.61^{a}	4.26	23.88^{a}	3.49	24.45^{a}	2.56	22.97^{a}	4.48
Word Recall	24.13^{a}	2.74	23.96^{a}	3.56	24.41^{a}	3.36	23.62^{a}	3.03
VISUAL-SPATIAL WORKING MEMORY AND NUMBER SENSE								
Dot Matrix	21.45^{a}	5.46	21.12^{a}	5.69	18.59^{a}	3.54	20.95^{a}	4.84
Spatial Span	16.45^{a}	4.55	14.62^{a}	6.49	13.59^{a}	4.58	13.51^{a}	5.59
Odd One Out	16.94^{a}	3.43	15.77^{a}	5.58	14.00	4.36	15.13^{a}	4.71
Number line estimation (R^2)	0.95^{a}	0.034	0.882^{a}	0.178	0.820^{b}	0.171	0.878^{ab}	0.127

TD, typically developing; RSD, reading/spelling disabilities; MD, mathematical disabilities; RSD+MD, comorbid group; Group means with the same superscripts do not differ ($p < 0.05$).

Rapid Automatized Naming

The Continu Benoemen and Woorden Lezen test (CB and WL; Van den Bos and Lutje Spelberg, 2007) includes rapid naming of letters (s, p, a, d, o), digits (2, 4, 8, 5, 9), pictures (bicycle, tree, chair, duck, scissors) and colors (black, green, yellow, red, green). Children were instructed to name the visually presented information as quickly as possible without making mistakes. Raw scores (time in seconds) were used. Split-half reliability varied between subtests from 0.82 to 0.90 (Evers et al., 2009–2012).

Memory

Subtests of the Automated Working Memory Assessment (AWMA; Alloway, 2007) were used to assess the different memory components. Verbal STM was measured using the digit recall and word recall subtests. For visuospatial WM, dot matrix, spatial span, and odd one out subtests were used. All tasks correspond to the Baddeley WM model (1986). Per subtest, testing was terminated after three incorrect responses. Raw scores (i.e., number of correct items) were used in the analyses. A description of the tasks as well as subtest reliabilities can be found in Alloway et al. (2009).

Number Sense

NS was assessed with the number line estimation task reported in Kolkman et al. (2013). This task demanded children to indicate where the researcher should place a lever on a number line from 0 to 100 to position a presented digit. The proportion of explained variance (R^2) was computed by fitting the answers of each child on a linear curve (see also Kolkman et al., 2013). The task was administered on a laptop computer using E-prime 1.2 software (Psychological Software Tools, http://pstnet.com). Internal consistency of the test was 0.79 (Kolkman et al., 2013).

Procedure

All children were tested individually by a trained and supervised graduate student in a quiet room at school or at home. The neuropsychological and behavioral test battery comprised 2.5 to 3 h, depending on whether intelligence measures were available, with ample breaks between tasks. Parents and schools could indicate whether they wanted a test report children received a reward (i.e., a sticker) after every test they completed. For this study, data from largely the same set of participants was used as is in Donker et al. (2016). The IQ range was limited to 80–125, excluding three participants with an IQ > 125. Hence, whereas the total sample of Donker et al.'s study included 133 students, our study included 130 participants. This resulted in slightly weaker correlations between the math and literacy outcome variables and the RAN measures, although the p-values remained similar.

Data Analysis

Correlational analyses revealed that for some of the variables performance increased as a linear function of age. These variables (EMT, PI-dictation, TTR, CITO math, NS, RAN letters and RAN numbers) were transformed into age-residualized scores by regressing the variable on age and age squared and saving the unstandardized residuals (see also McGrath et al., 2011). The PM task results were log-transformed in order to approximate a normal distribution. Outliers (z-scores > 3.29 or < -3.29) were removed from the data.

Confirmatory Factor Analyses (CFAs) and SEM were performed in Mplus version 6.12 (Muthén and Muthén, 2007). Maximum likelihood estimation with robust standard errors (i.e., MLR) was used to deal with non-normality in some of the variables and avoid listwise deletion. Missing data was minimal for both the behavioral and the cognitive measures (0–10%) and handled using full information maximum likelihood (FIML) estimation.

In order to test our hypotheses, a four-step approach was taken to build toward a comorbidity model. First, CFAs were run on the continuously distributed symptom (i.e., math and literacy) and cognitive dimensions (NS, visuospatial WM, PA, RAN, Verbal STM) separately. In these measurement models, the latent factors represented the continuously distributed symptoms of MD and RSD. Second, a single risk factor model was tested, in which one deterministic risk factor for both disabilities was regressed on literacy and math. Based on evidence from previous empirical studies on the etiology of MD and RSD and correlational analyses (**Table 2**), NS and PA were selected as the specific cognitive risk factors for these analyses. Third, a multi-factorial specific risk factor model was tested in which NS, visuospatial WM, PA, RAN, and Verbal STM were all included as specific risk factors for the individual difficulties. Fourth, a comorbidity model was tested in which a shared risk factor was added to the multi-factorial model. Satorra-Bentler chi-square difference tests were used to compare model fit of all three SEM models. The following criteria for model evaluation were used: chi-square value (χ^2) with associated p-value, RMSEA including $p$close, CFI, and SRMR (Kline, 2011; Little, 2013). For good model fit, chi-square should have a non-significant p-value (i.e., >0.05), RMSEA should be <0.05 (<0.08 is acceptable), with $p$close >0.05, CFI being >0.95 (>0.90 is acceptable), and SRMR being <0.05 (<0.08 is acceptable; Kline, 2011; Little, 2013).

RESULTS

Preliminary correlational analyses were conducted on the raw scores, while correcting for age in months, in order to assess whether the cognitive variables were associated with literacy and math outcomes (**Table 2**). The math ability tasks correlated significantly with the NS, visual-spatial WM, and PA measures, and to a lesser extent with the RAN measures. Correlations between literacy and the cognitive measures for PA and RAN were significant (see **Table 2** for detailed information).

Measurement Models

Symptom Dimensions

The measurement model for the symptom dimensions of MD and RSD (with literacy and math ability as continuously distributed outcomes) was first fitted to the data. An error correlation between word reading and pseudoword reading as well as between the multiplication and division scores were allowed after consulting the Modification Indices. The residual variance of the spelling measure was set to zero since it was not significant. After these adjustments, the proposed model showed a good fit, χ^2 $(18, n = 130) = 18.85$, $p = 0.40$, RMSEA = 0.02, 90% Confidence Interval (CI) = [0.00 – 0.08], $p$close >0.05, CFI = 1.00, SRMR = 0.03. A depiction of the measurement model for the MD and RSD symptoms is included in the Appendix, **Figure A1**.

Cognitive Dimensions

The measurement model for the continually distributed cognitive dimensions (NS, visuospatial WM, PA, alphanumeric and non-alphanumeric RAN, and Verbal STM) fitted the data well, χ^2 $(40, n = 130) = 49.87$, $p = 0.14$, RMSEA = 0.04, 90% CI = [0.00 − 0.08], $p$close > 0.05, CFI = 0.98, SRMR = 0.05. The residual variance of the single indicator for the NS latent variable was fixed to zero. A figure depicting the measurement model for the cognitive dimensions is included in the Appendix, **Figure A2**.

Structural Equation Models

The measurement models for the cognitive and symptom dimensions were combined and structural relations were included in the model equations in order to create a SEM. Three (nested) models were fitted to the data: a single risk factor model, a multi-factorial risk factor model and a comorbidity (shared risk factor) model, in order to test the hypothesis that the latter model most adequately explains the MD/RSD symptoms in this sample. Depictions of the first two models are included in the Appendix: **Figures A3**, **A4**.

Single Risk Factor Model

A deterministic, single risk factor model was fitted to the data with NS as a risk factor for MD and PA as a risk factor for RSD. This model indicated a just sufficient fit to the data, with χ^2 $(152, n = 130) = 259.97$, $p < 0.01$, RMSEA = 0.07, 90% CI = [0.06 − 0.09], $p$close <0.05, CFI = 0.90, SRMR = 0.13. NS was a significant predictor for MD ($\beta = 0.45$) and PA for RSD ($\beta = 0.61$). In total, NS explained 21% of the variance in the children's math ability and PA explained 38% of the variance in children's literacy (reading and spelling) ability.

Multi-Factorial Risk Model

A probabilistic, multi-factorial risk factor model was fitted in order to compare it to the single risk factor model. This model included the following specific risk factors: for math ability, we included NS and visuospatial WM as risk factors for MD. For literacy, we included PA, alphanumeric and non-alphanumeric RAN, and Verbal STM as potential risk factors for RSD. The

TABLE 2 | Correlations between symptom and cognitive dimensions corrected for age.

	FAT		Number sense	Verbal STM		Visuospatial WM			RAN			
Variable	**PD**	**PM**	r^2	**DR**	**WR**	**SS**	**DM**	**OOO**	**Colors**	**Digits**	**Pictures**	**Letters**
EMT	0.49**	0.44**	0.14	0.09	0.06	0.18	0.01	0.22*	−0.28**	−0.50**	−0.44**	−0.65**
Klepel	0.50**	0.47**	0.05	0.11	0.05	0.14	0.01	0.19	−0.34*	0.50**	−0.42**	−0.58**
PI-dictee	0.59**	0.62**	0.15	0.14	0.11	0.26*	0.16	0.26*	−0.27**	−0.30**	−0.30**	−0.46**
TTR +	0.25*	0.36**	0.36**	0.03	0.11	0.30**	0.38**	0.27**	−0.13	−0.28**	−0.26**	−0.25*
TTR -	0.31**	0.37**	0.41**	−0.02	0.10	0.38**	0.37**	0.28**	−0.22*	−0.17	−0.16	−0.10
TTR x	0.18	0.31**	0.32**	−0.14	−0.08	0.22*	0.23*	0.15	−0.23*	−0.19	−0.25*	−0.22*
TTR:	0.28**	0.41**	0.27**	−0.01	0.15**	0.34**	0.34**	0.34**	−0.31**	−0.16	−0.20*	−0.12
Cito	0.28**	0.40**	0.30**	0.17	0.19	0.38**	0.31**	0.36**	−0.28**	−0.00	−0.12	−0.21*

*EMT, word reading; Klepel, nonword reading; PI dictee, spelling task; TTR, speeded arithmetic task; Cito, mathematics task; FAT, phonological awareness task; STM, short-term memory; WM, working memory; RAN, rapid automatized naming; PD, phoneme deletion; PM, phoneme manipulation; DR, digit recall; WR, word recall; SS, spatial span; DM, dot matrix; OOO, odd one out. *$p < 0.05$, **$p < 0.01$; $N = 94$.*

model fit was considered sufficient, χ^2 (148, $n = 130$) = 245.87, $p < 0.01$, RMSEA = 0.07, 90% CI = [0.05 – 0.09], *p*close < 0.05, CFI = 0.91, SRMR = 0.10. Of the proposed risk factors for math ability, both NS ($\beta = 0.35$) and visuospatial WM ($\beta = 0.40$) were significant predictors. For literacy, PA predicted the reading and spelling outcomes significantly ($\beta = 0.70$), as well as alphanumeric and non-alphanumeric RAN ($\beta = -0.29$ and $\beta = 0.30$). Verbal STM was not significantly related to literacy ($\beta = -0.03$). A Satorra-Bentler scaled Chi-square difference test indicated that the probabilistic, multi-factorial risk model fitted the data better than the deterministic, single risk factor model, $\chi^2_{(4)} = 14.101$, $p < 0.01$. The specific risk factors together explained 36% of the variance in children's math ability and 44% in their literacy scores.

Comorbidity Model

In order to test the proposed shared etiology between MD and RSD, we included PA, alphanumeric RAN, and non-alphanumeric RAN successively as potential shared risk factors in the multi-factorial risk factor model. The model with PA as a shared risk factor fitted the data best, χ^2 (147, $n = 130$) = 237.52, $p < 0.01$, RMSEA = 0.07, 90% CI = [0.05 – 0.09], *p*close < 0.05, CFI = 0.92, SRMR = 0.09. The comorbidity model is depicted in **Figure 1**. A Satorra-Bentler Chi-square difference test indicated that the less restricted model (shared risk factor model) provided a better fit to the data than the multi-factorial risk factor model, $\chi^2_{(1)} = 8.06$, $p < 0.01$. PA was identified as a shared risk factor ($\beta = 0.34$ for math and $\beta = 0.74$ for literacy). In total, the cognitive predictors explained 41% of the variance in the children's math ability and 48% of the variance in children's literacy (reading and spelling) ability. The symptom dimensions of MD and RSD were still significantly related, but the relation weakened after adding PA to the model (from $\beta = 0.30$ to $\beta = 0.23$).

DISCUSSION

In order to explain the high comorbidity rates between mathematical learning disability (MD) and reading and spelling difficulties (RSD), 7-to-10-year-old Dutch primary school children were assessed on a wide range of cognitive skills related to math and literacy. Following the line of research using multi-factorial risk models, both specific and shared risk factors for MD and RSD were anticipated. Specifically, we expected (a) to find at least one unique predictor for both MD and RSD separately, and a possible shared phonological processing-related risk factor (partly) accounting for the comorbidity between the two. We also hypothesized that (b) a multi-factorial risk factor model would provide a better fit to the data than a single risk factor model and (c) a shared risk factor model would provide a better fit than a multi-factorial risk factor model. All three hypotheses were confirmed.

The results of our study clearly support the multiple-deficit framework proposed by Pennington (2006) in that MD and RSD can be considered two separate but correlated disabilities (Willcutt et al., 2013). In line with previous research, visual-spatial working memory (visuospatial WM) and number sense (NS) were found to be uniquely associated with math ability, constituting specific risk factors for MD (e.g., Schuchardt et al., 2008; Landerl et al., 2009). Similarly, phonological awareness (PA) was a unique predictor of literacy, constituting a specific risk factor for RSD, as has been shown in the literature (e.g., Vellutino et al., 2004; Hulme and Snowling, 2014).Verbal STM did not predict literacy, which can be aligned with findings that the influence of Verbal STM decreases over time as the influence of PA increases (De Jong and Van der Leij, 1999, 2003). In line with the literature, rapid automatized naming (RAN) was also a significant risk factor related to literacy (Van den Bos et al., 2003; Melby-Lervåg et al., 2012; Norton and Wolf, 2012; Protopapas et al., 2013). An important result of the current study is that we found a significant association between NS and MD. More specifically, we used a numberline estimation task measuring the ability to map numbers to "space" (Kolkman et al., 2014). The task however also may require some other forms of strategy use, e.g., proportion judgment (Slusser et al., 2013). Still, our study confirmed that the ability to place numbers on a line seems an important predictor of MD. Another important finding was that we identified PA as a shared cognitive risk factor for MD and

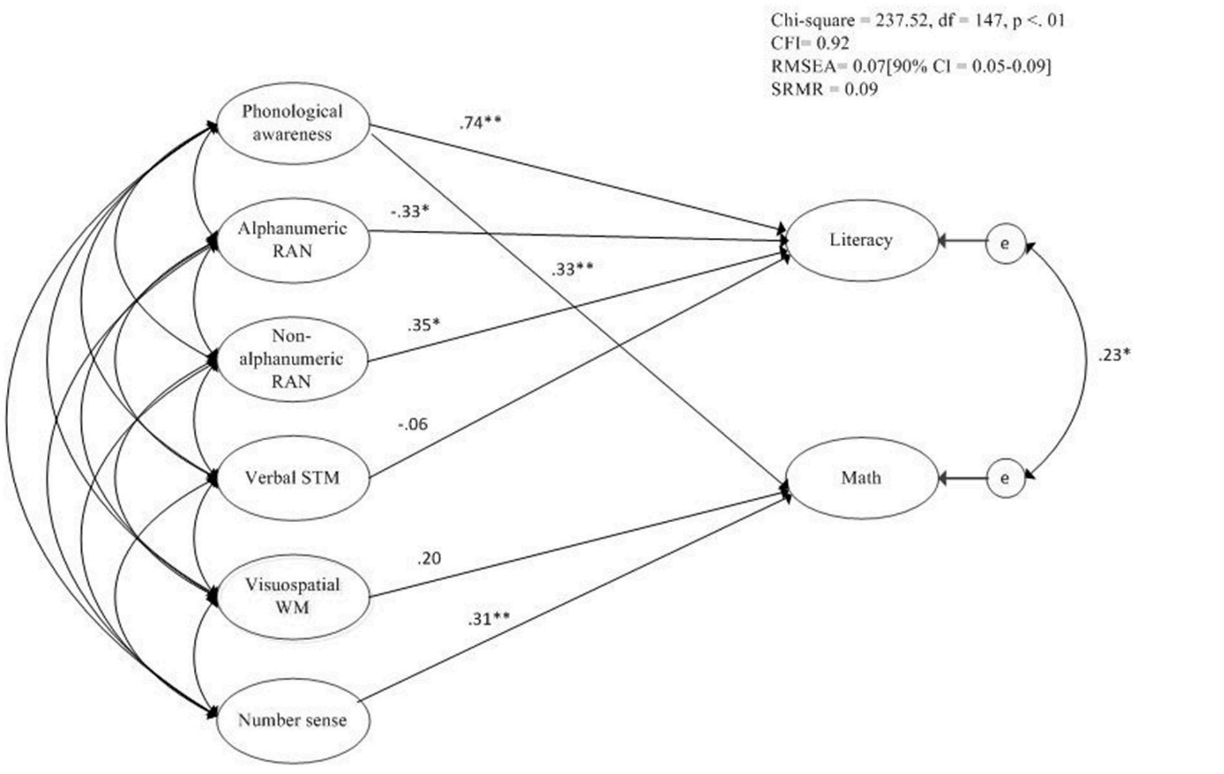


FIGURE 1 | Comorbidity model including unique and shared risk factors for both MD and RSD. $^*p < 0.05$; $^{**}p < 0.01$.

RSD; the comorbidity model better fitted the data and explained more variance in both literacy and math performance than the multi-factorial risk factor model without any shared risk factors. These results suggest that MD and RSD co-occur due to a shared underlying deficit (Willcutt et al., 2013). Previous research has suggested the possibility of a phonological processing deficit as a shared risk factor underlying MD and RSD symptoms, but little evidence has been found thus far (Landerl et al., 2009; Wilson et al., 2015).

That PA was identified as a shared risk factor, indicates that phonological skills not only play a role in reading and spelling, but also in mathematics. This supports the findings by Lopes-Silva et al. (2016) that phoneme awareness relates to both word reading and spelling as well as number reading and writing in typically developing children. It also relates to findings by Simmons and Singleton (2007) that the phonological processing deficits of children with dyslexia impair aspects of mathematics that involve the manipulation of verbal codes (e.g., counting speed, number fact recall) and is consistent with the finding that children with dyslexia and mathematical problems often have slow and inaccurate number fact retrieval (Geary et al., 2000). These difficulties with basic arithmetic skills may impact more advanced mathematics directly and indirectly.

Alternatively, the finding of PA as a shared risk factor could indicate that individuals with comorbid MD and RSD might represent a verbal subtype of MD (Geary, 2004; Moll et al., 2015). Researchers have suggested that MD children with difficulties in arithmetic fact retrieval were found to have weaknesses in symbolic number processing (Wilson and Dehaene, 2007; Geary, 2010). This is taken to reflect an access deficit (Skagerlund et al., 2016), relating to problems with accessing the verbal codes of numerical information, requiring phonological processing (Hecht et al., 2001). This could explain the association between PA and math ability. Vice versa, the PA deficit in RSD children could impair aspects of mathematics that involve the manipulation of verbal codes (e.g., counting speed, number fact recall; Simmons and Singleton, 2007). PA could thus be a factor related to verbal codes and subsequent slow and inaccurate number retrieval. It is deemed important that future research further investigates the association between phonological processing and (comorbid) RSD and MD.

An alternative explanation for our finding is that the PA tasks in our study required executive functioning (EF), particularly the phoneme manipulation task were children have to blend and segment words. This "spoonerism" task according to Landerl and Wimmer (2000) includes not only phonological awareness, but also complex memory and monitoring skills. Hence, EF could play a role in the association between PA and MD/RSD rather than phonological awareness itself. However, it must be stressed that the other PA task (phoneme switching) to a much lesser extent appeals to EF and that the PA tasks used in our study are also applied in clinical practice. Nonetheless, it is a serious limitation of the current study that no measures were included on executive functioning (e.g., attentional control, inhibition).

Previous research has suggested associations between attention problems and processing speed and comorbid RSD/MD (Willcutt et al., 2013; Moll et al., 2014c; Peterson et al., 2016). However, results from these studies are not unequivocal: associations between executive functions and MD/RSD symptoms were not robust. Future research might therefore try to adopt the multiple-deficit view to individual cases, in order to gain more insight into the clinical utility of these models for explaining comorbidity between RSD and MD (Pennington et al., 2012).

In general, this study has shown that a multiple-deficit framework is suitable for testing shared etiological influences in neurodevelopmental disabilities, but also illustrated the complexity of including multiple unique and shared risk factors into one multiple risk factor model. Although the present study included a wide range of cognitive risk factors, these factors only accounted for 41% of the variance in the MD symptoms and 48% of the RSD symptoms. For example, domain-general factors such as verbal comprehension and processing speed were previously found to be responsible for overlap between behavioral outcomes of math and literacy (e.g., Willcutt et al., 2013; Peterson et al., 2016). Future research could focus on including more domain-general candidate shared risk factors, such as attentional control (Geary, 2013) and executive functioning (i.e., updating; Van der Ven et al., 2012). Also, more specific risk factors that are supposedly uniquely associated with MD and RSD can be included, such as (non-)symbolic comparison skills for MD (Toll et al., 2015) and visual attention span for RSD (VAS; Valdois et al., 2012; Van den Boer et al., 2015). Theoretically and clinically, it is important to account for both MD and RSD as well as the comorbidity between the two. Our study is a stepping stone for future studies in this field.

AUTHOR CONTRIBUTIONS

ES is responsible for the analyses and the story line in the introduction. SV and ED contributed equally to the manuscript. EK had a supervising role. ES and SV together gathered the data in 2013, supervised by ED and EK.

REFERENCES

Alloway, T. P. (2007). *Automated Working Memory Assessment.* London: Harcourt Assessment.

Alloway, T. P., Gathercole, S. E., Kirkwood, H., and Elliott, J. (2009). The cognitive and behavioral characteristics of children with low working memory. *Child Dev.* 80, 606–621. doi: 10.1111/j.1467-8624.2009.01282.x

Baddeley, A. (1986). *Working Memory*. Oxford: Clarendon Press.

Brus, B. T., and Voeten, M. J. M. (1999). *Eén-Minuut-Test [One-Minute-Test]*. Lisse: Swets and Zeitlinger.

Cirino, P. T., Fletcher, J. M., Ewing-Cobbs, L., Barnes, M. A., and Fuchs, L. S. (2007). Cognitive arithmetic differences in learning difficulty groups and the role of behavioral inattention. *Learn. Disabil. Res. Pract.* 22, 25–35. doi: 10.1111/j.1540-5826.2007.00228.x

Cirino, P. T., Fuchs, L. S., Elias, J. T., Powell, S. R., and Schumacher, R. F. (2015). Cognitive and mathematical profiles for different forms of learning difficulties. *J. Learn. Disabil.* 48, 156–175. doi: 10.1177/0022219413494239

De Jong, P. F., and Van der Leij, A. (1999). Specific contributions of phonological abilities to early reading acquisition: results from a Dutch latent variable longitudinal study. *J. Educ. Psychol.* 91, 450–476. doi: 10.1037/0022-0663.91.3.450

De Jong, P. F., and Van der Leij, A. (2003). Developmental changes in the manifestation of a phonological deficit in dyslexic children learning to read a regular orthography. *J. Educ. Psychol.* 95, 22–40. doi: 10.1037/0022-0663.95.1.22

De Weerdt, F., Desoete, A., and Roeyers, H. (2013). Working memory in children with reading disabilities and/or mathematical disabilities. *J. Learn. Disabil.* 46, 461–472. doi: 10.1177/0022219412455238

Donker, M., Kroesbergen, E. H., Slot, E. M., Van Viersen, S., and De Bree, E. H. (2016). Alphanumeric and non-alphanumeric Rapid automatized naming in children with reading and/or spelling difficulties and mathematical difficulties. *Learn. Individ. Differ.* 47, 80–87. doi: 10.1016/j.lindif.2015.12.011

Evers, A., Egberink, I. J. L., Braak, M. S. L., Frima, R. M., Vermeulen, C. S. M., and Van Vliet-Mulder, J. C. (2009–2012). *COTAN Documentatie [COTAN Documentation]*. Amsterdam: Boom.

Geary, D. C. (1993). Mathematical disabilities: cognition, neuropsychological and genetic components. *Psychol. Bull.* 114, 345–362. doi: 10.1037/0033-2909.114.2.345

Geary, D. C. (2004). Mathematics and learning disabilities. *J. Learn. Disabil.* 37, 4–15. doi: 10.1177/00222194040370010201

Geary, D. C. (2010). Mathematical disabilities: reflections on cognitive, neuropsychological, and genetic components. *Learn. Individ. Differ.* 20, 130–133. doi: 10.1016/j.lindif.2009.10.008

Geary, D. C. (2013). Early foundations for mathematics learning and their relations to learning disabilities. *Curr. Dir. Psychol. Sci.* 22, 23–27. doi: 10.1177/0963721412469398

Geary, D. C., Bailey, D. H., and Hoard, M. K. (2009). Predicting mathematical achievement and mathematical learning disability with a simple screening tool the number sets test. *J. Psychoeduc. Assess.* 27, 265–279. doi: 10.1177/0734282908330592

Geary, D. C., Hamson, C. O., and Hoard, M. K. (2000). Numerical and arithmetical cognition: a longitudinal study of process and concept deficits in children with learning disability. *J. Exp. Child Psychol.* 77, 236–263. doi: 10.1006/jecp.2000.2561

Geelhoed, J., and Reitsma, P. (1999). *PI-dictee [PI-dictation Test]*. Amsterdam: Harcourt Test Publishers.

Georgiou, G. K., Parrila, R., and Papadopoulos, T. C. (2008). Predictors of word decoding and reading fluency across languages varying in orthographic consistency. *J. Educ. Psychol.* 100, 566–580. doi: 10.1037/0022-0663.100.3.566

Georgiou, G. K., Torppa, M., Manolitsis, G., Lyytinen, H., and Parrila, R. (2012). Longitudinal predictors of reading and spelling across languages varying in orthographic consistency. *Read. Writ.* 25, 321–346. doi: 10.1007/s11145-010-9271-x

Gross-Tsur, V., Manor, O., and Shalev, R. S. (1996). Developmental dyscalculia: prevalence and demographic features. *Dev. Med. Child Neurol.* 38, 25–33. doi: 10.1111/j.1469-8749.1996.tb15029.x

Hecht, S. A., Torgesen, J. K., Wagner, R. K., and Rashotte, C. A. (2001). The relations between phonological processing abilities and emerging individual differences in mathematical computation skills: a longitudinal study from second to fifth grades. *J. Exp. Child Psychol.* 79, 192–227. doi: 10.1006/jecp.2000.2586

Hulme, C., and Snowling, M. J. (2014). The interface between spoken and written language: developmental disorders. *Philos. Trans. R. Soc. B* 369:20120395. doi: 10.1098/rstb.2012.0395

Janssen, J., Scheltens, F., and Kraemer, J. M. (2005). *Leerling- en Onderwijsvolgsysteem Rekenen-Wiskunde [Student Monitoring System Mathematics]*. Arnhem: Cito.

Janssen, J., Verhelst, N., Engelen, R., and Scheltens, F. (2010). *Wetenschappelijke Verantwoording Van De Toetsen LOVS Rekenenwiskunde Voor Groep 3 Tot En Met 8 [Scientific Justification of the Mathematics Test for Grade 1 to Grade 6]*. Arnhem: Cito.

Kaufman, A. S., Kaufman, J. C., Balgopal, R., and McLean, J. E. (1996). Comparison of three WISC-III short forms: weighing psychometric, clinical, and practical factors. *J. Clin. Child Psychol.* 25, 97–105. doi: 10.1207/s15374424jccp2501_11

Kleijnen, R., Bosman, A., de Jong, P., Henneman, K., Pasman, J., Paternotte, A., et al. (2008). *Diagnose en Behandeling van Dyslexie*. Bilthoven: Stichting Dyslexie Nederland.

Kline, R. B. (2011). *Principle and Practice of Structural Equation Modeling*. New York, NJ: The Guildford Press.

Kolkman, M. E., Kroesbergen, E. H., and Leseman, P. P. M. (2013). Early numericaldevelopment and the role of non-symbolic and symbolic skills. *Learn. Inst.* 25, 95–103. doi: 10.1037/0022-0663.91.3.450

Kolkman, M. E., Kroesbergen, E. H., and Leseman, P. P. M. (2014). Involvement of working memory in longitudinal development of number–magnitude skills. *Infant Child Dev.* 23, 36–50. doi: 10.1037/0022-0663.91.3.450

Kort, W., Schittekatte, M., Bosmans, M., Compaan, E. L., Dekker, P. H., Vermeir, G., et al. (2005). *WISC III-NL. Wechsler Intelligence Scale for Children III*. Amsterdam: Pearson.

Kroesbergen, E.H., and Van Dijk, M. (2015). Working memory and number sense as predictors of mathematical (dis-)ability. *Zeitschrift für Psychologie* 223, 102–109. doi: 10.1027/2151-2604/a000208

Kuijpers, C., van der Leij, A., Been, P., van Leeuwen, T., ter Keurs, M., Schreuder, R., et al. (2003). Leesproblemen in het voortgezet onderwijs en de volwassenheid [Reading problems at the secondary school level and in adulthood]. *Pedagogische Studiën* 80, 272–287.

Landerl, K., Bevan, A., and Butterworth, B. (2004). Developmental dyscalculia and basic numerical apacities: a study of 8–9 year old students. *Cognition* 93, 99–125. doi: 10.1016/j.cognition.2003.11.004

Landerl, K., Fussenegger, B., Moll, K., and Willburger, E. (2009). Dyslexia and dyscalculia: two learning disabilities with different cognitive profiles. *J. Exp. Child Psychol.* 103, 309–324. doi: 10.1016/j.jecp.2009.03.006

Landerl, K., and Moll, K. (2010). Comorbidity of learning disabilities: prevalence and familial transmission. *J. Child Psychol. Psychiatry* 51, 287–294. doi: 10.1111/j.1469-7610.2009.02164.x

Landerl, K., Ramus, F., Moll, K., Lyytinen, H., Leppänen, P. H., Lohvansuu, K., et al. (2013). Predictors of developmental dyslexia in European orthographies with varying complexity. *J. Child Psychol. Psychiatry* 54, 686–694. doi: 10.1111/jcpp.12029

Landerl, K., and Wimmer, H. (2000). Deficits in phoneme segmentation are not the core problem of dyslexia: evidence from German and English children. *Appl. Psycholinguist.* 21, 243–262. doi: 10.1017/S0142716400002058

Lewis, C., Hitch, G. J., and Walker, P. (1994). The prevalence of specific arithmetic difficulties and specific reading difficulties in 9- to 10-year-old boys and girls. *J. Child Psychol. Psychiatry* 35, 283–292. doi: 10.1111/j.1469-7610.1994.tb01162.x

Little, T. D. (2013). Longitudinal structural equation modeling. New York, NJ: The Guildford Press.

Lopes-Silva, J. B., Moura, R., Júlio-Costa, A., Wood, G., Salles, J. F., and Haase, V. G. (2016). What is specific and what is shared between numbers and words? *Front. Psychol.* 7:22. doi: 10.3389/fpsyg.2016.00022

McGrath, L. M., Pennington, B. F., Shanahan, M. A., Santerre-Lemmon, L. E., Barnard, H. D., and Willcutt, E. G., et al. (2011). A multiple deficit model of reading disability and attention-deficit/hyperactivity disability: searching for shared cognitive deficits. *J. Child Psychol. Psychiatry* 52, 547–557. doi: 10.1111/j.1469-7610.2010.02346.x

Melby-Lervåg, M., Lyster, S. A. H., and Hulme, C. (2012). Phonological skills and their role in learning to read: a meta-analytic review. *Psychol. Bull.* 138, 322–352. doi: 10.1037/a0026744

Moeller, K., Fischer, U., Cress, M. U., and Nuerk, H.C. (2012). "Diagnostics and intervention in developmental dyscalculia: Current issues and novel perspectives," in *Reading, Writing, Mathematics and the Developing Brain: Listening to Many Voices*, eds Z. Brezinitz, O. Rubinsten, V. J. Molfese, and D. L. Molfese (Dordrecht: Springer Science/Business Media B.V.), 233–275.

Moll, K., Göbel, S. M., Gooch, D., Landerl, K., and Snowling, M. J. (2014c). Cognitive risk factors for specific learning disorder processing speed, temporal processing, and working memory. *J. Learn. Disabil.* 49, 272–281. doi: 10.1177/0022219414547221

Moll, K., Göbel, S. M., and Snowling, M. J. (2015). Basic number processing in children with specific learning disorders: comorbidity of reading and mathematics disorders. *Child Neuropsychol.* 21, 399–417. doi: 10.1080/09297049.2014.899570

Moll, K., Kunze, S., Neuhoff, N., Bruder, J., and Schulte-Körne, G. (2014a). Specific learning disorder: prevalence and gender differences. *PLoS ONE* 9:e103537. doi: 10.1371/journal.pone.0103537

Moll, K., and Landerl, K. (2009). Double dissociation between reading and spelling deficits. *Sci. Stud. Read.* 13, 359–382. doi: 10.1080/10888430903162878

Moll, K., Ramus, F., Bartling, J., Bruder, J., Kunze, S., Neuhoff, N., et al. (2014b). Cognitive mechanisms underlying reading and spelling development in five European orthographies. *Learn. Inst.* 29, 65–77. doi: 10.1016/j.learninstruc.2013.09.003

Muthén, L. K., and Muthén, B. O. (2007). *Mplus User's Guide, 6th Edn*. Los Angeles, CA: Muthén and Muthén.

Norton, E. S., and Wolf, M. (2012). Rapid automatized naming (RAN) and reading fluency: implications for understanding and treatment of reading disabilities. *Annu. Rev. Psychol.* 63, 427–452. doi: 10.1146/annurev-psych-120710-100431

Pennington, B. F. (2006). From single to multiple deficit models of developmental disabilities. *Cognition* 101, 385–413. doi: 10.1016/j.cognition.2006.04.008

Pennington, B. F., Santerre-Lemmon, L., Rosenberg, J., MacDonald, B., Boada, R., Friend, A., et al. (2012). Individual prediction of dyslexia by single versus multiple deficit models. *J. Abnorm. Psychol.* 121, 212–224. doi: 10.1037/a0025823

Peterson, R. L., Boada, R., McGrath, L. M., Willcutt, E. G., Olson, R. K., and Pennington, B. F. (2016). Cognitive prediction of reading, math, and attention shared and unique influences. *J. Learn. Disabil.* doi: 10.1177/0022219415618500. [Epub ahead of print].

Protopapas, A., Altani, A., and Georgiou, G. K. (2013). Development of serial processing in reading and rapid naming. *J. Exp. Child Psychol.* 116, 914–929. doi: 10.1016/j.jecp.2013.08.004

Raghubar, K. P., Barnes, M. A., and Hecht, S. A. (2010). Working memory and mathematics: a review of developmental, individual difference, and cognitive approaches. *Learn. Individ. Differ.* 20, 110–122. doi: 10.1016/j.lindif.2009.10.005

Rose, J. (2009). *Identifying and Teaching Children and Young People with Dyslexia and Literacy Difficulties: An Independent Report*. Available online at: http://dera.ioe.ac.uk/14790/7/00659-2009DOM-EN_Redacted.pdf

Rousselle, L., and Noël, M. P. (2007). Basic numerical skills in children with mathematics learning disabilities: a comparison of symbolic vs. non-symbolic number magnitude. *Cognition* 102, 361–395. doi: 10.1016/j.cognition.2006.01.005

Schuchardt, K., Maehler, C., and Hasselhorn, M. (2008). WM deficits in children with specific learning disabilities. *J. Learn. Disabil.* 41, 514–523. doi: 10.1177/0022219408317856

Simmons, F. R., and Singleton, C. (2007). Do weak phonological representation impact on arithmetic development? A review of research into arithmetic and dyslexia. *Dyslexia* 14, 77–94. doi: 10.1002/dys.341

Slusser, E. B., Santiago, R. T., and Barth, H. C. (2013). Developmental change in numerical estimation. *J. Exp. Psychol.* 142, 193–208. doi: 10.1037/a0028560

Skagerlund, K., Karlsson, T., and Träff, U. (2016). Magnitude processing in the brain: an fMRI study of time, space, and numerosity as a shared cortical system. *J. Exp. Child Psychol.* 143, 85–101.

Smythe, I., Everatt, J., Al-Menaye, N., He, X., Capellini, S., Gyarmathy, E., et al. (2008). Predictors of word-level literacy amongst Grade 3 children in five diverse languages. *Dyslexia* 14, 170–187. doi: 10.1002/dys.369

Swanson, H. L., Zheng, X. H., and Jerman, O. (2009). Working memory, short-term memory, and reading disabilities a selective meta-analysis of the literature. *J. Learn. Disabil.* 42, 260–287. doi: 10.1177/0022219409331958

Toll, S. W. M., van Viersen, S., and van Luit, J. E. H. (2015). The development of (non-)symbolic comparison skills throughout kindergarten and their relations with basic mathematical skills. *Learn. Individ. Differ.* 38, 10–17. doi: 10.1016/j.lindif. 2014.12.006

Valdois, S., Lassus-Sangosse, D., and Lobier, M. (2012). Impaired letter string processing in developmental dyslexia: what visual-to-phonological code mapping disability? *Dyslexia* 18, 77–93. doi: 10.1002/dys.1437

Van Bergen, E., Van der Leij, A., and De Jong, P. F. (2014). The intergenerational multiple deficit model and the case of dyslexia. *Front. Hum. Neurosci.* 8:346. doi: 10.3389/fnhum.2014.00346

Van den Boer, M., van Bergen, E., and de Jong, P.F. (2015). The specific relation of visual attention span with reading and spelling in Dutch. *Learn. Individ. Differ.* 39, 141–149. doi: 10.1016/j.lindif.2015.03.017

Van den Bos, K. P., and Lutje Spelberg, H. C. (2007). *CB&WL. Continu Benoemen &Woorden Lezen [Continuous naming and word reading].* Amsterdam: Boom.

Van den Bos, K. P., Lutje Spelberg, H. C., and de Groot, B. J. A. (2009). *Fonemische Analyse Test (FAT) [Phonemic Analysis Test].* Amsterdam: Pearson.

Van den Bos, K. P., Lutje Spelberg, H. C., Scheepstra, A. J. M., and De Vries, J. R. (1994). *De Klepel [Pseudoword reading test].* Nijmegen: Berkhout.

van den Bos, K. P., Zijlstra, B. J., and lutje Spelberg, H. C. (2002). Life-span data on continuous-naming speeds of numbers, letters, colors, and pictured objects, and word-reading speed. *Sci. Stud. Reading* 6, 25–49. doi: 10.1207/S1532799XSSR0601_02

Van den Bos, K. P., Zijlstra, B. J., and Van den Broeck, W. (2003). Specific relations between alphanumeric-naming speed and reading speeds of monosyllabic and multisyllabic words. *Appl. Psycholinguist.* 24, 407–430. doi: 10.1017/s0142716403000213

Van der Ven, S. H. G., Kroesbergen, E. H., Boom, J., and Leseman, P. P. M. (2012). The development of executive functions and early mathematical skills: a dynamic relationship. *Br. J. Educ. Psychol.* 82, 100–119. doi: 10.1111/j.2044-8279.2011.02035.x

Vellutino, F. R., Fletcher, J. M., Snowling, M. J., and Scanlon, D. M. (2004). Specific reading disability (dyslecia): what have we learned in the past four decades? *J. Child Psychol. Psychiatry* 45, 2–40. doi: 10.1046/j.0021-9630.2003.00305.x

Von Aster, M., Schweiter, M., and Weinhold Zulauf, M. (2007). Rechenstörungen bei Kindern: Vorläufer, Prävalenz und psychische Symptome. *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie* 39, 85–96. doi: 10.1026/0049-8637.39.2.85

De Vos, T. (1992). *Tempo-Test Rekenen [Speeded arithmetic test].* Nijmegen: Berkhout.

Willcutt, E. G., Petrill, S. A., Wu, S., Boada, R., DeFries, J. C., Olson, R. K., et al. (2013). Comorbidity between reading disability and math disability: concurrent psychopathology, functional impairment, and neuropsychological functioning. *J. Learn. Disabil.* 46, 500–516. doi: 10.1177/0022219413477476

Willburger, E., Fussenegger, B., Moll, K., Wood, G., and Landerl, K. (2008). Naming speed in dyslexia and dyscalculia. *Learn. Individ. Differ.* 18, 224–236. doi: 10.1016/j.lindif.2008.01.003

Wilson, A. J., Andrewes, S. G., Struthers, H., Rowe, V. M., Bogdanovic, R., and Waldie, K. E. (2015). Dyscalculia and dyslexia in adults: cognitive bases of comorbidity. *Learn. Individ. Differ.* 37, 118–132. doi: 10.1016/j.lindif.2014.11.017

Wilson, A. J., and Dehaene, S. (2007). "Number sense and developmental dyscalculia," in *Human Behavior, Learning, and the Developing Brain: Atypical Development*, eds D. Coch, G. Dawson, and K. Fischer (New York, NJ: Guilford Press), 212–238. doi: 10.1037/0022-0663.91.3.450

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

APPENDIX

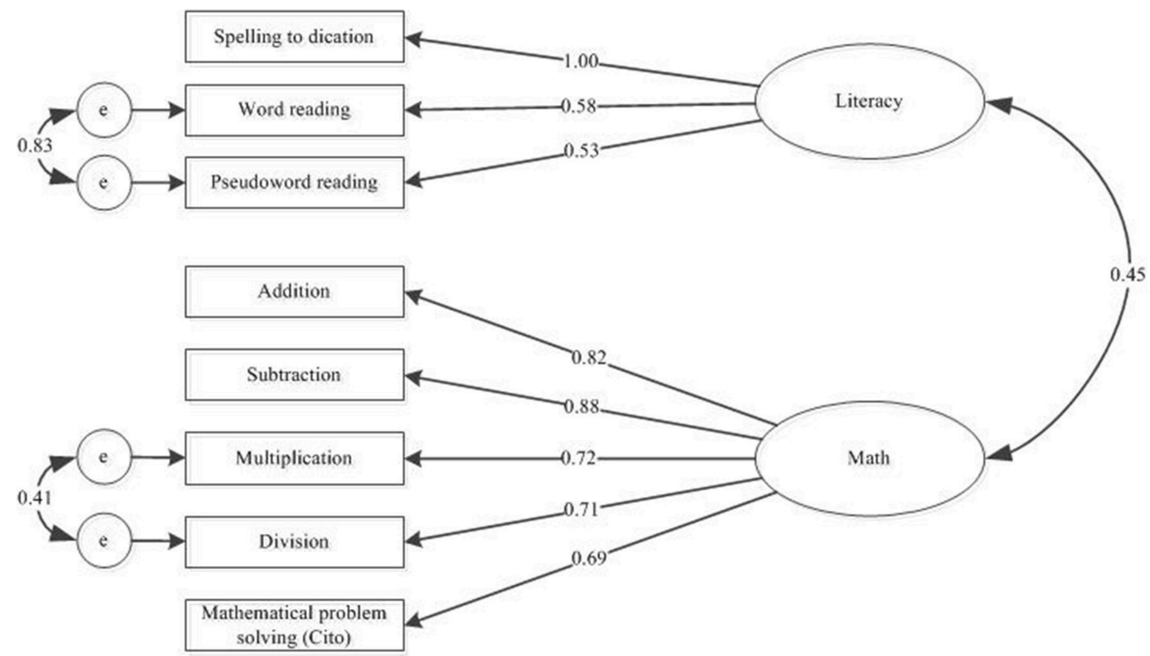


FIGURE A1 | Measurement model for the symptom dimensions literacy and math. Standardized path coefficients are depicted.

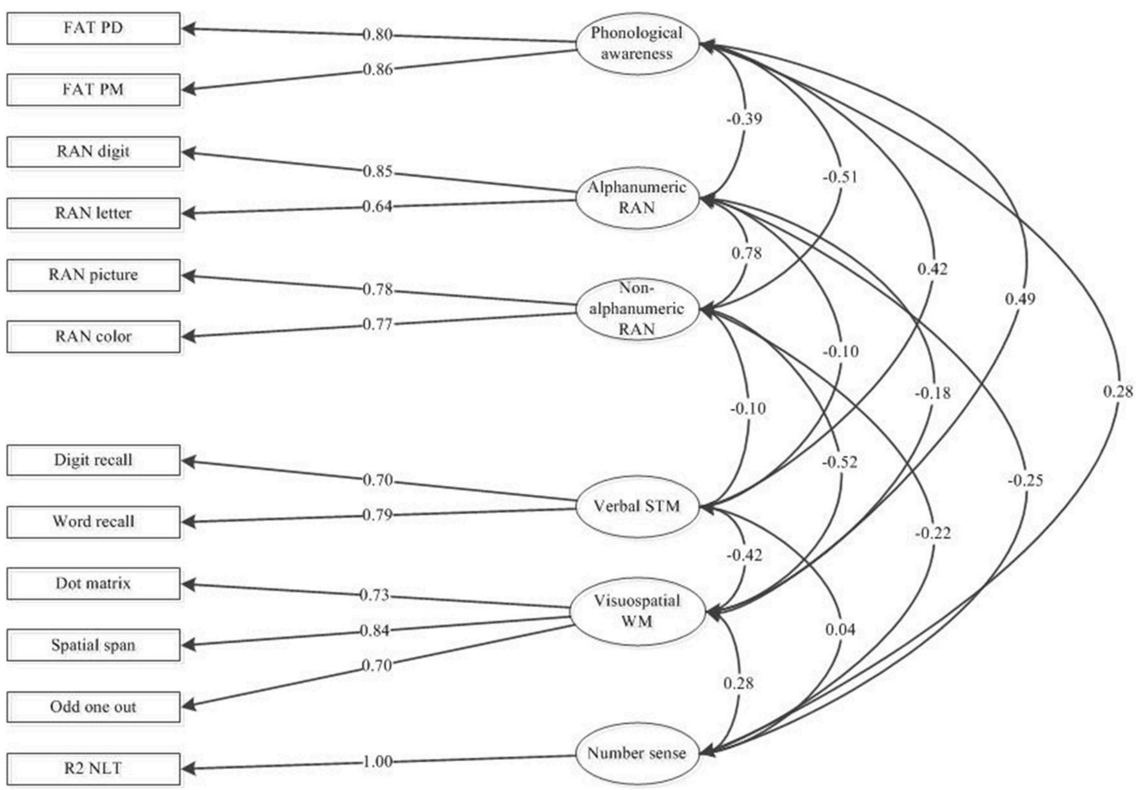


FIGURE A2 | Measurement model for the cognitive dimensions NS, visuospatial WM, PA, RAN, and verbal STM. Standardized path coefficients are depicted.

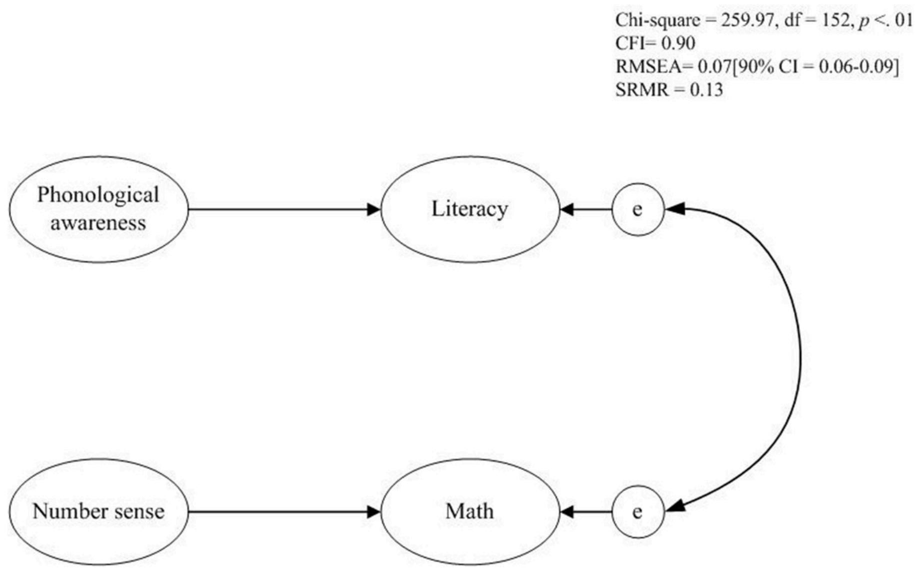


FIGURE A3 | Single risk factor model. Standardized path coefficients are depicted.

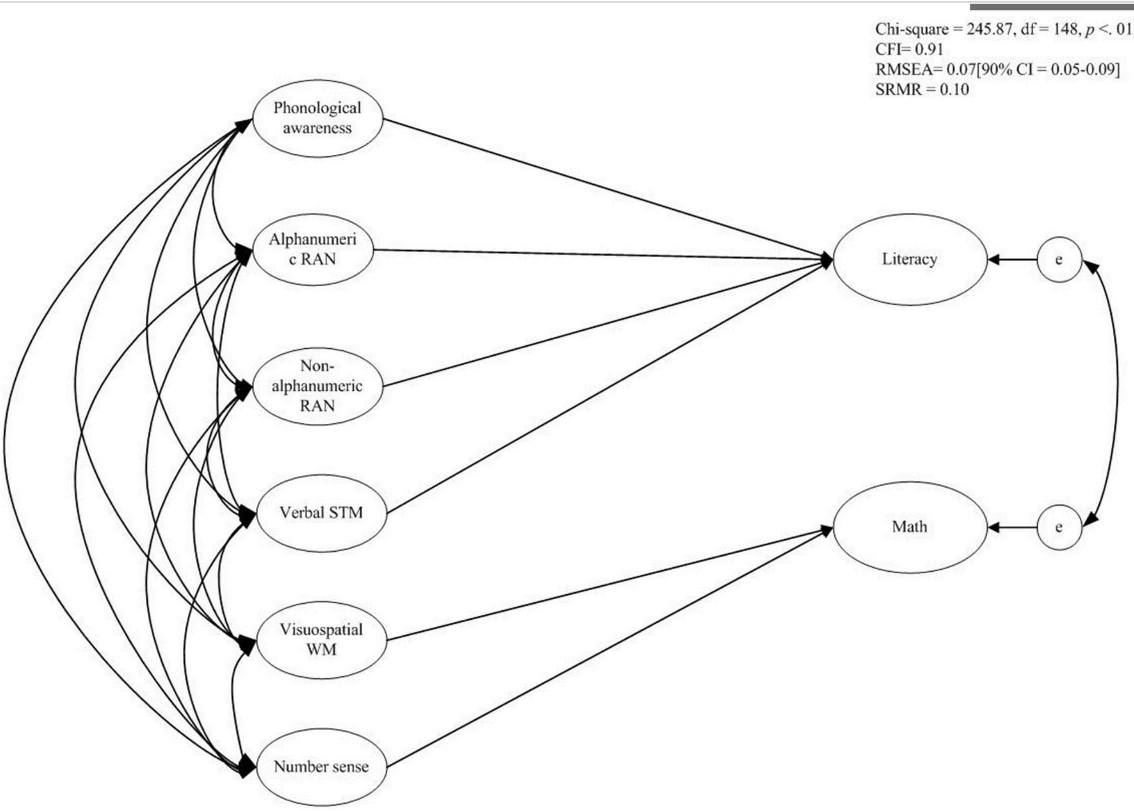


FIGURE A4 | Multi-factorial risk factor model. Standardized path coefficients are depicted.

Advantages of publishing in Frontiers

OPEN ACCESS
Articles are free to read, for greatest visibility

COLLABORATIVE PEER-REVIEW
Designed to be rigorous – yet also collaborative, fair and constructive

FAST PUBLICATION
Average 85 days from submission to publication (across all journals)

COPYRIGHT TO AUTHORS
No limit to article distribution and re-use

TRANSPARENT
Editors and reviewers acknowledged by name on published articles

SUPPORT
By our Swiss-based editorial team

IMPACT METRICS
Advanced metrics track your article's impact

GLOBAL SPREAD
5'100'000+ monthly article views and downloads

LOOP RESEARCH NETWORK
Our network increases readership for your article

Frontiers
EPFL Innovation Park, Building I • 1015 Lausanne • Switzerland
Tel +41 21 510 17 00 • Fax +41 21 510 17 01 • info@frontiersin.org
www.frontiersin.org

Find us on