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Poor academic achievement in reading and mathematics among primary school children: The role of cognitive, socioeconomic, and emotional factors

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Abstract

Poor academic achievement in reading and mathematics among primary school children: The role of cognitive, socioeconomic, and emotional factors

The acquisition of reading and mathematics in elementary school represents a critical stage in children's development, laying the foundation for later academic and professional success. Nevertheless, a substantial proportion of children struggle to achieve adequate proficiency in these domains. Unlike children formally diagnosed with specific learning disorders, poor readers and poor mathematics achievers frequently lack targeted support and constitute largely understudied populations, with the sources of their difficulties remaining insufficiently understood. Previous research has identified a range of factors influencing achievement in these domains, including cognitive, socioeconomic and emotional factors. Cognitive factors comprise both domain-general skills (e.g., executive functions, selective attention) and domain-specific skills (e.g., phonological awareness, rapid automatized naming (RAN), oral language, and visual-attention span for reading; and non-symbolic and symbolic magnitude processing, transcoding, and number ordering for mathematics). Moreover, parental socioeconomic status (SES) and emotional factors such as math anxiety (MA), also influence academic performance. Yet, these various factors have rarely been considered together within an integrated framework. This thesis aims to advance understanding of the multifaceted determinants of poor reading and mathematics achievement and to characterize interindividual variability among low-performing children. To this end, 472 third-grade children were recruited. Study 1 examined the effect of SES on reading and mathematics outcomes and investigated whether domain-general and domain-specific cognitive factors mediated these associations. Results indicated that the SES-reading link was exclusively mediated by domain-specific skills (phonological awareness, oral language, and visual-attention span), whereas the SES-mathematics link was mediated by both domain-specific (transcoding) and domain-general (working memory) skills. Study 2 examined whether MA influenced mathematics performance beyond SES and whether cognitive factors mediated this relationship. Findings showed that MA negatively affected mathematics performance independently of SES, with mediation effects of both working memory and symbolic processing skills. Study 3 addressed cognitive heterogeneity among poor readers and poor mathematics achievers. Latent profile analysis revealed two distinct profiles within each group.

Among poor readers, one profile exhibited broad cognitive weaknesses, while the other showed a specific weakness in visual-attention span. Among poor mathematics achievers, one profile displayed broad cognitive weaknesses, whereas the other was characterized by weaknesses in working memory and symbolic comparison. Finally, Study 4 examined the cognitive correlates of poor achievement by distinguishing co-occurring reading and mathematics difficulties from isolated difficulties. Results indicated that co-occurring difficulties were uniquely associated with a combination of weaknesses in working memory, RAN, visual-attention span, transcoding and symbolic comparison, reflecting the cumulative cognitive characteristics of the single-difficulty groups. Taken together, these findings underline the importance of a comprehensive approach when characterizing the determinants of poor reading and mathematics performance in elementary school. They further highlight the need to account for interindividual variability when designing interventions, thereby enabling support tailored to children's specific profiles.

Keywords: poor academic achievement, reading, mathematics, primary school, cognitive profiles, socioeconomic status, math anxiety

Résumé

Faibles performances scolaires en lecture et en mathématiques à l'école primaire: rôle des facteurs cognitifs, socio-économiques et émotionnels

L'acquisition des compétences en lecture et en mathématiques à l'école primaire représente une étape clé du développement des enfants, posant les bases de la réussite académique et professionnelle future. Néanmoins, une proportion importante d'enfants peine à atteindre un niveau de compétence suffisant dans ces domaines. Contrairement aux enfants diagnostiqués avec un trouble spécifique des apprentissages, les faibles lecteurs et les enfants en difficulté en mathématiques bénéficient rarement d'un soutien ciblé et constituent une population largement sous-étudiée, dont les sources de difficultés demeurent insuffisamment comprises. Les recherches antérieures ont identifié divers facteurs influençant les performances dans ces domaines, incluant des facteurs cognitifs, socio-économiques et émotionnels. Les facteurs cognitifs comprennent à la fois des compétences domaine-générales (e.g., fonctions exécutives, attention sélective) et domaine-spécifiques (e.g., conscience phonologique, dénomination rapide automatisée (RAN), langage oral, et empan visuo-attentionnel pour la lecture ; traitement de la magnitude non-symbolique et symbolique, transcodage et traitement de l'ordre numérique pour les mathématiques). Par ailleurs, le statut socio-économique parental (SES) et des facteurs émotionnels, tels que l'anxiété mathématique (MA), sont également liés aux performances scolaires. Cependant, ces différents facteurs ont rarement été étudiés conjointement. L'objectif de cette thèse est de mieux comprendre les déterminants multifactoriels des faibles performances en lecture et en mathématiques et de caractériser la variabilité interindividuelle parmi les enfants en difficulté. À cette fin, 472 enfants de CE2 ont été recrutés. L'étude 1 a examiné l'effet du SES sur les performances académiques et le rôle médiateur des compétences cognitives domaine-générales et domaine-spécifiques. Les résultats ont montré que la relation SES-lecture était médiée exclusivement par des compétences domaine-spécifiques (conscience phonologique, langage oral, empan visuo-attentionnel), tandis que la relation SES-mathématiques était médiée par des compétences domaine-spécifiques (transcodage) et domaine-générales (mémoire de travail). L'étude 2 a examiné si la MA influençait les performances en mathématiques au-delà du SES et si les compétences cognitives jouaient un rôle médiateur. Les résultats ont révélé un effet négatif de la MA sur les performances mathématiques, indépendant du SES, avec un rôle

médiateur de la mémoire de travail et des compétences de traitement symbolique. L'étude 3 a exploré l'hétérogénéité cognitive au sein des faibles lecteurs et des enfants en difficulté en mathématiques. Une analyse de profils latents a mis en évidence deux profils distincts pour chaque groupe. Chez les faibles lecteurs, un profil présentait des faiblesses cognitives générales, tandis que l'autre montrait une faiblesse spécifique de l'empan visuo-attentionnel. Chez les enfants en difficulté en mathématiques, un profil présentait des faiblesses cognitives générales, tandis que l'autre se caractérisait par des faiblesses en mémoire de travail et en comparaison symbolique. Enfin, l'étude 4 a distingué les difficultés combinées en lecture et en mathématiques des difficultés isolées. Les résultats ont montré que les difficultés combinées étaient associées à un ensemble de faiblesses en mémoire de travail, RAN, empan visuo-attentionnel, transcodage et comparaison symbolique, reflétant la combinaison cumulative des caractéristiques cognitives observées dans les groupes présentant des difficultés isolées. Dans l'ensemble, ces résultats soulignent l'importance d'une approche compréhensive dans l'étude des facteurs impliqués dans les faibles performances en lecture et en mathématiques à l'école primaire et mettent en lumière la nécessité de tenir compte de la variabilité interindividuelle afin de concevoir des interventions adaptées aux profils spécifiques des enfants.

Mots-clés : faibles performances scolaires, lecture, mathématiques, école primaire, profils cognitifs, statut socio-économique, anxiété mathématique

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Table of acronyms

ANS	approximate number system
CFA	confirmatory factor analysis
CFI	comparative fit index
CI	confidence interval
FIML	full information maximum likelihood
LPA	latent profile analysis
MA	math anxiety
OR	odds ratio
PCA	principal component analysis
PM	poor mathematics achievers only
PR	poor readers only
PR-PM	co-occurring poor readers and poor mathematics achievers
RAN	rapid automatized naming
RMSEA	root mean square error of approximation
SE	standard error
SEM	structural equation modeling
SES	socioeconomic status
SRMR	standardized root mean square residual

Part 1: Theoretical background

The acquisition of reading and mathematics skills during the early elementary school years represents a pivotal period in children's cognitive and academic development, providing the foundation for all other subsequent academic learning. This period involves intensive formal instruction that fosters the progressive mastery of symbolic systems – alphabetic characters in reading and numerical symbols in mathematics (Purpura et al., 2019). In both domains, learning unfolds through successive developmental stages. Initially, explicit instruction supports the acquisition of systematic correspondences among visual, phonological, and semantic representations (Fuchs et al., 2016; Ziegler et al., 2020; Ziegler & Goswami, 2005). This phase is typically followed, during second and third grade, by procedural automatization, marked by the development of increasingly rapid, efficient, and effortless operations. These processes enable fluent word recognition and the consolidation of orthographic representations in reading (Ehri, 2005; Ziegler et al., 2020), as well as the direct retrieval of arithmetic facts in mathematics (S. Cho et al., 2011; Geary, 2004). Such automatized processes are essential for the acquisition of higher-order literacy and numeracy competencies in later grades (Fuchs et al., 2016; Geary, 2004).

Yet, the development of reading and mathematical skills is marked by substantial variability, and a notable proportion of children struggle to attain adequate proficiency in these domains during the elementary school years. The present theoretical section first provides an overview of the extent and nature of poor academic achievement in reading and mathematics among primary school children. It then reviews a range of the multifaceted determinants of poor academic performance, including cognitive, socioeconomic, and emotional dimensions. Finally, it examines the interindividual variability observed among children with poor reading and/or poor mathematics achievement.

1. Poor academic achievement in reading and mathematics among primary school children

1.1. Definition and prevalence

To date, research on academic difficulties in reading and mathematics has primarily focused on their most extreme forms, namely dyslexia and dyscalculia (Peterson & Pennington, 2015; Price & Ansari, 2013). These specific learning disorders are characterized by severe and persistent impairments in written word recognition fluency and/or accuracy in the case of dyslexia (Carroll et al., 2025; Lopes et al., 2020) or in the development of arithmetic skills in dyscalculia (Kaufmann et al., 2013; Price & Ansari, 2013). They are typically identified through comprehensive standardized diagnostic assessments (Billard & Barbe, 2016; Carroll et al., 2025; Kaufmann & Aster, 2012; Price & Ansari, 2013), and estimated prevalence rates average 6 to 7% for both disorders (Morsanyi, Van Bers, McCormack, et al., 2018; L. Yang et al., 2022). However, children diagnosed with dyslexia or dyscalculia represent only a subset of the broader population of children experiencing difficulties in reading and mathematics (Astle et al., 2022; Billard & Barbe, 2016; Dowker, 2024), highlighting the importance of examining a wider spectrum of learning challenges in academic achievement (Snowling & Hulme, 2024; X. Zhang et al., 2020).

Evidence from international and national assessments reveals that poor academic achievement in reading and mathematics is widespread and extends far beyond clinically diagnosed learning disorders. The 2021 Progress in International Reading Literacy Study (PIRLS) reported that 25% of fourth-grade students across all participating countries performed at a low or very low level in reading comprehension, with the proportion rising to 28% in France (Conceiçao et al., 2023; Mullis et al., 2023). In mathematics, the situation appears even more concerning: the 2023 Trends in International Mathematics and Science Study (TIMSS) found that 44% of French fourth graders scored below proficiency levels, compared to an international average of 30% (Cioldi & Raffy, 2024; Von Davier et al., 2024). This pattern is also observed in younger children. For instance, national assessments conducted in 2024 by the Direction de l'Évaluation, de la Prospective et de la Performance (DEPP) of the French Ministry of Education indicate that 22% of second-grade and 34% of third-grade students in France display weak or deficient literacy skills, particularly in reading aloud (Desclaux et al., 2025; Evrard et al., 2025). In mathematics, 31% of second graders and 37% of third graders demonstrate poor or very poor performance, with particular difficulties

in arithmetic fact retrieval, calculation, and problem-solving skills (Desclaux et al., 2025; Evrard et al., 2025). These findings extend results from studies conducted over 15 years ago in France, which already reported that 13–14% of second-grade children showed a reading delay of at least 1 year relative to age-expected levels (Ecalle & Magnan, 2006; Fluss et al., 2009). Notably, cohort data point to a gradual increase in the proportion of low-performing students in both academic domains since the early 2000s (Colmant & Le Cam, 2017; Ninnin & Pastor, 2020).

A substantial proportion of children experience significant difficulties in acquiring adequate reading and mathematical skills during the elementary school years. In most empirical studies, such academic difficulties are defined as performance falling below a specific cut-off point (e.g., percentile rank) on standardized academic assessments (Dowker, 2024; Peng et al., 2022; X. Zhang et al., 2020). However, there is considerable heterogeneity across studies in the cut-off criteria employed, with some using highly stringent thresholds (e.g., performance below the 5th percentile), while others adopt much more lenient benchmarks (e.g., performance below the 48th percentile) (Kivirähk-Koor & Kiive, 2025; Kroesbergen et al., 2023; Murphy et al., 2007; Peng et al., 2022; Swanson & Jerman, 2006). Strict criteria are generally intended to identify children with severe learning difficulties (i.e., those likely to meet criteria for specific learning disorders), whereas more liberal thresholds are typically used to capture a broader population of low-performing students who do not necessarily meet diagnostic thresholds (Kroesbergen et al., 2023; Peng et al., 2022; Swanson et al., 2018; X. Zhang et al., 2020).

Despite the substantial prevalence of low academic performance among elementary school children, research has disproportionately focused on specific learning disorders, leaving the broader population of poor achievers largely understudied (Fluss et al., 2009). Consequently, our understanding of the multifactorial origins underlying poor performance in reading and mathematics remains limited. This gap is particularly concerning given that poor achievers constitute the largest subgroup of learners experiencing academic difficulties (Cioldi & Raffy, 2024; Conceiçao et al., 2023), often face challenges that significantly interfere with their everyday lives (Astle et al., 2022), and yet rarely have access to appropriate educational support from which they could nonetheless benefit (Billard & Barbe, 2016; X. Zhang et al., 2020). Furthermore, the persistent nature of these difficulties raises serious concerns about their long-term consequences across academic, socioeconomic, and psychological domains.

1.2. Long-term impact of poor reading and poor mathematics achievement

1.2.1. Academic trajectories

Longitudinal research examining the developmental trajectories of children with early difficulties in reading or mathematics has consistently shown that such difficulties tend to persist over time, with long-lasting consequences for subsequent academic achievement (Duncan et al., 2007; McNamara et al., 2011; Morgan et al., 2011). In the reading domain, Billard et al. (2010) reported that, among French primary school children, the performance gap in decoding between poor and proficient readers remained stable from second to fourth grade, suggesting limited spontaneous improvement. In mathematics, Geary et al. (2012) found that children identified as low performers in first grade exhibited significantly slower growth in mathematical ability through fifth grade compared to their peers without mathematical difficulties, indicating a progressive widening of the achievement gap over the primary school years.

Moreover, academic difficulties in reading and mathematics among low-achieving children often persist beyond the primary years and continue to hinder learning throughout secondary education (Sainio et al., 2021). Importantly, longitudinal studies show that approximately 70% of children identified as poor readers at the beginning of elementary school continue to struggle with reading in upper elementary grades (Landerl & Wimmer, 2008; Smart et al., 2005), with many also developing difficulties in other academic domains, such as mathematics (Andersson, 2010; Smart et al., 2005). Similarly, children with poor mathematical performance at age 9 typically do not catch up with their peers by age 13 (Andersson, 2010). Although some variability in the academic trajectories of low-achieving children has been documented (Mattison et al., 2023), the majority continue to experience persistent academic challenges over time, particularly in the absence of targeted intervention (Aubrey et al., 2006) – a developmental pattern closely resembling that observed in children with specific learning disorders (Billard et al., 2010; Shalev et al., 2005).

1.2.2. Social and economic consequences

Low academic achievement in reading and mathematics during elementary school has also been associated with substantial long-term socioeconomic consequences. In a large-scale longitudinal study conducted in the United Kingdom, Ritchie and Bates (2013) found that children with the lowest reading and mathematics scores at age 7 obtained lower educational qualifications and reached significantly lower socioeconomic levels by age 42, even after controlling for parental socioeconomic background. More broadly, adults with poor literacy

and/or numeracy skills face an increased risk of unemployment and are more likely to earn lower wages (Carneiro & Gordon, 2013; Parsons & Bynner, 2005). These findings underline the considerable societal costs associated with persistent difficulties in reading and mathematics. Reducing the prevalence of poor academic achievement in these foundational learning domains could therefore yield significant socioeconomic benefits (OECD, 2010), including enhanced productivity, competitiveness, and innovation (Carneiro & Gordon, 2013), as well as narrowing socioeconomic disparities (Ritchie & Bates, 2013).

1.2.3. Psychological consequences

In addition to educational and socioeconomic consequences, low academic performance in reading and mathematics has been associated with adverse psychological outcomes. For instance, Morgan et al. (2012) found that children with poor reading or poor mathematical skills in third grade were significantly more likely to experience emotional maladjustment by the end of elementary school, reporting higher levels of sadness and loneliness compared to their peers without academic difficulties. These effects are also evident in adulthood, where low literacy and/or numeracy skills have been linked to an increased risk of mental health problems, including low self-esteem (Parsons & Bynner, 2005), social isolation (Carneiro & Gordon, 2013), addictive behaviors (Yates, 2013), and depressive symptoms (Parsons & Bynner, 2005).

Collectively, these considerations highlight the necessity of a comprehensive understanding of the multiple factors underlying interindividual differences in reading and mathematics achievement during the early school years. Such knowledge is essential for the development of targeted interventions that can effectively support children facing challenges within these two domains. Given the range of factors influencing academic performance in reading and mathematics during primary school (e.g., Bonte & Brem, 2024; Chiu et al., 2012; Dalmaijer et al., 2023; Fluss et al., 2009; Lavelle-Hill et al., 2024), the following sections provide a focused overview of some key influences, including cognitive, socioeconomic, and emotional dimensions.

2. Cognitive factors and academic achievement

Academic achievement in reading and mathematics in primary school relies on a broad range of cognitive factors. Some of these are domain-specific, reflecting the particular demands of reading or mathematics themselves, while others are domain-general, supporting learning across different academic domains. This theoretical section offers a focused overview of the main cognitive factors associated with academic proficiency and difficulties in reading and mathematics, first addressing domain-specific factors, and then domain-general ones. In each subsection, cognitive factors will first be examined in terms of how they relate to reading and/or mathematics in the general population, before reviewing evidence of corresponding deficits in children experiencing difficulties in these domains.

2.1. Domain-specific cognitive factors

2.1.1. Domain-specific factors related to reading

A variety of domain-specific cognitive processes have been shown to support reading development and to contribute to reading difficulties when impaired. These include, on the one hand, language-related skills such as phonological awareness, rapid automatized naming, and oral language abilities (Hulme & Snowling, 2013), and, on the other hand, visuo-attentional processes, particularly visual-attention span (Valdois et al., 2004). Although the latter has received comparatively less attention in the literature, its role in reading acquisition has gained increasing recognition over the past years (J. Liu et al., 2023; Tang et al., 2023; Valdois, 2022).

2.1.1.1. Phonological awareness

Phonological awareness refers to the ability to recognize, identify, and manipulate the phonological components of spoken language, encompassing units of varying granularity such as syllables, onsets, rhymes, and phonemes – the latter representing the smallest units of sound in spoken language (Ehri et al., 2001; Landerl et al., 2022; Ziegler & Goswami, 2005). This skill is typically assessed through tasks requiring reflection upon or manipulation of phonological segments within words or pseudowords (Hulme & Snowling, 2013; Melby-Lervåg et al., 2012). Among these, phoneme deletion tasks – where a specific sound must be removed from a verbal string and the resulting sequence articulated – are among the most commonly used paradigms (Hulme & Snowling, 2013; Landerl et al., 2022). Phonological awareness plays

a pivotal role in the development of decoding skills during early reading acquisition, as it underpins the understanding of grapheme-phoneme correspondences. It enables beginning readers to become aware that spoken words can be segmented into discrete phonemic units, which in turn map onto graphemes (i.e., letters or groups of letters) in written language (Shaywitz et al., 2007).

Phonological awareness has been consistently identified as a robust correlate of reading proficiency, influencing both word and pseudoword reading across diverse orthographies (Landerl et al., 2022; Melby-Lervåg et al., 2012; Ruan et al., 2018; S. Song et al., 2016). Its predictive strength is particularly pronounced in orthographic systems with a high degree of grapheme-phoneme inconsistency, commonly referred to as opaque orthographies (Landerl et al., 2022). Longitudinal research further supports the role of phonological awareness in reading development (Melby-Lervåg, 2012). Specifically, phonological awareness skills assessed in kindergarten (Bianco et al., 2012; Kirby et al., 2003; McIlraith, 2018; Roth et al., 2002) and early elementary school (Kirby et al., 2025; Muter et al., 2004; Silva et al., 2025) reliably predict later reading outcomes. Some evidence also suggests reciprocal relationships between phonological awareness and reading over the course of development (Hogan et al., 2005). However, Castles and Coltheart (2004) have questioned the causal nature of this relationship, noting that many longitudinal studies do not include children who are completely non-readers at baseline, or fail to control for pre-existing literacy skills. Addressing this limitation, D. Powell and Atkinson (2021) followed a cohort of 4-year-old children confirmed to be non-readers and found that phonological awareness at that age predicted word reading performance 18 months later, shortly before entry into first grade – thus supporting the hypothesis of a causal role for phonological awareness in reading acquisition.

Furthermore, empirical evidence from intervention studies indicates that phonological awareness training generally leads to significant improvements in reading performance compared to untrained control groups (see Bus & van IJzendoorn, 1999; Ehri et al., 2001, for meta-analyses). However, the long-term efficacy of such interventions often appears limited. Notably, their effectiveness is enhanced when phoneme-level training is combined with letter-level instruction (Bus & van IJzendoorn, 1999). In the French educational context, computerized training programs aimed at strengthening grapheme-phoneme correspondences have been implemented at both the kindergarten (Potier Watkins & Dehaene, 2024) and first-grade levels (Lassault et al., 2022). These programs have yielded promising results, enhancing phonological awareness and producing transfer effects on reading fluency. Nonetheless, concerns persist regarding the durability of these gains, with

some evidence suggesting that reading improvements may not be sustained in the long term (Potier Watkins & Dehaene, 2024).

Additional support for the critical role of phonological awareness in reading acquisition comes from studies on children with reading difficulties, who have been consistently found to exhibit substantial deficits in phonological awareness – not only compared to age-matched peers without reading difficulties but also to younger children with equivalent reading levels (Melby-Lervåg et al., 2012). These findings have led to the widely accepted view that phonological awareness deficits represent the core cognitive impairment underlying developmental dyslexia (Vellutino et al., 2004). Longitudinal research using growth modeling has further showed that children who struggle to acquire phonological awareness skills in kindergarten exhibit slower reading progress throughout the early elementary years (Boscardin et al., 2008). Finally, intervention programs targeting phonological skills have been found to improve reading outcomes in poor and very poor readers (e.g., Ecalle et al., 2020; Zoubrinetzky et al., 2019), further reinforcing the central role of phonological awareness in reading proficiency and difficulties.

2.1.1.2. Rapid automatized naming

Rapid automatized naming (RAN) is another cognitive factor that has been repeatedly associated with reading achievement. RAN refers to the capacity to quickly name sequences of highly familiar visual stimuli – either alphanumeric (e.g., letters, digits) or non-alphanumeric (e.g., objects, colors) – presented serially and repeatedly in random order (Kirby et al., 2010; Landerl et al., 2019). Performance is typically assessed by recording the total time required to name all items, line by line, from left to right (Norton & Wolf, 2012). Involving both visual and phonological components, RAN resembles the reading process in several respects, including the serial processing of visual information, access to and retrieval of phonological and lexical representations, and the articulation of an oral response (Georgiou, Parrila, et al., 2013; Georgiou & Parrila, 2020; Norton & Wolf, 2012).

Debate remains as to whether RAN constitutes a construct independent from phonological processing or reflects a component thereof (Norton & Wolf, 2012). However, several arguments support a dissociation between the two constructs. These include the moderate correlations typically observed between RAN and phonological awareness, the improved model fit when they are treated as separate latent factors rather than a single one, and their independent contributions to reading outcomes (Norton & Wolf, 2012; D. Powell et

al., 2007). A similar controversy concerns whether RAN reflects a skill distinct from general processing speed. Yet again, findings indicate that RAN retains predictive power for reading even after controlling for general processing speed (Kirby et al., 2010; Norton & Wolf, 2012). Based on this body of evidence, Kirby et al. (2010) concluded that RAN partially overlaps with, but is not reducible to, phonological, orthographic, or processing speed components.

Regarding the relationship between RAN and reading, moderate to strong associations have been demonstrated (see Araújo et al., 2015, for a meta-analysis) and consistently observed across diverse orthographies (Kirby et al., 2010; Landerl et al., 2019; Norton & Wolf, 2012; S. Song et al., 2016). Specifically, RAN relates to various reading outcomes, including word, pseudoword, and text reading (Araújo et al., 2015; Kirby et al., 2010). While RAN is predominantly linked to reading fluency, relationships with reading accuracy and comprehension have also been reported (Araújo et al., 2015; Kirby et al., 2010; Norton & Wolf, 2012). Moreover, the nature of stimuli used in RAN tasks influences the magnitude of these associations, with alphanumeric stimuli yielding stronger correlations than non-alphanumeric stimuli (Araújo et al., 2015; Kirby et al., 2010; McWeeny et al., 2022; S. Song et al., 2016).

Evidence for a causal link between RAN and reading performance has been provided by longitudinal studies, showing that RAN skills assessed in kindergarten (Gray & Powell-Smith, 2025; Kirby et al., 2003; McWeeny et al., 2022; Poulsen et al., 2015) and early elementary school (Kirby et al., 2025; Silva et al., 2025) predict later reading outcomes – even after controlling for phonological awareness. Interestingly, Kirby et al. (2003) found that while phonological awareness predicted reading primarily in the early grades, RAN remained a significant predictor throughout elementary school, with its influence increasing over time. Furthermore, although evidence for the effectiveness of RAN-focused interventions and their transfer to reading remains limited (Kirby et al., 2010), a training program targeting object naming speed yielded promising results among French-speaking second graders (Vander Stappen & Reybroeck, 2018). Children receiving the training showed greater improvements in word reading fluency than peers who received a phonological awareness training, further supporting the hypothesis of a causal link between RAN and reading – particularly reading fluency.

Finally, lower RAN performance has consistently been observed in children with reading difficulties compared to peers with age-appropriate reading skills (Park & Uno, 2012; S. Song et al., 2020; Valdois et al., 2021; Ziegler et al., 2008), with severe RAN deficits reportedly affecting over 60% of struggling readers (Norton & Wolf, 2012; Ziegler et al., 2008;

but see Valdois et al., 2021). Crucially, early RAN deficits have been shown to predict later reading difficulties, independently of phonological awareness abilities (Billard et al., 2010; Carroll et al., 2016; Grigorakis et al., 2022). Notably, Kirby et al. (2003) demonstrated that children with the lowest RAN scores in kindergarten – regardless of whether phonological awareness deficits were present – were most at risk for persistent reading underachievement throughout elementary school and for developing significant reading difficulties by fifth grade. Taken together, these findings underline the critical role of RAN not only in reading acquisition, but also as a potential underlying factor in the emergence of reading difficulties.

2.1.1.3. Oral language

Although phonological awareness and RAN are widely recognized as central linguistic predictors of reading success, broader oral language abilities – such as vocabulary knowledge and oral comprehension – also substantially influence reading development (e.g., Hjetland et al., 2020). Vocabulary refers to the set of words an individual can produce (expressive vocabulary) or understand (receptive vocabulary) and is typically assessed using naming or definition tasks for expressive vocabulary, and picture selection tasks in response to spoken words for receptive vocabulary (Spiegel et al., 2021). Alongside syntactic processing, vocabulary forms a core component of oral comprehension – defined as the ability to derive meaning from spoken language (Spiegel et al., 2021) – which has been shown to significantly support reading acquisition (Nation & Snowling, 2004).

Much of the existing literature on oral language in relation to reading has focused on its contribution to reading comprehension. Understandably, children must know the meaning of the words they encounter in a text in order to fully comprehend it (Ricketts et al., 2007). More specifically, Gough and Tunmer (1986) proposed the Simple View of Reading, a model that conceptualizes reading comprehension as the product of two core components: decoding and listening comprehension. According to this framework, deficits in either domain – or in both – can impede a child's ability to understand written material. Empirical evidence supports this model, with studies indicating that oral language and word reading each make unique contributions to early reading comprehension (Foorman et al., 2015; Kendeou et al., 2009; Solari et al., 2018; Wolf et al., 2019). Notably, M. Yan et al. (2021) found that while both components predicted reading comprehension from first to third grade, the influence of decoding declined over time, whereas oral language became increasingly important. Longitudinal research further reinforces these findings, demonstrating that oral language and word reading skills assessed at the end of first grade independently predict reading

comprehension in second and third grade, even after controlling for earlier comprehension levels (P. F. De Jong & Van Der Leij, 2002; Metsala et al., 2021). Moreover, Lervåg et al. (2018) showed that decoding, oral language, and their interaction accounted for over 95% of the variance in reading comprehension among second-grade children. Interestingly, oral language skills in second grade also predicted long-term growth in reading comprehension up to fifth grade, whereas decoding predicted short-term gains, and only among children with the lowest initial decoding abilities.

However, the role of oral language in reading extends beyond its impact on comprehension, also contributing to the acquisition of word reading skills. Although phonological factors have traditionally received more attention in this domain, the contribution of oral language abilities has also been underlined (Ricketts et al., 2007). Studies have shown that oral language predicts word reading performance – particularly for irregular words – in both cross-sectional and longitudinal designs, even after controlling for earlier phonological skills and reading level (Nation & Cocksey, 2009; Nation & Snowling, 2004; Ricketts et al., 2007; Valdois et al., 2021). This suggests that oral familiarity with a word can support its recognition in print, especially when grapheme-phoneme correspondence rules are insufficient for accurate decoding. Interestingly, vocabulary knowledge has also been associated with pseudoword reading performance (Ouellette, 2006), possibly because a growing lexicon demands more fine-grained sublexical representations, which in turn may enhance phonological awareness and thereby support decoding processes (Ouellette, 2006; Walley et al., 2003). Moreover, evidence points to a reciprocal relationship between vocabulary and word reading development throughout elementary school (Killingly et al., 2025; M. Yan et al., 2021).

Longitudinal research examining the respective contributions of oral language and phonological processing to reading development – including both decoding and reading comprehension – has underlined the importance of both cognitive abilities, albeit via distinct pathways (Hjetland et al., 2019, 2020; NICHD Early Child Care Research Network, 2005). One pathway reflects a direct influence of oral language on later reading comprehension. A second, indirect, pathway involves a serial influence, whereby oral language supports early phonological processing, which in turn facilitates decoding skills, ultimately contributing to later reading comprehension (Hjetland et al., 2019; NICHD Early Child Care Research Network, 2005). Broad oral language abilities and code-related language skills thus appear to be differentially linked to specific reading components, with oral language explaining more variance in reading comprehension, and phonological awareness contributing more strongly

to decoding (Bianco et al., 2012). These patterns are further supported by intervention studies. For instance, Bianco et al. (2012) found that phonological awareness training in kindergarten improved decoding in first grade but had no effect on comprehension, whereas oral language training enhanced reading comprehension, but not decoding.

Finally, poor oral language performance has been documented in children with reading difficulties, both among poor decoders (Park & Uno, 2012; Valdois et al., 2021) and poor comprehenders with adequate decoding skills (Ricketts et al., 2007). Furthermore, early deficits in oral language at the start of elementary school have been linked to a heightened risk of developing significant reading comprehension difficulties in later grades, independently of phonological awareness and RAN abilities (Billard et al., 2010; Grigorakis et al., 2022). These findings highlight the need to support oral language skills as early as possible in children entering school with poor verbal abilities (Bowyer-Crane et al., 2008).

2.1.1.4. Visual-attention span

Beyond language-specific cognitive factors, recent research has increasingly emphasized the role of visuo-attentional processes in reading development and related difficulties. In particular, visual-attention span – defined as the number of distinct visual elements (e.g., orthographic units) within a multi-element array that can be processed simultaneously in a single glance – has received growing attention (Bosse et al., 2007; Frey & Bosse, 2018; Valdois, 2022). Visual-attention span is most commonly assessed through multi-character report tasks, including both global and partial report paradigms (Frey & Bosse, 2018; Valdois, 2022). In these tasks, multi-character strings (typically consonant letters) are briefly presented (up to 200 ms), allowing for parallel processing during a single visual fixation. Participants are then required either to report as many letters as possible, regardless of order (global report), or to identify a single cued letter (partial report) (Frey & Bosse, 2018). A schematic representation of these tasks is provided in Figure 1 below. To control for potential confounds related to basic letter recognition, performance on an isolated letter recognition task is typically accounted for (Valdois, 2022).

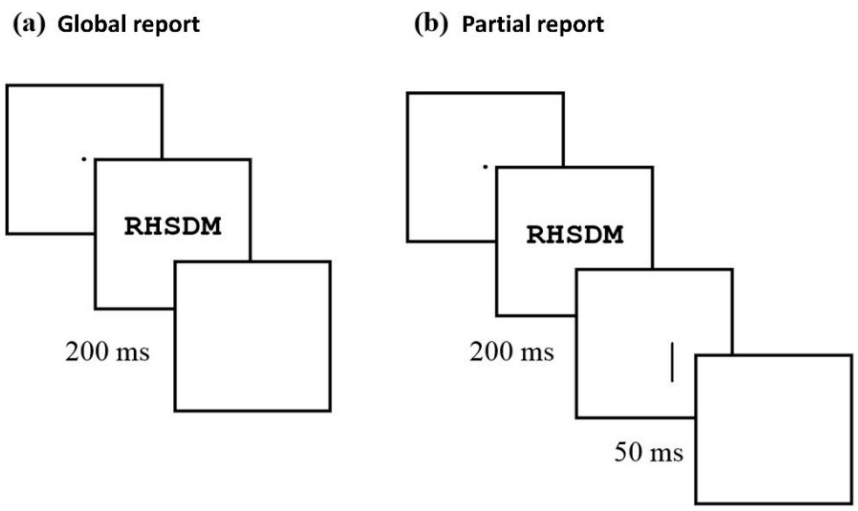

Figure 1. Schematic representation of the global and partial report tasks typically used to assess visual-attention span. Adapted from Valdois et al. (2010).

Given its contribution to distributing attentional resources across multiple letters processed simultaneously, visual-attention span plays a crucial role in the reading process (Frey & Bosse, 2018). When a reader's visual-attention span is broad enough to encompass the entire letter sequence of a known word, it enables rapid and direct word recognition (Valdois, 2010; van den Boer et al., 2015) – a process reflecting the global procedure described in the multiple-trace memory model developed by Ans et al. (1998). In contrast, a limited visual-attention span may prevent this direct recognition, requiring sequential visual fixations on sublexical units to build the phonological output and decode the word via an analytic procedure (Ans et al., 1998; van den Boer et al., 2015). Such reliance on the analytic route often involves applying grapheme-phoneme correspondences to smaller orthographic segments, increasing the risk of errors when reading irregular words – particularly regularization errors (Ans et al., 1998; Valdois, 2010). Moreover, a severely reduced visual-attention span may further compromise the decoding of complex multi-letter graphemes (e.g., "eau", "ain") within the analytic procedure, forcing the reader to rely on letter-by-letter decoding, which can hinder the reading of both regular words and pseudowords (Ans et al., 1998; Valdois, 2010). Ultimately, by reducing the likelihood of direct recognition through the global route and necessitating subsequent activation of the analytic route, a reduced visual-attention span may result in slower and less fluent reading (Ans et al., 1998).

A substantial body of evidence shows that visual-attention span is closely linked to reading performance throughout development, independently of language-related skills such as phonological awareness, RAN, and oral language (Bosse & Valdois, 2009; Valdois et al., 2021; van den Boer et al., 2015; van den Boer & de Jong, 2018). It has been found to predict word reading performance for irregular, regular, and pseudowords across all elementary grades and in orthographies with varying transparency (Bosse & Valdois, 2009; van den Boer et al., 2015; van den Boer & de Jong, 2018). Notably, Bosse and Valdois (2009) reported that, among French primary school children, while its predictive influence on regular and pseudoword reading decreased with schooling, its effect on irregular word reading remained stable over time – a pattern suggesting a specific and lasting contribution to orthographic knowledge development.

Longitudinal research further supports the influence of visual-attention span on reading achievement. Valdois et al. (2019) showed that kindergarten visual-attention span significantly predicted first-grade reading fluency, even after controlling for phonological awareness and early literacy skills. However, evidence for a causal relationship at more advanced stages remains mixed. For instance, van den Boer & de Jong (2018) found that third-grade visual-attention span did not predict fourth-grade reading once initial reading ability was taken into account. Intervention studies nonetheless reinforce its role in reading acquisition. Valdois et al. (2025) reported that first-grade children receiving tablet-based visual-attention span training at the start of the school year made greater gains in word reading fluency by year's end than peers trained on grapheme-phoneme correspondences. Moreover, time spent engaging with the training correlated positively with reading improvement, and post-training increases in visual-attention span predicted reading gains even after controlling for other domain-specific factors such as phonological awareness, RAN, and oral language. Overall, these findings support a potential causal role of visual-attention span in early reading acquisition and suggest that targeted training of this skill may help prevent reading difficulties (Valdois et al., 2025).

Notably, reduced visual-attention span has been documented in children with reading difficulties across diverse orthographies (Bosse et al., 2007; J. Liu et al., 2023; Saksida et al., 2016; Tang et al., 2023; Valdois et al., 2021), and such deficits appear to occur independently of language-related impairments (Bosse et al., 2007; Valdois et al., 2021). For instance, Valdois et al. (2021) found that about 20% of low-achieving sixth-grade French readers displayed an isolated visual-attention span deficit with intact phonological awareness and RAN. Intervention studies further indicate that visual-attention span training can improve reading

performance in children with reading difficulties (Zhao et al., 2019; Zoubrinetzky et al., 2019). Specifically, Zhao et al. (2019) reported that such training benefited only children with a visual-attention span deficit, not those with preserved visual-attention span. Taken together, these findings challenge the view that phonological deficits alone underlie reading difficulties (Valdois et al., 2004) and underline the importance of addressing multiple factors, including both phonological skills and visual-attention span, in remediation (Valdois et al., 2025).

Overall, evidence indicates that reading outcomes are influenced by multiple domain-specific cognitive factors, including language-related abilities – such as phonological awareness, RAN, and oral language – as well as visuo-attentional processes, particularly visual-attention span. Although few studies have simultaneously examined the unique predictive power of these factors, existing findings suggest that each contributes distinctly to reading proficiency (Valdois et al., 2021). These insights highlight the importance of comprehensively characterizing the specific cognitive factors underlying academic success and difficulties.

2.1.2. Domain-specific factors related to mathematics

Similarly to reading, a range of cognitive factors have been specifically linked to success and difficulties in mathematics. These domain-specific factors encompass, on the one hand, non-symbolic processes – namely the ability to process approximate quantities (non-symbolic magnitude processing) – and, on the other hand, symbolic processes, including: (i) understanding number symbols and their associated semantic meanings (symbolic magnitude processing); (ii) mastering different symbolic codes (e.g., oral and written formats) and converting between them (transcoding); and (iii) representing ordinal relations between numbers (ordering) (Geary, 2013).

2.1.2.1. Non-symbolic magnitude processing

The ability to process and manipulate non-symbolic magnitudes approximately is considered an innate skill, independent of culture, shared with other species, and observable very early in development, well before the start of formal schooling (Feigenson et al., 2004; Mishra & Khan, 2023; Odic & Starr, 2018). This capacity is thought to rely on the Approximate Number System (ANS), a cognitive system that enables the approximate representation, estimation, and discrimination of numerosities (i.e., item quantities) without the aid of

symbols or language (Szücs & Myers, 2017). ANS performance is most often assessed through non-symbolic comparison tasks, in which two sets of items (e.g., dot arrays) are presented simultaneously for a brief duration that prevents counting, and participants must identify which set contains more items (Mishra & Khan, 2023; Odic & Starr, 2018). Accuracy in these tasks is ratio-dependent, declining as the numerical difference between sets decreases (Halberda et al., 2008). For example, distinguishing between 10 and 8 items (ratio of 1.25) is more difficult than distinguishing between 10 and 5 items (ratio of 2). Ratio sensitivity, known as ANS acuity, is typically indexed by the Weber fraction (*w*) – a measure of noise in an individual's approximate number representation – where higher *w* values indicate lower precision (Mishra & Khan, 2023; Price et al., 2012). ANS acuity improves with age (Mazzocco et al., 2011b; Mishra & Khan, 2023; Piazza et al., 2010) and is often considered a foundational skill for acquiring more sophisticated numerical concepts, particularly symbolic number representations (Feigenson et al., 2004; Mishra & Khan, 2023; Odic & Starr, 2018). However, this view remains debated, with some authors arguing that symbolic number processing does not depend on prior ANS acuity but instead relies on a distinct representational system responsible for processing exact symbolic numerical values (e.g., Lyons et al., 2018; Matejko & Ansari, 2016; Sasanguie et al., 2014).

Evidence indicates that ANS acuity is related to mathematics performance, although meta-analyses suggest that this association is relatively weak (Chen & Li, 2014; Fazio et al., 2014; Schneider et al., 2017), particularly after age 6 (Fazio et al., 2014). Notably, ANS has been shown to correlate with early mathematical skills in preschool children, prior to formal instruction (Decarli et al., 2023; Libertus et al., 2011). Longitudinal studies further support this link (Chen & Li, 2014), showing that ANS acuity measured in preschool (Mazzocco et al., 2011b) and kindergarten (Bull et al., 2021; Desoete et al., 2012; Toll et al., 2015) predicts mathematics achievement in first grade across multiple outcomes, such as word problem-solving, calculation, and math fluency (Bull et al., 2021). Remarkably, ANS performance in infancy has also been found to predict preschool mathematical abilities, highlighting very early developmental links (Decarli et al., 2023). Importantly, evidence also suggests that this relationship may be bidirectional (L. Elliott et al., 2019). The hypothesis of a causal relationship, however, remains debated, as there is little evidence that ANS training improves mathematical outcomes (Qiu et al., 2021; Szücs & Myers, 2017).

Nevertheless, a substantial body of literature indicates that children with mathematical difficulties exhibit alterations in ANS precision (Haberstroh & Schulte-Körne, 2022; Schwenk et al., 2017), particularly among those with the most severe cases of dyscalculia (Decarli et al.,

2022; Feigenson et al., 2013; Mazzocco et al., 2011a; Piazza et al., 2010; but see Iuculano et al., 2008). For children with milder mathematical difficulties, findings are less consistent, with some studies reporting ANS deficits (Pinheiro-Chagas et al., 2014) and others not (W. W. L. Chan et al., 2013; T. T.-Y. Wong et al., 2017). Notably, Desoete et al. (2012) showed that poor ANS performance in kindergarten differentiated children with and without math difficulties in first and second grade, but only for those with the most severe mathematical difficulties. In contrast, Van Herwegen et al. (2018) found that training targeting non-symbolic abilities enhanced mathematical performance among low-performing children identified using a very liberal criterion (performance at or below the 45th percentile on a standardized math test). Overall, evidence regarding non-symbolic numerical abilities in children with mathematical difficulties remains mixed, whereas impairments in symbolic number processing appear to be more consistently documented across different age groups (see De Smedt et al., 2013, for a review).

2.1.2.2. Symbolic magnitude processing

In contrast to other species, humans develop, alongside the ANS, a specialized system for representing exact magnitudes (Qiu et al., 2021). The ability to process and manipulate exact numerosities fundamentally relies on the acquisition of numerical symbols, such as number words and Arabic numerals (Feigenson et al., 2004; Geary, 2013). This ability is culturally transmitted, language-dependent, and emerges only after several years of exposure to symbolic representations of number (Feigenson et al., 2004; Hawes, Nosworthy, et al., 2019; Mishra & Khan, 2023). Symbolic magnitude processing is typically assessed through number comparison tasks, in which participants are presented with two Arabic numerals and asked to identify the numerically larger one (Finke et al., 2022). Performance on such tasks provides an index of the understanding of number symbols and the precise quantities they denote (Hawes, Nosworthy, et al., 2019), a core skill that underpins the development of formal mathematics, where information is predominantly conveyed in symbolic form (Schneider et al., 2017).

Numerous studies have robustly demonstrated an association between symbolic magnitude processing and mathematical performance, with meta-analyses consistently showing a stronger relationship than that observed for non-symbolic magnitude processing (Amland et al., 2024; Fazio et al., 2014; Schneider et al., 2017). Importantly, symbolic comparison abilities have been found to predict mathematics achievement throughout elementary school, independently of non-symbolic skills (Lyons et al., 2014). Several studies further suggest that symbolic comparison skills may mediate the relationship between ANS

acuity and mathematics performance (Finke et al., 2020; Y. Li et al., 2018; Price & Fuchs, 2016). Longitudinal evidence substantiates the predictive role of symbolic magnitude processing in mathematical development, showing that symbolic skills in kindergarten (Desoete et al., 2012; Hawes, Nosworthy, et al., 2019) and early elementary school (Finke et al., 2022; Sasanguie et al., 2013) relate to later mathematics achievement, as well as growth in mathematical proficiency (Mononen et al., 2025). Furthermore, Toll et al. (2015) reported that improvement in symbolic comparison performance between kindergarten and first grade was the strongest predictor of first-grade mathematical outcomes, including both math fluency and word problem-solving.

Finally, difficulties in symbolic magnitude processing have been consistently documented in children with mathematical difficulties (De Smedt et al., 2013; Haberstroh & Schulte-Körne, 2022; Iuculano et al., 2008; Schwenk et al., 2017), across varying levels of impairment severity (T. T.-Y. Wong et al., 2017). Nevertheless, whether these symbolic deficits represent the sole source of cognitive difficulties remains debated. Some studies report impairments in both symbolic and non-symbolic processing among children with mathematical difficulties (Decarli et al., 2022; Olsson et al., 2016), whereas others suggest that difficulties are confined to symbolic processing, pointing to challenges in accessing numerosity through symbols rather than in numerosity processing per se (Iuculano et al., 2008; Rousselle & Noël, 2007). Notably, Desoete et al. (2012) found that although second-grade children with mathematical difficulties exhibited both symbolic and non-symbolic deficits in kindergarten, only symbolic deficits persisted by second grade. Furthermore, interventions targeting symbolic processing in preschoolers at risk for mathematical difficulties have proven more effective than non-symbolic training, allowing these children to attain mathematical performance levels comparable to peers not identified as at risk by first grade (Tobia et al., 2021).

2.1.2.3. Transcoding

Among the symbolic processes involved in mathematical development, transcoding – the ability to switch between numerical codes such as verbal and Arabic representations – plays a pivotal role. Transcoding refers to the capacity to convert number words (auditory-verbal code) into Arabic numerals (visual Arabic code) and vice versa (Banfi et al., 2022). This skill supports the understanding of the structure of the number system and the place-value of digits, thereby constituting a crucial step toward more complex arithmetic learning (Banfi et al., 2022; Moura et al., 2013). Transcoding is usually assessed through tasks

requiring conversion between number notations, including number writing (oral-to-written code) and number reading (written-to-oral code) (Moura et al., 2015). Whether semantic representations of quantity are necessarily accessed during such transitions remains debated (Moura et al., 2013), with some models assuming access to semantic meaning (e.g., McCloskey, 1992), whereas others argue that it can occur without (e.g., Barrouillet et al., 2004). Emerging prior to formal instruction, transcoding relies on the acquisition of a numerical lexicon and mastery of number syntax. Transcoding skills improve steadily throughout the elementary years and are generally consolidated by fourth grade (Moura et al., 2013, 2015). In the early grades, transcoding performance is strongly influenced by number length and syntax complexity. While transcoding of two-digit numbers is typically mastered by second grade, accurate transcoding of three- and four-digit numbers usually appears only from third grade onward (Moura et al., 2013, 2015).

Transcoding skills have been identified as a robust predictor of mathematical achievement in the early school years. Longitudinal studies show that first-grade transcoding abilities predict mathematics outcomes in second and third grades, independently of earlier arithmetic knowledge as well as symbolic and non-symbolic magnitude processing (Banfi et al., 2022; Göbel et al., 2014; Malone et al., 2020, 2021). Notably, Göbel et al. (2014) found that transcoding was the only significant predictor of later mathematical performance, whereas magnitude processing did not contribute uniquely. The developmental importance of transcoding is further underlined by evidence that transcoding skills as early as age 4 – before the onset of formal mathematics instruction – already predict first-grade mathematical achievement, suggesting that transcoding constitutes an early foundation for formal arithmetic development (Habermann et al., 2020).

Finally, transcoding impairments have been documented in children with mathematical difficulties (Kivirähk-Koor & Kiive, 2025; Moura et al., 2013). Notably, children with low mathematics achievement have been found to exhibit persistent transcoding deficits at an age when typically achieving peers demonstrate mastery, namely in the later elementary grades (Moura et al., 2013). Interestingly, error analyses revealed that in the early elementary grades, children with mathematical difficulties produced both lexical errors (e.g., “forty-two” written as 43, or 13 read as “fourteen”) and syntactic errors (e.g., “one thousand three hundred” written as 1000300, or 593 read as “five hundred thirty-nine”), whereas typically achieving peers produced only syntactic errors. In the later grades, children with mathematical difficulties continued to make syntactic errors, while their typically achieving peers reached ceiling performance on transcoding tasks. These findings suggest a developmental delay in the

acquisition of transcoding skills among children with mathematical difficulties, with transcoding deficits persisting into late elementary school (Moura et al., 2013).

2.1.2.4. Number ordering

Numbers convey meaning not only through their absolute magnitudes but also through their relative position within a numerical sequence (Finke et al., 2022). Although relatively understudied, the ability to process ordinal relations between numbers plays a central role in establishing inter-item associations among numerical symbols – which supports complex arithmetic operations (Devlin et al., 2022; Finke et al., 2022; Lyons & Beilock, 2011). Number ordering is typically assessed with order verification tasks, where participants judge whether digit triplets are presented in the correct numerical order (e.g., 1–2–3 or 3–5–7) or not (e.g., 2–3–1 or 7–5–3) (Devlin et al., 2022; Finke et al., 2022). The ability to recognize ordered numerical sequences develops gradually and is usually mastered during first grade (Hutchison et al., 2022). However, recognizing ordered but non-adjacent sequences (e.g., 3–5–7) emerges later than recognizing adjacent ones (e.g., 3–4–5) and may still pose difficulties at the end of first grade, thus representing a developmental hurdle that children must overcome to achieve a mature sense of ordinality (Hutchison et al., 2022). This delay may reflect the greater difficulty of retrieving non-adjacent sequences from the verbal counting list stored in long-term memory (Finke et al., 2022; Hutchison et al., 2022).

Number ordering abilities are significantly associated with mathematical performance in elementary school children (Morsanyi et al., 2020), with their importance increasing with age (Lyons et al., 2014). Notably, Lyons et al. (2014) found that number ordering did not explain unique variance in mathematics performance in first grade beyond other factors such as symbolic and non-symbolic magnitude processing. Yet, its predictive power rose steadily across grades, ultimately becoming the strongest predictor of mathematics performance by sixth grade. This developmental trajectory suggests a shift from cardinal to ordinal processing throughout elementary education. Consistently, Finke et al. (2022) showed in a longitudinal study that symbolic comparison – but not ordering – predicted change in arithmetic performance between first and second grade, whereas number ordering predicted arithmetic development between second and third grade, with symbolic comparison losing its predictive value. Moreover, number ordering has been suggested to mediate the relationship between ANS acuity and later mathematics achievement (Malone et al., 2021), underlining its central role in mathematical development.

Finally, emerging evidence indicates that number ordering deficits may characterize children with mathematical difficulties, particularly in more severe cases (Decarli et al., 2022; Morsanyi, Van Bers, O'Connor, et al., 2018; Slipenkyj et al., 2025). Interestingly, Slipenkyj et al. (2025) found that, in children aged 9 to 13 with persistent mathematical difficulties, these number ordering deficits were confined to the identification of non-adjacent numerical sequences (e.g., 3–5–7). This pattern suggests selective difficulties in the more complex ability to extend the concept of ordinality beyond directly adjacent numbers.

Overall, success and difficulties in primary school mathematics are influenced by multiple domain-specific cognitive factors, including both non-symbolic processes, such as ANS acuity, and symbolic processes, such as symbolic comparison, transcoding, and number ordering (Haberstroh & Schulte-Körne, 2022; Ruiz et al., 2024). However, these abilities have rarely been examined together in research. Consequently, as in the reading domain, there is a need for more comprehensive investigations of the cognitive factors underlying academic success and difficulties, which should also, in parallel, consider domain-general cognitive abilities that operate across learning domains.

2.2. Domain-general cognitive factors

Academic performance in reading and mathematics is supported not only by cognitive skills specific to each learning domain but also by cognitive processes involved across domains. These domain-general abilities, commonly referred to as executive functions, encompass higher-order control processes that allow individuals to regulate their thoughts and actions during goal-directed behavior and to adapt to novel or complex situations (Cartwright, 2012; Cragg & Gilmore, 2014; Dajani & Uddin, 2015; Diamond, 2013; Friedman & Miyake, 2017; Strobach & Karbach, 2021). Although executive functions are widely recognized as a multidimensional construct, there is considerable debate regarding their precise components (Dias et al., 2024; Strobach & Karbach, 2021). The predominant model of executive functions distinguishes three distinct but interrelated functions – namely, working memory, inhibition, and cognitive flexibility – reflecting a pattern of both unity and diversity within executive functioning (Friedman & Miyake, 2017; Miyake et al., 2000). Other frameworks suggest that these three core functions underpin higher-order executive processes, such as reasoning and planning (Diamond, 2013). Additionally, selective attention has occasionally been included under the executive function umbrella (e.g., Malone et al., 2022; Mulder et al., 2017), though

evidence indicates that its association with fundamental executive function components, such as working memory, may be relatively weak (Kotyusov et al., 2023).

Executive functions emerge early in development, prior to formal schooling, and continue to mature throughout adolescence (Best & Miller, 2010), becoming increasingly differentiated over time (Karr et al., 2018). They are essential for both reading acquisition (Cartwright, 2012) and the development of mathematical cognition (Hohol et al., 2017). Meta-analytic evidence indicates that executive functions are robustly associated with reading decoding and comprehension as well as with mathematics outcomes (Cortés Pascual et al., 2019; Follmer, 2018; Jacob & Parkinson, 2015; Ober et al., 2020; Spiegel et al., 2021; Zhong et al., 2022). Moreover, deficits in executive functions have been observed in children with difficulties in reading (Booth et al., 2010; Peng et al., 2022), as well as mathematics (Peng, Wang, & Namkung, 2018). Importantly, weak executive function performance prior to primary school entry predicts later challenges in both reading and mathematics, highlighting their critical role in academic development (Morgan et al., 2017; Röthlisberger et al., 2013). Together, these findings emphasize the importance of considering domain-general cognitive skills when characterizing the factors involved in reading and mathematics achievement, with a focus on distinct executive function components.

2.2.1. Working memory

Working memory refers to the ability to actively maintain and manipulate goal-relevant information that is no longer perceptually available (Baddeley, 1992; Bayliss et al., 2005; Bunge et al., 2000; Diamond, 2013). It is distinct from short-term memory – which involves only the maintenance of information (Diamond, 2013; Jacob & Parkinson, 2015; Morris & Lonigan, 2022) – and encompasses both verbal and visuospatial dimensions (Diamond, 2013). In the most widely used model, working memory consists of two storage systems – the phonological loop, supporting verbal information, and the visuospatial sketchpad, supporting visual or spatial information – both supervised by a central executive system that operates on their contents (Aben et al., 2012; Alloway et al., 2006; Baddeley, 1992; Bunge et al., 2000). Working memory is typically assessed with tasks requiring both storage and manipulation of information, such as the backward digit span (i.e., reciting a sequence of digits presented orally in reverse order) or other reordering tasks (e.g., repeating a set of randomly presented digits in ascending order) (Aben et al., 2012; Diamond, 2013). By contrast, tasks limited to simple maintenance of information, such as the forward digit span (i.e., repeating digits in the same order as presented), are generally considered measures of short-term rather than working

memory (Aben et al., 2012; Diamond, 2013). Notably, working memory is critical for reading, as it supports the temporary storage and integration of phonemes during word decoding and of words across sentences to enable comprehension (Diamond, 2013; Meiri et al., 2019; Spiegel et al., 2021). In mathematics, it sustains the retention and manipulation of operands and intermediate results, the monitoring of ongoing calculations, and the efficient processing of information in complex, multi-step problem-solving (Meiri et al., 2019; Spiegel et al., 2021; Titz & Karbach, 2014).

Meta-analyses indicate robust associations between working memory and academic performance in both reading and mathematics. Notably, these associations extend across multiple subskills within each domain, including reading accuracy, fluency, and comprehension on the one hand, and word problem-solving, calculation, and math fluency on the other (Friso-van den Bos et al., 2013; Ji & Guo, 2023; Peng, Wang, Li, et al., 2018; Spiegel et al., 2021). Spiegel et al. (2021) further reported that in both domains, working memory showed weaker associations with fluency outcomes than with other reading or mathematical skills. Cross-sectional studies also suggest that the influence of working memory on mathematics increases across the school years, whereas its effect on reading decreases over time (Gathercole et al., 2004; Geary, 2011).

Importantly, longitudinal research underlines the role of working memory in academic achievement, showing that working memory in the early elementary grades predicts later outcomes in both reading (S. Liu et al., 2025) and mathematics (Banfi et al., 2022; Passolunghi et al., 2014), even after accounting for domain-specific factors. Greater working memory capacity has also been linked to faster growth in reading (Swanson & Jerman, 2007) and mathematics (Cahoon et al., 2021; K. Lee & Bull, 2016) over time. However, despite robust evidence for its influence on academic performance, meta-analyses indicate that working memory training produces only limited transfer effects, with working memory gains rarely generalizing to improvement in reading or mathematics (Melby-Lervåg & Hulme, 2013; Sala & Gobet, 2020).

Finally, working memory deficits have been documented in children with reading difficulties (Kudo et al., 2015; Swanson, Xinhua Zheng, et al., 2009) as well as in those with mathematics difficulties (David, 2012; Kroesbergen et al., 2023), across varying severity levels of academic difficulties (e.g., Mammarella et al., 2018). Importantly, these impairments often co-occur with domain-specific deficits, highlighting that the cognitive challenges underlying academic difficulties are multifaceted rather than confined to a single core deficit

(Kroesbergen et al., 2023; Kudo et al., 2015). Moreover, working memory weaknesses observed in kindergarten have been linked to an increased risk of later difficulties in reading and, even more strongly, in mathematics by first grade (Morgan et al., 2017) – with potential longer-term effects limiting growth in both academic domains over time (Jerman et al., 2012).

2.2.2. Inhibition

Inhibition refers to the ability to suppress goal-irrelevant stimuli or responses in order to regulate attention, behavior, thoughts, and emotions (Dajani & Uddin, 2015; Diamond, 2013; Tiego et al., 2018). It is typically described as comprising distinct subcomponents, including response inhibition – the suppression of a prepotent motor response – and interference control – the ability to resist distraction from irrelevant or conflicting stimuli (Diamond, 2013; Kang et al., 2022; Tiego et al., 2018). Response inhibition is commonly assessed with tasks requiring participants to respond rapidly to certain stimuli while withholding responses to others (e.g., go/no-go or stop-signal tasks) (Diamond, 2013). Interference control, in contrast, is measured with tasks that demand inhibition of a salient but task-incongruent stimulus feature (e.g., in the Stroop task, suppressing automatic word reading to report the ink color, such as saying “red” when the word “green” is printed in red) (Diamond, 2013). Inhibition plays a critical role in academic learning. In reading, it is involved in the discrimination between mirror letters (e.g., p/q or b/d) which necessitates inhibiting mirror generalization (Ahr et al., 2016), and helps suppress irrelevant word meanings (e.g., homonyms), thereby facilitating comprehension (Spiegel et al., 2021). In mathematics, inhibition is needed to suppress inappropriate problem-solving strategies – for example, when the required operation is inconsistent with the relational term in a problem (Lubin et al., 2013) – and to resist previously learned but misleading representations of whole numbers, such as in the case of fractions or decimals (Roell et al., 2019; Spiegel et al., 2021).

Evidence from meta-analyses demonstrates that inhibition is associated with performance in both reading and mathematics during elementary school (Spiegel et al., 2021; Zhu et al., 2025) and also contributes to early literacy and numeracy in preschool (Allan et al., 2014; Zhong et al., 2022). At the level of specific subskills, inhibition appears more strongly related to reading fluency and comprehension than to reading accuracy, while showing comparable associations with word problem-solving, calculation, and math fluency (Spiegel et al., 2021). However, these associations are generally of moderate to weak magnitude, and inhibition tends to be a weaker predictor of academic outcomes than other executive functions, particularly working memory (Allan et al., 2014; Spiegel et al., 2021; Zhong et al.,

2022; Zhu et al., 2025). Longitudinal studies further suggest that inhibition at the beginning of elementary school predicts later reading comprehension (Meixner et al., 2019) and word problem-solving (Swanson, 2011). Yet, such effects are not consistently supported by intervention studies. For instance, Johann & Karbach (2020) found that inhibition training in children aged 8 to 11 led to gains in reading speed, but not in reading comprehension or mathematics, indicating that transfer effects to academic skills may be specific and limited.

Findings regarding inhibition deficits in children with academic difficulties remain mixed. While some studies have reported impaired inhibition in poor readers (Chung et al., 2022) and poor math achievers (Passolunghi & Siegel, 2001), others have found no such deficits (Censabella & Noël, 2007; Engel De Abreu et al., 2014). However, Booth et al. (2014) showed that poor inhibitory abilities significantly predicted membership in a group of children with reading difficulties, relative to both age-matched peers without difficulties and younger children matched for reading level. Furthermore, weaker inhibition has been identified as a risk factor for underachievement in reading and mathematics, particularly during middle school, when academic demands increase (Doyle et al., 2018; Iglesias-Sarmiento et al., 2023).

2.2.3. Cognitive flexibility

Cognitive flexibility refers to the ability to adaptively switch between tasks, goals, or mental processes to adjust to changing environmental demands (Buttelmann & Karbach, 2017; Dajani & Uddin, 2015; Diamond, 2013; Spiegel et al., 2021). This capacity involves both disengaging from irrelevant information or tasks and re-engaging with new ones by configuring a new response set (Buttelmann & Karbach, 2017; Dajani & Uddin, 2015; Diamond, 2013; Spiegel et al., 2021). Cognitive flexibility relies on other executive functions, as inhibiting a previous perspective is necessary to load a new one into working memory (Dajani & Uddin, 2015; Diamond, 2013). Consequently, it is considered one of the most demanding executive functions, emerging later in development and continuing to mature into young adulthood (Buttelmann & Karbach, 2017; Diamond, 2013). It is typically assessed using task-switching or set-shifting paradigms (Dajani & Uddin, 2015; Diamond, 2013). In task-switching paradigms, participants alternate between different instructions as a function of a given stimulus (e.g., indicating color when stimuli appear on one side of the screen but shape when they appear on the other), whereas set-shifting paradigms require alternating between stimulus criteria according to instruction (e.g., sorting items by color, then shape, then number) (Dajani & Uddin, 2015; Diamond, 2013). In both paradigms, reconfiguring a new response set while inhibiting the previous one results in higher reaction times and error rates, reflecting switching

costs (Dajani & Uddin, 2015). Cognitive flexibility contributes to academic learning by supporting reading through shifts between phonological processing for decoding and semantic processing for comprehension (Colé et al., 2014), as well as integrating textual information with prior knowledge (Spiegel et al., 2021). In mathematics, it enables switching between operations and problem-solving strategies (Meiri et al., 2019; Spiegel et al., 2021) and facilitates the adoption of novel approaches that may conflict with previously learned procedures (McGowen & Tall, 2013).

Cognitive flexibility has been linked to academic achievement in both reading and mathematics (see Santana et al., 2022; Spiegel et al., 2021; Yeniad et al., 2013, for meta-analyses). Meta-analytic evidence suggests that, in mathematics, it may be more strongly associated with word problem-solving than with calculation, and may not be related to math fluency (Spiegel et al., 2021). In reading, Spiegel et al. (2021) reported comparable associations across different reading outcomes, whereas other studies suggest a primary role in reading comprehension (Colé et al., 2014; Johann et al., 2020). Notably, the relationship between cognitive flexibility and reading comprehension remains significant even after accounting for language-related domain-specific factors and other domain-general factors such as working memory and inhibition (Kieffer et al., 2013). Longitudinal evidence further supports these findings, showing that cognitive flexibility at the start of elementary school predicts later reading comprehension (Meixner et al., 2019) and overall mathematics performance (H. Zhang et al., 2023), with potential bidirectional influences across the elementary years (H. Zhang et al., 2023). Nonetheless, consistent with findings on inhibition, interventions targeting cognitive flexibility appear to produce transfer effects that are limited to specific processes – particularly improving reading comprehension, but not generalizing to other reading skills, such as reading speed, or to other academic domains, including mathematics (Johann & Karbach, 2020).

Deficits in cognitive flexibility have been reported in children with poor mathematics achievement (van der Sluis et al., 2004) and poor reading, whether difficulties concern decoding, comprehension, or both (Cadime et al., 2024; Cartwright et al., 2017). Longitudinal evidence further shows that low cognitive flexibility in kindergarten is associated with an increased risk of developing reading and mathematics difficulties in first grade, independently of other risk factors such as poor working memory (Morgan et al., 2017). Furthermore, intervention studies suggest that flexibility-based training can improve reading fluency and comprehension development in first- to third-grade children identified as poor decoders (Cartwright et al., 2019) or poor comprehenders (Cartwright et al., 2017). However, since the

training paradigm involved alternating between phonological and semantic word sorting, it remains unclear whether the observed improvements stem from genuine gains in cognitive flexibility or, rather, enhanced domain-specific language skills.

2.2.4. Selective attention

Selective attention refers to the ability to focus on a task by selecting relevant information, while ignoring distracting stimuli, whether external (e.g., visual or auditory noise) or internal (e.g., thoughts or emotions) (Diamond, 2013; Stevens & Bavelier, 2012). This capacity relies on other domain-general processes, including working memory – to maintain prioritization of relevant stimuli – and inhibition – to suppress attention to irrelevant information (De Fockert et al., 2001; Diamond, 2013). Selective attention is typically assessed through paradigms that require participants to selectively attend to specific stimuli while ignoring others. Common examples include the Flanker task, where participants must indicate the direction of a central target while ignoring surrounding flankers (Diamond, 2013), and visual search tasks, which involve visually scanning an array of stimuli to identify a target stimulus among distractors (Cirino et al., 2022; Tulloch & Pammer, 2019). Visual search paradigms have been particularly used in reading research, as they partially mimic the reading process, which requires extracting letters or words from a crowded array of text (Tulloch & Pammer, 2019). Selective attention also guides eye movements across graphemes, words, and lines in a spatially ordered fashion (e.g., from left to right in most alphabetic languages) (Cirino et al., 2022; J. L. Peters et al., 2019; Stevens & Bavelier, 2012). Although less extensively studied in mathematics, selective attention likewise supports mathematical learning by enabling learners to focus on problem-relevant information while disregarding irrelevant details (Stevens & Bavelier, 2012).

Empirical evidence highlights associations between selective attention and academic performance. In reading, Guilbert and Guiraud-Vinatea (2022) showed that both accuracy and organizational strategies in a visual search task were correlated with reading performance in French elementary school children. By contrast, among older students in seventh and eighth grade, no such link was found between visual search performance and reading skills, which were instead strongly associated with visual-attention span – suggesting that not all aspects of visual attention contribute equally to reading (Cirino et al., 2022). In mathematics, selective attention has been associated with calculation skills (Commodari & Di Blasi, 2014), math fluency (Meiri et al., 2019), and overall mathematics achievement (Memisevic et al., 2018) in elementary school. Importantly, selective attention has been shown to predict reading and

mathematics outcomes independently of other domain-general factors such as working memory and inhibition (S. Liu et al., 2025; Memisevic et al., 2018). Longitudinal findings further support the role of selective attention in reading. Notably, Franceschini et al. (2012) demonstrated that pre-reading selective attention skills in preschool predicted reading acquisition in first and second grade, even when controlling for key domain-specific factors such as phonological awareness and RAN. These results are corroborated by intervention studies showing that visuo-attentional training enhances reading performance across different orthographic systems (see J. L. Peters et al., 2019, for a review).

Finally, selective attention difficulties have been documented in children with academic difficulties in reading and mathematics (Agostini et al., 2022; Stevens & Bavelier, 2012). Notably, Franceschini et al. (2012) reported that up to 60% of children identified as poor readers in first and second grade already displayed visual selective attention deficits during preschool. Such challenges have also been observed in more severe cases of reading disability, with dyslexic children showing lower accuracy and less efficient visual search strategies compared to typically achieving peers (Guilbert & Rochette, 2023; Vialatte, Chabanat, et al., 2023). Moreover, interventions targeting visual selective attention have been found to improve reading performance in children with reading difficulties (Vialatte, Aguera, et al., 2023). These findings thus underline the role of visual selective attention in academic difficulties, with its effects more documented in reading.

Overall, various domain-general cognitive factors – including working memory, inhibition, cognitive flexibility, and selective attention – support academic achievement in reading and mathematics in school-aged children. However, the unique contribution of each factor remains unclear, as they are rarely examined simultaneously. Furthermore, although both reading and mathematics are influenced by domain-specific and domain-general processes, only a few studies have investigated both types of factors together, providing some insights on their relative contributions to performance in each academic domain.

2.3. Relative contributions of domain-specific and domain-general factors to reading and mathematics achievement

A growing body of research highlights that academic learning in reading and mathematics is shaped by both domain-specific and domain-general factors. However, since these factors have predominantly been examined in isolation, a central question concerns the extent to

which they each exert independent effects on reading and mathematics performance. The following subsections review the evidence on this issue, beginning with reading and then addressing mathematics.

2.3.1. Domain-specific and domain-general influences on reading

In the reading domain, only a limited number of studies have examined the joint contribution of domain-specific and domain-general factors, and their findings remain inconsistent. For instance, Cirino et al. (2019) reported that both types of factors independently contributed to reading performance in children from third to fifth grade across different reading outcomes. Specifically, executive functions, phonological awareness, and RAN predicted word reading fluency, while executive functions and oral language were associated with reading comprehension. However, other studies have shown that when domain-specific and domain-general factors are considered together, only domain-specific predictors remain significant (Cirino et al., 2018; Peng, Wang, Li, et al., 2018). Longitudinal evidence supports these latter findings. For example, Malone et al. (2022) found that executive functions at age 5 predicted reading performance in first grade only when domain-specific skills were not included in the model. By contrast, once phonological awareness and RAN were added, executive functions no longer predicted subsequent reading achievement. Similarly, Dolean et al. (2021) reported that oral language, but not executive functions, predicted both initial levels and growth in reading comprehension among children aged 7 to 9.

Findings regarding the cognitive characteristics of children with reading difficulties also remain inconsistent. Notably, meta-analytic studies provide evidence for the co-occurrence of both domain-specific and domain-general deficits (Kudo et al., 2015; Peng et al., 2022). However, Peng et al. (2022) further showed that although both types of factors uniquely contribute to reading difficulties, domain-specific abilities – particularly phonological processing and oral language – exert a comparatively stronger influence. Other findings further identified phonological awareness and RAN, but not working memory, as significant predictors of reading difficulties in elementary school children (Slot et al., 2016).

2.3.2. Domain-specific and domain-general influences on mathematics

A larger number of studies have investigated the joint influence of domain-specific and domain-general factors in mathematics, but the evidence remains mixed. Some studies have reported that both types of factors make unique contributions, both cross-sectionally (Caviola

et al., 2020; Starling-Alves et al., 2024) and longitudinally (Banfi et al., 2022; Toll et al., 2016), whereas others have highlighted a role of domain-specific factors only (Hawes, Moss, et al., 2019; Malone et al., 2020, 2022). Notably, an important aspect in disentangling the effects of domain-general and domain-specific factors on mathematics achievement is the developmental period. For instance, Gimbert et al. (2019) demonstrated age-related differences, showing that in 5-year-olds, ANS but not working memory predicted mathematical skills, whereas the reverse pattern emerged in 7-year-old children, following the onset of formal instruction. These findings are consistent with longitudinal results indicating that domain-general factors, particularly working memory, become increasingly important over development (Passolunghi et al., 2014). Similarly, Träff et al. (2025) reported that while both types of factors were associated with arithmetic performance in first grade, only working memory predicted arithmetic growth from first to second grade. By contrast, Mononen et al. (2025) observed that symbolic comparison, but not working memory, predicted growth in math fluency from first to third grade. Critically, such discrepancies may also partly reflect differences in the outcome measures considered, since the relative contributions of domain-specific and domain-general factors may vary across mathematical subskills (Cirino et al., 2018; Fuchs et al., 2010; Träff, 2013; Träff et al., 2023). Specifically, domain-general processes appear to be more predictive of complex abilities such as multi-digit calculation and word problem-solving, whereas domain-specific factors might be more closely associated with basic single-digit calculation and arithmetic fact retrieval, as assessed in math fluency tasks. An illustration of this differential involvement across mathematical subskills is presented in Figure 2 on the following page.

Evidence from intervention studies further supports the combined role of domain-specific and domain-general factors in mathematics. Notably, DePascale et al. (2024) compared the effects of three types of training in children aged 5 to 7: a domain-specific intervention targeting number knowledge, a domain-general intervention targeting working memory, and a combined intervention addressing both abilities. Results showed that while all training conditions led to significant or marginally significant improvements in mathematics relative to an active control group immediately after training, only the combined training produced significantly higher gains at a delayed post-test assessed four to six weeks following the end of the training. These findings suggest that mathematical learning relies on both domain-specific and domain-general processes, and that interventions addressing both are important for maximizing long-term effects.

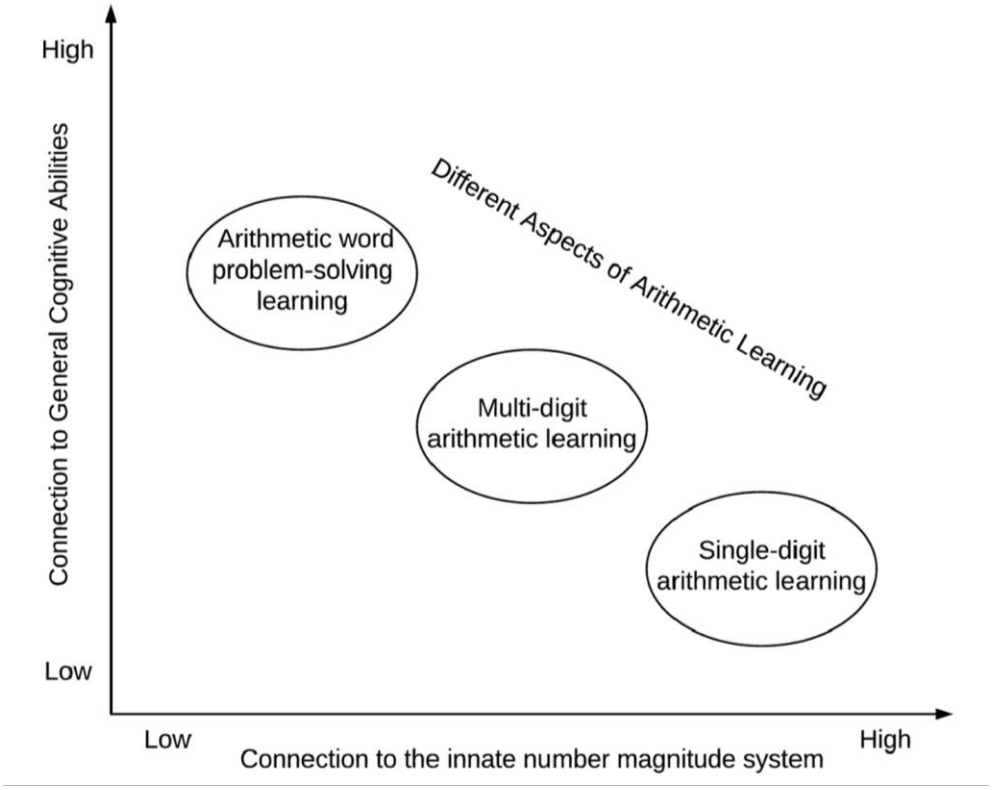

Figure 2. Schematic representation of the theoretical contribution of domain-specific and domain-general cognitive abilities to different aspects of arithmetical learning. From Träff et al. (2023).

Finally, evidence consistently indicates that children with mathematical difficulties exhibit both domain-specific and domain-general deficits, although the profile of these deficits appears to vary with the severity of difficulties (Andersson & Östergren, 2012; R. Cowan & Powell, 2014; Kroesbergen et al., 2023; Mishra & Khan, 2023). Domain-specific impairments are observed in both dyscalculic and low-achieving children (Geary et al., 2009, 2017; Kivirähk-Koor & Kiive, 2025). By contrast, domain-general deficits – particularly in working memory – are consistently reported in severe forms of mathematical difficulties, but findings remain mixed for more moderate cases (Kivirähk-Koor & Kiive, 2025; Mishra & Khan, 2023). Some studies nevertheless highlight the joint role of both types of factors in predicting poor mathematics performance (Slot et al., 2016). Furthermore, combined deficits in symbolic or non-symbolic magnitude processing, together with working memory weaknesses in kindergarten, have been shown to predict poorer mathematics performance in first grade than isolated deficits alone (Toll et al., 2016). Taken together, these findings support the view that

mathematical difficulties can arise from multiple cognitive vulnerabilities – both specific and general – underlining the need for integrative approaches in their investigation.

Overall, the evidence reviewed in this section indicates that both reading and mathematics achievement rely on a complex interplay between domain-specific and domain-general cognitive factors. Importantly, these abilities are also shaped by broader environmental contexts, with parental socioeconomic status (SES) emerging as a significant factor associated with children's academic and cognitive development. The following section therefore examines the role of SES in reading and mathematics, considering both its direct effects and indirect relations through cognitive processes.

3. Socioeconomic status (SES) and academic achievement

3.1. Definition and measurement of SES

While various definitions of SES have been proposed, the construct of SES is most commonly understood as an individual's access to economic, social, and cultural resources that are normatively valued and confer particular social positioning and privileges (Antonoplis, 2023; C. D. Cowan et al., 2012; Duncan & Magnuson, 2012). SES is therefore conceptualized as a multidimensional construct, encompassing both economic resources and non-economic dimensions, including social prestige, hierarchical status, and education (Hackman & Farah, 2009). Reflecting this conceptual diversity, SES has also been operationalized inconsistently across studies. Nonetheless, parental education, occupation, and income – either separately or in combination – represent the most widely used indicators of SES (Antonoplis, 2023; C. D. Cowan et al., 2012; Duncan & Magnuson, 2012; Hackman & Farah, 2009; Ursache & Noble, 2016). Less frequently used indicators include household wealth and possessions, neighborhood and school resources, or subjective perceptions of social status (i.e., subjective SES) (C. D. Cowan et al., 2012; Ursache & Noble, 2016). These latter measures are generally regarded as complementary to, rather than substitutes for, the three primary indicators – parental education, occupation, and income – that form the core operationalization of SES (C. D. Cowan et al., 2012).

Education is typically assessed by either the total number of years of schooling completed or the highest educational qualification attained (Galobardes, 2006; Ursache & Noble, 2016). Occupation reflects an individual's relative social position and is usually measured by the current occupation or the one held for the longest period (Galobardes, 2006). However, the social prestige associated with occupations can be difficult to quantify, as it varies across cultural and historical contexts (Ursache & Noble, 2016). To address this, occupations are generally assigned a continuous score using classification systems that rank occupational status based on multiple criteria, such as the educational level and income typically associated with a given profession (e.g., Ganzeboom et al., 1992). Income, in turn, reflects household material resources and can be measured in absolute terms (e.g., monthly or annual household income) or in equivalized terms, adjusting for family size (Galobardes, 2006; Ursache & Noble, 2016). Compared with education and occupation, income is often regarded as less reliable because it tends to fluctuate more over time (Galobardes, 2006; Shavers, 2007). Furthermore, as it can be considered more sensitive and personal information in some cultures, income

measurement is frequently associated with higher non-response rates than other SES indicators (Farah, 2017; Galobardes, 2006; J. Lee et al., 2019; Shavers, 2007). For these reasons, many studies rely primarily on education and occupation when operationalizing SES (Farah, 2017).

The question of whether different SES indicators should be combined into a single composite score remains debated in the literature (Antonoplis, 2023; Ursache & Noble, 2016). Nonetheless, a panel of experts convened to provide guidance on SES operationalization concluded that the advantages of using a composite SES score outweigh the potential drawbacks, particularly in terms of enhanced reliability and a more comprehensive representation of SES dimensions (C. D. Cowan et al., 2012). In line with this conclusion, J. Lee et al. (2019) further demonstrated that composite SES scores, as implemented in large-scale assessments such as PISA (Programme for International Student Assessment), outperform individual SES variables in predicting academic achievement.

3.2. SES associations with reading and mathematics achievement

A substantial body of literature demonstrates a moderate yet robust association between SES and academic performance in both reading and mathematics, consistently reported across grade levels and countries (see J. Liu et al., 2022a; Selvitopu & Kaya, 2023; Sirin, 2005, for meta-analyses). Importantly, this relationship does not diminish over the course of schooling, but instead appears to remain stable or even strengthen over time (J. Liu et al., 2022a; Sirin, 2005). Cross-national evidence further indicates that France ranks among the countries with the largest SES-related disparities in academic achievement (Cioldi & Raffy, 2024; Murat, 2024; OECD, 2023). As observed in the PISA 2022 report, SES accounted for 17% of the variance in reading comprehension and 22% of the variance in mathematics among French 15-year-old students, compared with OECD (Organization for Economic Co-operation and Development) averages of 13% and 16%, respectively (OECD, 2023). These findings are further consistent with meta-analytic evidence suggesting that SES is generally more strongly associated with mathematics than with literacy (Selvitopu & Kaya, 2023; Sirin, 2005). Within each domain, SES has also been linked to a broad range of outcomes, including reading accuracy, fluency, and comprehension in reading (Asadi et al., 2023; Noble et al., 2006; Rassel et al., 2021), as well as calculation, math fluency, and word problem-solving in mathematics (Ayala et al., 2024). Crucially, SES-related performance gaps emerge even within the same schools and classrooms, thus occurring despite equivalent instruction (Silver & Libertus, 2022).

Longitudinal research demonstrates that SES predicts the development of reading and mathematics skills throughout schooling (Lawson & Farah, 2017), with children from low-SES backgrounds often showing slower growth in reading (Hecht et al., 2000; Lervåg et al., 2019; Muñez et al., 2022) and mathematics (N. C. Jordan et al., 2009) compared to their higher-SES peers during elementary school. Notably, Kieffer (2012) reported that these developmental trajectories vary by age. Specifically, children from low-SES backgrounds displayed faster reading growth than their higher-SES counterparts in the early elementary years – likely reflecting compensatory gains from lower initial proficiency – but this trend reversed from third grade onward, with slower growth persisting through eighth grade. These findings suggest that while formal schooling may partly help narrow SES-related disparities at the beginning of elementary education, it fails to sustain this effect across later grades, as academic demands become increasingly complex (Kieffer, 2012).

Critically, evidence indicates that children from low-SES backgrounds are significantly more likely to experience academic difficulties in reading and mathematics during primary school (Buckingham et al., 2014; Murat, 2024; Pace et al., 2017). The prevalence of these difficulties is disproportionately higher among low-SES children than among their higher-SES peers, both in reading (Billard & Barbe, 2016; Fluss et al., 2009; Romeo, Uchida, et al., 2022) and mathematics (N. C. Jordan & Levine, 2009). For example, Fluss et al. (2009) reported that while 12% of French second graders were identified as poor readers overall, this rate varied considerably by SES, ranging from 3% in high-SES areas to 24% in low-SES areas. Beyond these early academic challenges, low-SES children are also at greater risk of developing late-emerging difficulties relative to their higher-SES peers (Kieffer, 2010). Longitudinal evidence further shows that kindergarteners from low-SES backgrounds are more likely than their higher-SES peers to lag increasingly behind in reading and mathematics over time and to develop persistent academic difficulties throughout elementary and middle school (Morgan et al., 2011, 2016).

It is therefore important to examine how SES may relate to academic performance in reading and mathematics (Korous et al., 2022). Among the various factors potentially underlying the relationship between SES and academic achievement, one hypothesis is that SES may affect the development of cognitive processes that support learning in these academic domains, thereby influencing reading and mathematical achievement (Buckingham et al., 2014; Silver & Libertus, 2022).

3.3. Cognitive pathways linking SES to reading and mathematics

Research investigating the links between SES and the cognitive processes underlying reading and mathematics has focused predominantly on domain-general and language-related factors (Hackman & Farah, 2009; Merz et al., 2019; Taylor et al., 2023), leaving other domain-specific factors relatively understudied.

3.3.1. SES and domain-general cognitive factors

Meta-analytic evidence indicates a significant small-to-medium effect of SES on children's domain-general abilities, particularly executive functions (Lawson et al., 2018). Among these, while this effect has been consistently observed for working memory (see Mooney et al., 2021, for a meta-analysis), findings for inhibition and cognitive flexibility remain mixed, with some studies reporting SES-related differences (Arán-Filippetti & Richaud De Minzi, 2012; Conway et al., 2018; Lipina et al., 2013; Sarsour et al., 2011) and others not (Chung et al., 2017; Last et al., 2018), across different age groups. Selective attention has been less frequently investigated, yet available evidence also points to SES disparities in this domain (Hackman & Farah, 2009; Schibli et al., 2017; Xia et al., 2024). Specifically, children from low-SES backgrounds have been shown to attend to information non-selectively, allocating attentional resources to both relevant and irrelevant stimuli (D'Angiulli et al., 2008, 2024; Schibli et al., 2017; Stevens et al., 2009).

Longitudinal studies further highlight the effect of SES on the development of executive functions, particularly working memory. Specifically, SES measured before age 3 has been shown to predict working memory performance in both kindergarten (Hackman et al., 2015) and elementary school, with children from low SES demonstrating approximately a 1-year lag in working memory capacity compared to their higher-SES peers (Mooney et al., 2022). A comparable developmental lag has also been reported for selective attention, with children from low-SES backgrounds performing at age 5 at a level typically observed in 4-year-old high-SES children (Hampton Wray et al., 2017).

Beyond the association between SES and domain-general cognitive skills, these abilities have also been shown to mediate the relationship between SES and academic achievement (see X. Ding et al., 2024, for a meta-analysis). This mediating role is consistently observed in mathematics, as evidenced by both cross-sectional (e.g., Bachman et al., 2022; Blakey et al., 2020; Dilworth-Bart, 2012; Fitzpatrick et al., 2014) and longitudinal studies (e.g., Albert et al., 2020; Lawson & Farah, 2017; Nesbitt et al., 2013; Ng et al., 2021). In contrast, findings for reading are more mixed. While some studies report that domain-general skills mediate the

SES-reading link (e.g., Z. T. Barnes et al., 2022; Corso et al., 2016), others have failed to identify such an effect (e.g., Lawson & Farah, 2017). Notably, the mediating role of executive functions in the SES-reading link has been shown to disappear when language abilities (Dilworth-Bart, 2012; Fitzpatrick et al., 2014) or prior reading performance (Waters et al., 2021) are accounted for. Moreover, when present, the mediating effect of domain-general skills in the SES-academic achievement association is generally weaker for reading than for mathematics (Albert et al., 2020; Nesbitt et al., 2013).

The question of whether all domain-general cognitive abilities – including working memory, inhibition, cognitive flexibility, and selective attention – mediate the relationship between SES and academic performance remains debated, with inconsistent findings across studies. Some research has identified working memory, but not inhibition, as a significant mediator of the SES-academic achievement link in reading and mathematics (Albert et al., 2020; Poon et al., 2022; Waters et al., 2021), whereas other studies have reported the opposite pattern, with inhibition, but not working memory, emerging as a significant mediator (Escobar et al., 2018; James-Brabham et al., 2023). Evidence regarding cognitive flexibility is similarly mixed, with some studies supporting a mediating role (Morgan et al., 2024; Poon et al., 2022) and others reporting no such effect (Escobar et al., 2018). To date, no study has directly examined whether selective attention may mediate the SES-academic achievement association. Deer et al. (2020), however, reported that a global measure of selective attention and inhibition between ages 7 and 11 did not significantly mediate the link between SES assessed before age 5 and overall academic performance at ages 16–18.

Overall, domain-general cognitive skills appear to play a mediating role in the relationship between SES and academic performance, with evidence being more robust for mathematics than for reading (e.g., Lawson & Farah, 2017). Whether all domain-general functions contribute equally to this mediation, however, remains widely debated, as relatively few studies have examined multiple domain-general abilities simultaneously, and those that have report inconsistent findings. Current research nevertheless indicates that working memory generally exerts a stronger mediating influence than other domain-general skills on the relationship between SES and academic achievement (Albert et al., 2020; Morgan et al., 2024; Poon et al., 2022). These mixed findings are further reflected in intervention studies showing contrasting effects of executive function training on reducing SES-related academic disparities (Blakey et al., 2020; Prager et al., 2023). Crucially, although reading and mathematics achievement also rely on domain-specific cognitive processes, these factors have typically not been considered alongside domain-general skills in the aforementioned evidence,

leaving unclear whether domain-general abilities are the primary contributors to the SES-academic achievement relationship.

3.3.2. SES and domain-specific cognitive factors

It is indeed possible that SES exerts an additional – or even preferential – effect on cognitive factors specifically related to reading or mathematics, thereby contributing to educational inequalities observed within each of these academic domains.

3.3.2.1. SES and domain-specific factors related to reading

Regarding the relationship between SES and cognitive factors specifically involved in reading, most studies have focused on language skills, consistently demonstrating a strong association between SES and language-related processes (Hackman & Farah, 2009; Merz et al., 2019; Taylor et al., 2023). In particular, oral language – and more specifically vocabulary – appears to be the language-related skill most sensitive to SES (Hoff, 2013), with disparities observable as early as 18 months of age (Fernald et al., 2013). These differences likely reflect variations in both the quantity and quality of language input available to children from high- versus low-SES backgrounds (Schwab & Lew-Williams, 2016). Low-SES children have been found to show weaker performance in both expressive and receptive vocabulary (Pace et al., 2017), as well as reduced ability to use known vocabulary to infer the meaning of novel words (Maguire et al., 2018). Longitudinal evidence further supports these findings, showing that SES predicts the rate of expressive vocabulary growth in both toddlers (Pungello et al., 2009) and early elementary school children (Lervåg et al., 2019).

Beyond oral language, SES is also related to other reading-specific cognitive skills, most notably phonological awareness (Hoff, 2013; Pace et al., 2017). Children from low-SES backgrounds generally exhibit weaker phonological awareness than their higher-SES peers, both prior to school entry (Alloway et al., 2014; Chung et al., 2017; McDowell et al., 2007) and after the onset of formal instruction (Rassel et al., 2021; Schiff & Lotem, 2011; but see Fluss et al., 2009). In contrast, evidence regarding SES effects on RAN is more mixed, with some studies that reported SES disparities in RAN (Dolean et al., 2019; Espinoza et al., 2022), while others found no such differences (Asadi et al., 2023; Lima et al., 2020; C. Liu & Georgiou, 2017), even within comparable age groups. Interestingly, Espinoza et al. (2022) observed that while SES-related gaps in oral language and phonological awareness remained stable between

kindergarten and first grade, the SES-related gap in RAN significantly decreased over the same developmental period.

Furthermore, domain-specific cognitive skills have also been shown to mediate the relationship between SES and reading performance. Meta-analytic evidence indicates that both oral language and phonological awareness serve as independent partial mediators of the SES-reading association, including reading accuracy, fluency, and comprehension (J. Li et al., 2023). Longitudinal studies further support this finding, showing that oral language and phonological awareness in kindergarten uniquely mediate the relationship between SES and subsequent reading outcomes in elementary school (Pan et al., 2017; Y. Zhang et al., 2013). Although less extensively studied, RAN has also been identified as a mediator in the SES-reading link. For example, Su et al. (2017) reported that RAN at age 4 significantly mediated the relationship between SES at birth and reading fluency in fifth grade, independently of oral language skills. Similarly, Dolean et al. (2019) found that RAN mediated the association between SES and reading growth from first to second grade, whereas phonological awareness, by contrast, did not emerge as a significant mediator.

Overall, these findings indicate that certain domain-specific cognitive skills contribute to the relationship between SES and reading performance. However, little is known about how these skills operate jointly, as no study has simultaneously examined the potential mediating roles of oral language, phonological awareness, and RAN. Moreover, despite its established contribution to reading proficiency, visual-attention span has never been investigated in relation to SES disparities or as a possible mediator of the SES-reading association. These gaps highlight the need for more integrative approaches to determine which cognitive factors most strongly drive SES effects on reading outcomes.

3.3.2.2. SES and domain-specific factors related to mathematics

In the mathematical domain, research on the potential links between SES and different domain-specific cognitive factors is even more limited than in reading, and the available evidence remains highly inconsistent. Regarding non-symbolic skills, some studies have reported SES-related differences in ANS acuity in preschool and kindergarten children (Bachman et al., 2022; H. Li et al., 2025; Meloni et al., 2023), whereas others have found no such association (Hua & Zhang, 2024; Sepúlveda et al., 2020; Slusser et al., 2019; Wei et al., 2020). Evidence for symbolic skills is similarly mixed, with significant relationships between SES and symbolic comparison (Sepúlveda et al., 2020) and between SES and transcoding (Meloni

et al., 2023) found in kindergarteners. By contrast, no effect of SES has also been observed for symbolic comparison (Meloni et al., 2023) and transcoding (Bernabini et al., 2020), highlighting the particularly controversial nature of the findings.

Moreover, very few studies have examined the unique effect of SES on both symbolic and non-symbolic domain-specific skills within the same statistical model. Among these, SES was found to relate to non-symbolic skills, but not to symbolic ones, in kindergarten (Bonifacci et al., 2021) and first-grade children (Braeuning et al., 2021). Yet, Guzmán et al. (2021) highlighted age-related variations, showing that while SES was linked to both symbolic and non-symbolic skills in preschool, only its association with symbolic skills persisted by second grade.

Overall, evidence indicates that the relationship between SES and various domain-specific mathematical skills remains unclear and underexplored. Importantly, potential SES-related disparities in other domain-specific abilities, such as number ordering, have yet to be investigated. Moreover, it remains unknown whether different domain-specific skills may mediate the link between SES and mathematics achievement. Notably, one study examining number word knowledge reports that this skill, in preschool, mediated the relationship between SES and mathematical performance in kindergarten (Slusser et al., 2019). This finding suggests that other unexplored domain-specific factors could similarly act as mediators in the SES-mathematics association.

Taken together, the evidence reviewed in this section indicates that various cognitive skills involved in reading and mathematics learning are associated with SES and can mediate the relationship between SES and academic performance in both domains. While the link between SES and domain-general processes has been extensively studied, considerably less attention has been given to domain-specific skills, particularly those related to mathematics. Moreover, domain-general and domain-specific abilities have rarely been examined jointly, leaving their respective contributions to the links between SES and academic outcomes poorly understood. This underlines the need for comprehensive studies investigating the potential mediating roles of multiple domain-general and domain-specific skills in the relationships between SES and reading, as well as SES and mathematics.

Furthermore, academic learning is shaped by more than SES and cognitive factors alone. Notably, emotional factors also play a critical role in academic achievement, with their impact particularly well-documented in mathematics (Batchelor et al., 2019). Among these, math anxiety (MA) has been identified as a key factor that may influence mathematical performance both directly and indirectly via cognitive processes.

4. Emotional factors and academic achievement: The role of math anxiety (MA)

4.1. Definition and prevalence of MA

MA refers to feelings of tension, apprehension, or fear experienced when engaging with mathematics, which interfere with mathematical performance (Ashcraft, 2002; Ramirez et al., 2018). For some individuals, everyday or academic situations involving number manipulation or mathematical problem-solving elicit an emotional response (i.e., heightened physiological reactivity), thereby disrupting task performance (Dowker et al., 2016; Luttenberger et al., 2018; Suárez-Pellicioni et al., 2016). Typical manifestations of MA include negative attitudes toward mathematics, stress in situations involving numerical information, avoidance of math-related activities, and physiological arousal during mathematical tasks (Rubinsten et al., 2018). Although related to other forms of anxiety, such as general anxiety – defined as a general tendency to experience anxiety across everyday situations (Carey et al., 2017) – MA is recognized as a distinct and specific construct (Chang & Beilock, 2016; Dowker et al., 2016). Indeed, correlations between MA and general anxiety are typically small to moderate (Carey et al., 2017; Dowker et al., 2016), and factor analyses demonstrate that MA represents an independent factor, distinct from other types of anxiety (Pizzie & Kraemer, 2019) as well as other socio-emotional dimensions such as mathematics interest (Cheng et al., 2022). Thus, as Dowker et al. (2016) aptly summarized, MA appears to be as much about "anxiety" as it is about "mathematics." Assessment of MA most often relies on self-report questionnaires and rating scales – including pictorial versions for children – in which participants indicate how they feel about various math-related situations (Dowker et al., 2016; Ramirez et al., 2018).

Although research on MA has long focused on adults, increasing attention has recently been devoted to its manifestation in elementary school children (Ramirez et al., 2018; Uğraş, 2025). Evidence shows that young children are not only capable of identifying and reporting their feelings of anxiety toward mathematics, but that MA also emerges very early – being observable as early as the first years of elementary school (Ramirez et al., 2018; Suárez-Pellicioni et al., 2016) – and tends to increase with age throughout childhood (Dowker et al., 2016). Estimating the prevalence of MA, however, remains challenging due to the absence of clear thresholds for what qualifies as high levels of MA (Dowker et al., 2016) and to variability across different MA components (Sorvo et al., 2017). For example, Sorvo et al. (2017) found that, among children in grades 2 through 5, about 10% reported feeling anxious when starting

a math task, 20% when answering teacher questions in math class, and 30% when unable to solve a mathematical problem. Such patterns appear even more pronounced in older students: in the 2022 PISA survey, around 40% of 15-year-olds across OECD countries reported feeling very nervous and helpless when solving mathematical problems (OECD, 2023). Taken together, these findings highlight that MA affects a substantial proportion of students, making it a major societal concern (Dowker et al., 2016) with repercussions for later academic and professional choices (Beilock & Maloney, 2015; Cuder et al., 2024; Eidlin-Levy et al., 2023).

4.2. MA influences on mathematics performance

Converging evidence indicates a moderate, negative correlation between MA and mathematical performance across age groups (see Barroso et al., 2021; Caviola et al., 2022; Namkung et al., 2019; J. Zhang et al., 2019, for meta-analyses). This association has been documented worldwide (OECD, 2023), emerges as early as elementary school (O'Connor et al., 2023; Sorvo et al., 2017; Wu et al., 2012), and persists throughout schooling into adulthood (Barroso et al., 2021; J. Zhang et al., 2019). Importantly, MA predicts mathematical outcomes over and above general anxiety in both children (e.g., Donolato et al., 2020; Justicia-Galiano et al., 2017) and adults (e.g., Daker et al., 2022), and this effect appears to be specific, as it is not observed in other academic areas such as reading (Passolunghi et al., 2016; Wu et al., 2012). MA has been shown to affect multiple mathematical subskills, including word problem-solving, calculation abilities, and math fluency (Barroso et al., 2021; Passolunghi et al., 2016; Schillinger et al., 2018; Skagerlund et al., 2024). While stronger associations are often reported for more complex mathematical skills such as problem-solving compared to basic calculation (Caviola et al., 2022; Namkung et al., 2019; J. Zhang et al., 2019), mixed findings also exist. For instance, some studies have found effects of MA on single-digit and multi-digit calculation but not on problem-solving, in both children (C. S. Song et al., 2021) and adults (Silver et al., 2022).

Longitudinal evidence further supports the detrimental impact of MA on mathematics, showing that higher MA at ages 6–7 predicts lower mathematical performance at ages 7–8 (Ching, 2017; Gashaj et al., 2023). Mononen et al. (2022) additionally demonstrated that changes in MA between first and second grade were associated with changes in mathematics achievement during the same period. Interestingly, Tomasetto et al. (2021) reported that in 6-year-olds, MA was linked not only to initial mathematical knowledge but also to the rate of learning new mathematical content, suggesting that MA may contribute to cumulative gaps in mathematics proficiency from the start of formal schooling. Still, the directionality of this relationship remains debated (Carey et al., 2016). Some studies have identified reciprocal

effects between MA and mathematics over time (Du et al., 2021; Szczygieł et al., 2024), whereas others point to unidirectional links – either from MA to later mathematics (Krinzinger et al., 2009) or, conversely, from mathematics to subsequent MA (X. Ma & Xu, 2004; C. S. Song et al., 2021; Z. Wang et al., 2020). Overall, however, literature reviews tend to provide stronger support for pathways from MA to mathematics (L. Wang, 2020), or at least for bidirectional relationships (Carey et al., 2016).

Finally, heightened MA is also associated with mathematics difficulties. Notably, elementary school students with poor mathematical achievement, as well as those with mathematics learning disabilities, have been shown to display higher levels of MA (Wu et al., 2014), while their anxiety toward other academic subjects was comparable to that of peers without such difficulties (Passolunghi, 2011). However, considerable variability exists in this regard, with some children struggling with mathematics exhibiting pronounced MA, whereas others appear largely unaffected (Dowker, 2024; Lievore et al., 2025).

Overall, the relationship between MA and mathematics, as well as the mechanisms underlying it, remain poorly understood. Several theories have been proposed to explain this association. A prominent theory is the disruption account, grounded in the Processing Efficiency Theory (PET) of general anxiety, originally developed by Eysenck and Calvo (1992). According to this view, when individuals with high MA face math-related situations, devoting attention to the negative thoughts and emotions that arise imposes a secondary, resource-demanding task, consuming limited working memory resources and ultimately interfering with mathematical performance. Consequently, performance is particularly impaired on tasks that heavily rely on working memory (Ashcraft, 2002; Ramirez et al., 2018; Suárez-Pellicioni et al., 2016). Extensions of this theory, such as the Attentional Control Theory (ACT; Eysenck et al., 2007), further posit that individuals with high MA struggle to inhibit internal or external task-irrelevant stimuli, thereby decreasing performance (Suárez-Pellicioni et al., 2016). Moreover, some studies indicate that deficits in low-level numerical processing skills (e.g., visual enumeration of quantities) may also occur in math-anxious individuals (Maloney et al., 2010), challenging the notion that MA primarily affects complex tasks dependent on working memory (Suárez-Pellicioni et al., 2016). Taken together, these findings suggest that multiple types of cognitive abilities may contribute to the link between MA and mathematics performance, although this question remains relatively underexplored.

4.3. Cognitive pathways linking MA to mathematics performance

A growing body of research indicates that MA may influence both domain-general and domain-specific cognitive abilities important for mathematical proficiency. However, little is known about whether these skills mediate the link between MA and mathematics achievement, with the role of domain-specific mathematical processes in this relationship remaining particularly understudied.

4.3.1. MA and domain-general cognitive factors

Among domain-general cognitive abilities, working memory appears to be the most consistently affected by MA, in line with the Processing Efficiency Theory (Eysenck & Calvo, 1992). Lower working memory performance has been observed in both children (Mammarella et al., 2015; Passolunghi et al., 2019; Witt, 2012) and adults (Pelegrina et al., 2020; Shi & Liu, 2016) with high MA compared to low-MA individuals. Interestingly, Passolunghi et al. (2016) found that children with high MA in grades 6–8 not only recalled fewer words correctly during a working memory task but also made more intrusive errors by recalling non-target words, suggesting additional difficulties in inhibiting irrelevant information. These findings are further in line with studies in adults reporting inhibition deficits in high-MA individuals (Colomé et al., 2023; Hopko et al., 2002; Núñez-Peña & Campos-Rodríguez, 2024; Van den Bussche et al., 2020). Moreover, difficulties in cognitive flexibility have also been reported in high-MA children (Skagerlund et al., 2024) and adults, who appear less efficient than low-MA individuals at switching between different arithmetic problems (González-Gómez et al., 2023), or at shifting to more effective problem-solving strategies (R. Jiang et al., 2021). Finally, an attentional bias toward numerical information has also been evidenced in math-anxious adults, reflected in greater allocation of attentional resources when anticipating and processing mathematical content (J. Liu et al., 2019; Rubinsten et al., 2015). However, this pattern remains debated, with some studies reporting rather an attentional disengagement bias from mathematical symbols (Pizzie & Kraemer, 2017), or even no attentional bias at all but instead difficulties in attentional control required for goal-directed allocation of attention (González-Gómez et al., 2024).

Furthermore, such domain-general factors have also been shown to mediate the relationship between MA and mathematical performance. Most consistently, working memory has been found to serve as a mediator across age groups (see Caviola et al., 2022; Finell et al., 2022, for meta-analyses). Notably, in elementary school students, this mediating effect has been reported for various mathematical abilities, including word problem-solving, calculation skills, and math fluency (Doz et al., 2024; Justicia-Galiano et al., 2017; Wu et al., 2017).

Longitudinal evidence further supports these findings, showing that working memory significantly mediates the relationship between MA and later mathematical skills in elementary school children (Del Río et al., 2025; Pellizzoni et al., 2022). Interestingly, Orbach et al. (2020) highlighted a serial mediation pathway in fourth and fifth graders, whereby high MA was associated with greater inattention, which in turn predicted weaker working memory, ultimately resulting in lower mathematics performance. However, the mediating role of multiple domain-general abilities considered simultaneously remains relatively underexplored, and findings differ across age groups. Among the three core executive functions – working memory, inhibition, and cognitive flexibility – only working memory emerged as a significant mediator in adults (Pelegrina et al., 2024), whereas only cognitive flexibility mediated the relationship between MA and mathematics in middle school adolescents aged 11–14 (Živković et al., 2022).

Thus far, evidence for a mediating role of domain-general skills in the relationship between MA and mathematical outcomes remains rather mixed and limited, particularly in elementary school children. Moreover, most studies have not simultaneously considered the potential contribution of domain-specific cognitive skills, leaving it unclear whether domain-general abilities are the primary drivers of this relationship.

4.3.2. MA and domain-specific cognitive factors

Compared to domain-general cognitive factors, fewer studies have investigated the influence of MA on math-related domain-specific skills. Among these, MA has been most consistently linked to symbolic numerical abilities. In particular, children (Mononen, Niemivirta, Korhonen, et al., 2022) and adults (Maloney et al., 2011; Núñez-Peña & Suárez-Pellicioni, 2014) with high MA show less accurate magnitude representations in symbolic comparison tasks. High MA is also associated with poorer number ordering skills, reflected in more errors and slower responses when judging whether triplets of digits are in the correct numerical order, in both children (Skagerlund et al., 2024) and adults (Colomé & Núñez-Peña, 2021; Dubinkina et al., 2023). In contrast, evidence linking MA to non-symbolic processing skills is less robust, with some studies reporting associations in children (Guzmán et al., 2021) and adults (Lindskog et al., 2017), but meta-analytic evidence indicating a non-significant relationship between MA and ANS acuity (Barroso et al., 2021).

The question of whether domain-specific skills may mediate the relationship between MA and mathematics, independently of domain-general abilities, has received limited

attention. Szczygieł (2021) reported that, in children in grades 1–3, the link between MA and overall mathematics achievement was not mediated by magnitude processing – whether symbolic or non-symbolic – but was instead exclusively mediated by working memory. In contrast, Skagerlund et al. (2019) found more nuanced results in adults, showing that while only working memory mediated the link between MA and word problem-solving, both working memory and symbolic processing jointly mediated the relationship between MA and arithmetic calculation skills. These findings suggest that domain-specific cognitive factors may contribute to the association between MA and certain mathematical subskills. However, because only working memory and magnitude processing were examined in the studies cited above, it remains unclear whether these skills would maintain a unique mediating role when considered alongside other domain-general and domain-specific abilities. This underlines the need for more comprehensive research simultaneously examining multiple cognitive factors as well as distinct mathematical subskills.

Taken together, the evidence reviewed in this section highlights that emotional factors such as MA can significantly affect academic performance in mathematics, and that both domain-general and domain-specific cognitive factors may contribute to this link. However, whether these mediating roles remain when accounting for SES is still unknown. Crucially, SES has been shown to relate not only to mathematics performance and the cognitive skills that support it (N. C. Jordan & Levine, 2009; Silver & Libertus, 2022), but also to the development of MA. Notably, children from low-SES backgrounds appear to be at greater risk of MA during schooling (Adimora et al., 2015; Guzmán et al., 2021). Yet, to date, no study has investigated the role of cognitive factors in the MA-mathematics link while controlling for the potential confounding effects of SES.

Moreover, while academic achievement in elementary school is influenced by multiple factors, the sources of poor reading and poor mathematics performance may differ across children. Addressing this variability is crucial for better understanding the challenges these children face and for designing more effective support.

5. Interindividual variability among children with poor academic achievement

Research increasingly indicates that poor academic achievers do not form a homogeneous group (Astle et al., 2019; Dowker, 2024). Building on this perspective, the present section examines interindividual variability among children with poor achievement in reading and mathematics. Two complementary levels of variability are considered: (i) the heterogeneity of cognitive profiles among children struggling in reading or mathematics, and (ii) the distinction between difficulties confined to a single academic domain and those spanning both reading and mathematics. Together, these perspectives provide a finer-grained understanding of the diverse challenges faced by low-achieving students.

5.1. Cognitive heterogeneity among poor academic achievers

Evidence indicates that children with reading or mathematics difficulties often exhibit cognitive impairments that may span both domain-specific and domain-general dimensions (e.g., Kroesbergen et al., 2023; Kudo et al., 2015). However, this does not imply that all low performers share the same profile of cognitive weaknesses. In particular, overreliance on group averages risks obscuring the interindividual variability among children with poor academic achievement (Astle et al., 2024). Examining this heterogeneity of cognitive profiles is therefore essential for developing a more fine-grained understanding of the diverse sources of reading and mathematics difficulties and for designing interventions tailored to individual needs.

5.1.1. Cognitive profiles of poor readers

Alterations in phonological processing are widely documented as a major contributor to reading difficulties. Yet, studies of individual differences show that phonological deficits affect only a subset of struggling readers, whereas others may predominantly present impairments in visual or visuo-attentional processes (Bosse et al., 2007; Carroll et al., 2016; J.-R. Cho & Ji, 2011; White et al., 2006; but see Saksida et al., 2016). For instance, Bosse et al. (2007) found that most dyslexic children exhibited an isolated deficit in either phonological awareness or visual-attention span. Similar findings were reported in dyslexic children selected for a homogeneous reading profile characterized by severe impairments in both irregular word and pseudoword reading (Zoubrinetzky et al., 2014). Although deficits in both phonological

awareness and visual-attention span might have been expected in this type of mixed reading difficulties, only 17% displayed combined deficits in both abilities, whereas most showed impairments confined to either phonological awareness (32%) or visual-attention span (34%). This heterogeneity was further underlined by Valdois et al. (2021), who examined the distribution of cognitive deficits in phonological awareness, visual-attention span, and RAN in French sixth-grade poor readers. Again, most poor readers showed an isolated deficit in phonological awareness (20%), visual-attention span (18%), or RAN (15%). A smaller proportion presented combined deficits in two cognitive skills (23%), while deficits across all three were rare (4%). Notably, across these studies, approximately 20% of children with reading difficulties exhibited no deficit in any of these cognitive skills (Bosse et al., 2007; Valdois et al., 2021; Zoubrinetzky et al., 2014), suggesting that additional, unmeasured factors may contribute to their difficulties.

Relatively few studies have examined the cognitive profiles of children with reading difficulties while considering domain-general cognitive skills, and the findings are not always consistent. For example, some research reports that around 30% of children with reading difficulties exhibit behavioral symptoms of inattention alone (Heim et al., 2008), whereas other studies find selective attention deficits to be rare (approximately 2%) and typically co-occurring with phonological deficits (Dębska et al., 2022). Working memory deficits have also been observed in certain subgroups of poor readers, but these are often accompanied by domain-specific impairments, such as phonological awareness or RAN (K. Chan et al., 2023; Willems et al., 2016). Importantly, other domain-general functions, including inhibition and cognitive flexibility, have not yet been examined in relation to the cognitive profiles of poor readers, leaving open the question of whether some subtypes may present deficits in these abilities, either alone or alongside domain-specific impairments.

5.1.2. Cognitive profiles of poor mathematics achievers

Similarly to findings in the reading domain, research indicates that children with mathematical difficulties also constitute a heterogeneous group. For example, von Aster (2000), using cluster analyses in children aged 8 to 10 with varying degrees of mathematical difficulties, identified four distinct subtypes: (i) a “verbal” subtype characterized by counting difficulties; (ii) an “Arabic” subtype marked by poor mastery of the symbolic code, particularly evident in transcoding tasks; (iii) a “pervasive” subtype exhibiting severe impairments across nearly all domain-specific skills; and (iv) a “moderately impaired” subtype showing more moderate alterations compared to children without mathematical difficulties. Notably, poor

ANS acuity – often posited as the core deficit underlying mathematical difficulties – has been shown to affect only a minority of children (Bartelet et al., 2014; W. W. L. Chan & Wong, 2020; Costa et al., 2018; Ouyang et al., 2024). Other subgroups of poor mathematics achievers, by contrast, have been characterized by specific symbolic processing deficits (Bartelet et al., 2014; W. W. L. Chan & Wong, 2020; Ouyang et al., 2024), visuospatial deficits (Bartelet et al., 2014; Costa et al., 2018), or even no identifiable cognitive deficits (Bartelet et al., 2014; W. W. L. Chan & Wong, 2020; Costa et al., 2018; Ouyang et al., 2024).

Few studies have simultaneously considered domain-general skills when examining the cognitive profiles of children with mathematical difficulties. Interestingly, W. W. L. Chan & Wong (2020) reported that in first grade, one subtype of poor mathematics performers showed combined symbolic processing and working memory deficits, whereas in second grade another subtype within the same group of children emerged characterized by working memory deficits alone, suggesting potential developmental changes in cognitive profiles over time. Furthermore, using cluster analysis in an unselected sample of third- to fifth-grade children, Salvador et al. (2019) found that children with mathematical difficulties could be identified among two distinct subgroups: one with poor visuospatial working memory and another with poor symbolic and non-symbolic magnitude processing. Likewise, Carriedo et al. (2024) reported that among second graders, distinct executive function profiles (e.g., deficits in working memory and cognitive flexibility, or in inhibition and cognitive flexibility) could give rise to similarly low mathematical performance.

Overall, children with poor reading or mathematics performance constitute heterogeneous populations comprising diverse cognitive subtypes. Yet, few studies have jointly considered both domain-specific and domain-general factors when examining this heterogeneity. A more comprehensive approach is therefore needed to capture a broader spectrum of the cognitive weaknesses these children may exhibit and to design interventions more closely tailored to individual needs.

Furthermore, beyond this cognitive heterogeneity observed among children with low academic performance, additional variability may stem from whether difficulties are isolated to a single academic domain or span both reading and mathematics.

5.2. Isolated and co-occurring difficulties in reading and mathematics

The heterogeneity of cognitive profiles among poor readers and poor mathematics achievers may partly reflect whether academic difficulties occur in isolation within a single domain or concurrently across both reading and mathematics (Brandenburg et al., 2021; Moll et al., 2019). Importantly, as most research has examined each domain separately, children with co-occurring difficulties remain relatively understudied (Ashkenazi et al., 2013; Starling-Alves et al., 2025), despite evidence that they may represent a distinct subtype altogether (Archibald et al., 2013) and respond differently to interventions (Espinas & Fuchs, 2025; S. R. Powell et al., 2020).

5.2.1. Prevalence and characteristics of isolated and co-occurring difficulties

The prevalence of children with co-occurring reading and mathematics difficulties varies widely across studies, ranging from 11% to 70% (Moll, 2022). Nevertheless, this rate exceeds what would be expected by chance, calculated by multiplying the prevalence of difficulties in each separate domain (Butterworth & Kovas, 2013; Dirks et al., 2008). For instance, in a large sample of Austrian children in grades 2 to 4, Landerl & Moll (2010) found that while approximately 15% exhibited poor reading performance, nearly 40% of these children also struggled in mathematics. Consequently, the risk of difficulties in one domain is four to five times higher among children already experiencing difficulties in the other domain, compared to the general population (Landerl & Moll, 2010). Overall, up to half of children with difficulties in one area may also struggle in the other (Grigorenko et al., 2020; Koponen et al., 2018), although prevalence estimates depend on cut-off criteria (Dirks et al., 2008; Landerl & Moll, 2010; Moll, 2022; Moll et al., 2014) and the specific measures used to assess reading and mathematics (Dirks et al., 2008; Moll et al., 2019). Critically, children from low-SES backgrounds – often at higher risk for academic difficulties (e.g., Morgan et al., 2011) – tend to be overrepresented among children with co-occurring reading and mathematics difficulties (Connors et al., 2025; N. C. Jordan & Levine, 2009; Khanolainen et al., 2023).

In terms of academic performance, children with co-occurring difficulties in reading and mathematics generally exhibit lower achievement in both domains compared to those with difficulties in only one area (M. A. Barnes et al., 2020; Cirino et al., 2015; Espinas & Fuchs, 2025; Stewart et al., 2025). Some research also reports slower growth in reading and mathematics over time for children with co-occurring difficulties (Khanolainen et al., 2023). However, this developmental pattern remains debated, as other studies have found growth trajectories similar to those of children with isolated difficulties (Andersson, 2010; Connors et

al., 2025; N. C. Jordan et al., 2003). Importantly, lower performance in children with co-occurring difficulties may depend on specific academic subskills. For example, they may perform worse than children with mathematics difficulties alone on language-related mathematical tasks, such as word problem-solving or mental arithmetic (Hanich et al., 2001; N. C. Jordan et al., 2003). Yet, comparable performance on such tasks reported in other studies suggests that both verbal and nonverbal cognitive processes may contribute to mathematics difficulties (Andersson, 2010; J. A. Jordan et al., 2015).

5.2.2. Cognitive underpinnings of isolated and co-occurring difficulties

Despite their substantial prevalence, co-occurring difficulties in reading and mathematics have received relatively little attention, leaving the cognitive mechanisms underlying them poorly understood (Starling-Alves et al., 2025). Several hypotheses have been advanced to explain their origins in comparison to isolated difficulties in reading or mathematics.

A first explanatory framework for co-occurring difficulties is the Additive model (Figure 3). According to this account, the co-occurrence of reading and mathematics difficulties arises from the cumulative effect of independent cognitive deficits specific to each learning domain (Ashkenazi et al., 2013; L. Peters & Ansari, 2019; Starling-Alves et al., 2025). Empirical evidence supports this view, showing that deficits observed in children with co-occurring difficulties reflect the sum of reading-related and math-related impairments found in children with isolated difficulties in each domain (see Viesel-Nordmeyer et al., 2023, for a meta-analysis). Specifically, phonological processing deficits are typically linked to reading difficulties, whereas impairments in magnitude processing, spatial skills, or executive functions are more closely associated with mathematics difficulties, with both sets of deficits present in children with co-occurring difficulties (Landerl et al., 2009; Moll et al., 2015; L. Peters et al., 2020; Schwenck et al., 2015). Interestingly, Moll et al. (2015) also reported that children with isolated reading difficulties may also exhibit weaknesses in certain math-related skills involving verbal number processing, particularly transcoding abilities – similarly to children with co-occurring difficulties.

A second explanatory account for the co-occurrence of reading and mathematics difficulties is the Three Independent Disorders model (Figure 3). According to this model, children with co-occurring difficulties exhibit a cognitive profile that is distinct from that of children with difficulties confined to a single domain, potentially involving different and/or

more severe cognitive impairments than those observed in isolated difficulty groups (Moll, 2022; Viesel-Nordmeyer et al., 2023). Notably, these co-occurring difficulties may stem from deficits in domain-general cognitive functions, which support a range of academic skills and can thus produce concurrent difficulties in reading and mathematics when compromised (Ashkenazi et al., 2013; L. Peters & Ansari, 2019; Starling-Alves et al., 2025). Supporting this hypothesis, children with co-occurring difficulties have been found to show greater executive function deficits than those with isolated difficulties, suggesting a distinct cognitive profile (De Weerdt et al., 2013; Willcutt et al., 2013). Furthermore, some studies have reported alterations unique to children with co-occurring difficulties, such as in brain regions involved in visual associative learning (Skeide et al., 2018).

A third explanatory account for the co-occurrence of reading and mathematics difficulties is the Increased Risk model (Figure 3). According to this model, reading difficulties and associated impairments in verbal processes increase the risk of developing difficulties in mathematics (L. Peters & Ansari, 2019; Starling-Alves et al., 2025). Specifically, language deficits, such as impairments in phonological awareness – typically linked to reading difficulties – may increase the likelihood of mathematical difficulties by affecting language-related mathematical processes, particularly word problem-solving and arithmetic fact retrieval, which relies on accessing the verbal forms of these facts in long-term memory (Ashkenazi et al., 2013; De Smedt et al., 2010; L. Peters & Ansari, 2019; Starling-Alves et al., 2025). Supporting this hypothesis, several studies have identified phonological awareness as a shared risk factor for both reading and mathematics difficulties (Fuchs et al., 2025; Mingozzi et al., 2024; Slot et al., 2016).

Overall, several theoretical models have been proposed to explain the origins of co-occurring reading and mathematics difficulties (see Figure 3, for a schematic overview). Empirical findings provide support for each model, with no single account receiving unequivocal evidence (L. Peters & Ansari, 2019). Importantly, these explanatory frameworks are not mutually exclusive and may represent different pathways leading to concurrent difficulties in reading and mathematics (Starling-Alves et al., 2025). Furthermore, the Multiple Deficit model offers an integrative perspective, suggesting that co-occurring difficulties result from the combined influence of probabilistic risk factors, including both factors specific to each domain and factors shared across domains (Moll, 2022; Pennington, 2006; Viesel-Nordmeyer et al., 2023). This model is supported by studies showing that children with co-occurring difficulties display both distinct and overlapping deficits compared to children with isolated difficulties (Andersson, 2010; Deng et al., 2022; Marks et al., 2024).

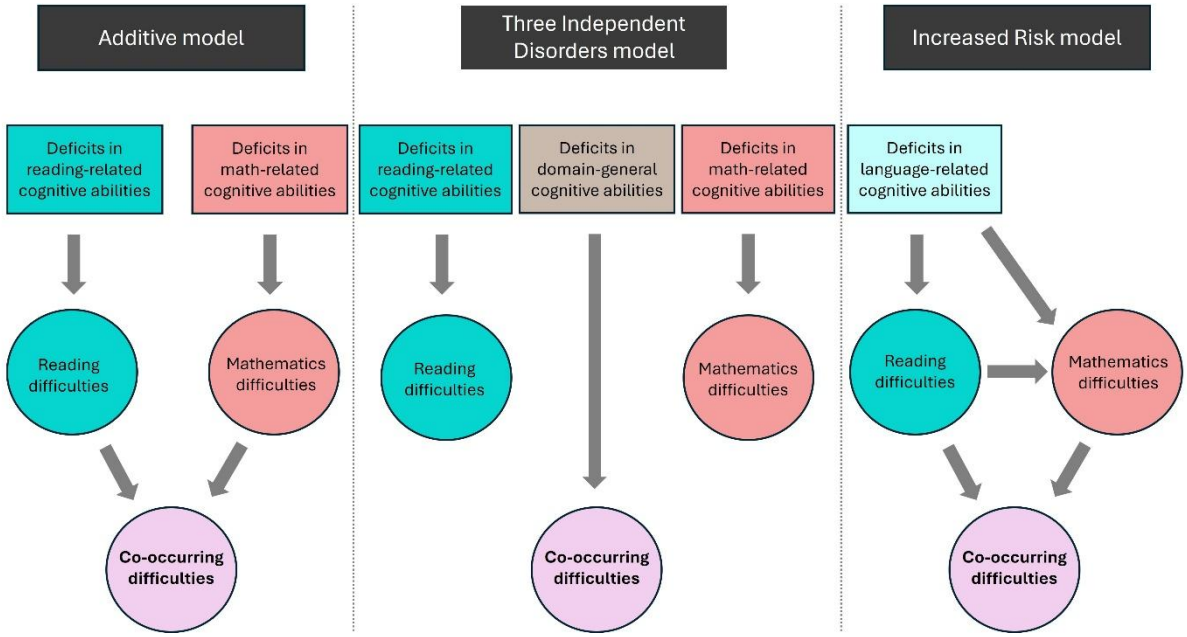

Figure 3. Schematic representation of theoretical accounts of co-occurring reading and mathematics difficulties. Adapted from Ashkenazi et al. (2013) and Starling-Alves et al. (2025).

It is therefore essential to investigate the cognitive characteristics underlying co-occurring reading and mathematics difficulties, considering both domain-specific factors linked to each academic area alongside domain-general factors (Starling-Alves et al., 2025). Such an approach is crucial for advancing our understanding of the cognitive processes underlying isolated versus co-occurring difficulties and for determining which types of interventions are likely to be most effective across distinct manifestations of academic difficulties (Moll, 2022).

Overall, the evidence reviewed in the present section highlights substantial interindividual variability among children with poor academic performance in reading and mathematics. This variability is evident both in the heterogeneous cognitive profiles observed among poor readers and poor mathematics achievers, and in the distinction between isolated and co-occurring difficulties across the two domains. Furthermore, domain-specific and domain-general factors have not yet been systematically integrated in this line of research, underlining the need for more comprehensive approaches to better capture the various cognitive underpinnings of poor performance in reading and/or mathematics.

6. Objectives of the thesis

6.1. Summary of research gaps

Overall, the literature reviewed in the previous sections highlights that academic performance in reading and mathematics is influenced by a complex interplay of factors, encompassing domain-specific and domain-general cognitive abilities, environmental aspects (e.g., SES), and emotional dimensions (e.g., MA). However, important gaps remain in our understanding of the determinants of low performance in reading and/or mathematics, particularly during the early years of primary school – a key developmental phase of learning.

Firstly, prior research has predominantly focused on children with the most severe manifestations of reading and mathematics difficulties (i.e., dyslexia and dyscalculia), who in fact represent only a minority of children struggling with reading or mathematics (Billard & Barbe, 2016; Dowker, 2024). As a result, the broader group of low-performing children has remained poorly characterized. This is particularly concerning, as these children often do not receive targeted support from which they could nevertheless benefit (Billard & Barbe, 2016; X. Zhang et al., 2020). Furthermore, although poor performance in reading and mathematics can arise from multiple sources, few studies have examined the combined contribution of different types of factors, including cognitive, socioeconomic, and emotional dimensions within a single experimental framework.

Secondly, research on reading and mathematics has largely examined the two domains in isolation, often focusing on a limited set of cognitive factors, despite evidence that both rely on multiple domain-specific and domain-general abilities (e.g., Kroesbergen et al., 2023; Kudo et al., 2015). Because few studies have adopted an integrative perspective simultaneously considering both types of cognitive factors, their relative contributions to each academic domain remain largely unclear. Moreover, the potential mediating role of these cognitive factors in SES-related achievement gaps, as well as in the relationship between emotional factors such as MA and mathematics performance, has yet to be investigated within a comprehensive framework.

Finally, interindividual variability among children with poor performance in reading and/or mathematics remains insufficiently understood, as most previous research has examined the existence of different profiles while considering only a limited set of cognitive skills. A broader range of factors, encompassing both domain-specific and domain-general abilities, is therefore necessary to capture the diversity of cognitive profiles that may exist

among low-performing children. This approach would also allow for a more precise characterization of co-occurring versus isolated reading and mathematics difficulties, and facilitate further investigation of whether distinct patterns may exist even within subgroups of children with poor reading only, poor mathematics only, or co-occurring difficulties in both domains (Starling-Alves et al., 2025).

6.2. Aims and contributions of the thesis

In this context, the overall objective of this thesis is to contribute to the understanding of the multifaceted determinants of poor academic achievement in reading and mathematics in primary school. Although many factors may influence academic performance in these domains, this thesis focuses on a selected subset of cognitive, socioeconomic, and emotional factors likely to play a significant role. By examining these factors, it aims to provide insights into potential intervention targets that may effectively support children struggling with reading and/or mathematics, while acknowledging that its scope is necessarily limited and does not encompass all possible influences.

More specifically, given that children from low-SES backgrounds are at higher risk of poor achievement in reading and mathematics (e.g., N. C. Jordan & Levine, 2009; Morgan et al., 2011; Pace et al., 2017), a first objective of this thesis is to examine whether cognitive abilities contribute to the associations between SES and academic performance in these domains. Understanding the cognitive factors involved in SES-related achievement gaps is crucial for preventing and mitigating academic difficulties in low-SES children, and thus reducing educational inequalities. To address this aim, **Study 1** investigates whether domain-general and/or domain-specific cognitive skills mediate the relationship between SES and reading outcomes, and the one between SES and mathematics outcomes.

Furthermore, because emotional factors such as MA have been linked to poorer mathematics performance (e.g., Barroso et al., 2021; Caviola et al., 2022; Namkung et al., 2019), a second objective of this thesis is to examine whether MA influences mathematical outcomes after accounting for SES, and whether cognitive factors play a mediating role in this relationship. Clarifying these links is essential for informing support strategies for children with high MA. Accordingly, **Study 2** investigates whether domain-general and/or domain-specific cognitive skills mediate the associations between MA and various mathematics outcomes, independently of SES – and other relevant covariates, such as general anxiety.

Moreover, because children struggling with reading or mathematics may exhibit heterogeneous cognitive profiles (e.g., W. W. L. Chan & Wong, 2020; Willems et al., 2016), a third objective of this thesis is to characterize the diversity of cognitive profiles among low-performing children. Understanding this variability is crucial for identifying the different challenges these children face and for designing interventions tailored to their individual needs. **Study 3** therefore investigates whether distinct cognitive profiles exist among children with poor reading and those with poor mathematics performance.

Finally, as the cognitive profiles of low-performing children may vary depending on whether difficulties are confined to a single academic domain or span both reading and mathematics (Brandenburg et al., 2021; Moll et al., 2019), the final objective of this thesis is to better understand the cognitive characteristics associated with poor performance in reading only, in mathematics only, and in both domains. Critically, interindividual variability may further exist within each of these groups, an issue that remains unexplored (Starling-Alves et al., 2025). **Study 4** therefore examines the cognitive factors related to poor performance in reading and/or mathematics, focusing on isolated versus co-occurring difficulties, and explores potential heterogeneity within each subgroup.

Overall, the studies included in this thesis aim to advance our understanding of the multifactorial determinants of poor reading and/or mathematics performance in primary school. Across all studies, a comprehensive approach is adopted, examining a broad range of cognitive factors, encompassing both domain-specific and domain-general abilities. Furthermore, multiple complementary levels of analysis are considered: first, through a dimensional perspective on an unselected sample of children with varying ability levels; and second, through a group-based and interindividual perspective focusing specifically on children with poor reading and/or mathematics performance.

All studies in this thesis rely on a single large sample of third-grade children. This age group was specifically selected because of its relevance to the various research objectives. Notably, third grade represents a developmental stage characterized by increasing mastery of multiple reading and mathematical subskills, rising academic demands and greater learning complexity in both domains, and enhanced differentiation between reading and mathematics (Fuchs et al., 2006, 2016). Moreover, this period is marked by widening SES-related achievement gaps (Kieffer, 2012) and the more prominent emergence of MA (Wu et al., 2012). Finally, poor academic performance at this age is likely to persist over time, rather than reflect

transient developmental delays, particularly for children with co-occurring reading and mathematics difficulties (Koponen et al., 2018). Altogether, these factors make third grade a particularly informative developmental window for investigating poor reading and mathematics performance, as well as associated cognitive, socioeconomic and emotional influences. The specific methodology employed in this thesis is described in the following section.

Part 2: Empirical contribution

1. General methodology

The four studies presented in this thesis share a common methodological framework. This section therefore outlines the general methodology applied across all studies, including a description of the participants, procedures, and measures. Specific methodological aspects of each study are detailed separately within their respective sections.

1.1. Participants

The participants recruited for this thesis were third-grade children enrolled in 19 elementary schools in Paris and its surrounding areas. These schools were part of the French priority education network (i.e., REP or REP+), a program providing additional resources to schools in underprivileged areas (Bénabou et al., 2009). In the Paris region, such schools are typically characterized by high social diversity, enabling the recruitment of children from a wide range of SES backgrounds while maintaining comparable instructional contexts. Schools were contacted via district educational advisors or laboratory contacts, and third-grade classes were recruited based on teacher's voluntary participation. Teachers who agreed to participate in the project provided parents with an information letter outlining the research, and only children with written parental consent who also gave their own assent took part in the project.

A total of 597 children from 44 third-grade classes were initially recruited. However, only participants meeting the following inclusion criteria were retained for the analyses: (i) normal or corrected-to-normal vision; (ii) no auditory, neurological, or neurodevelopmental disorders; (iii) no grade repetition or skipping; (iv) French language acquisition before age 3; and (v) a nonverbal IQ greater than 2 *SD* below the age norm. After applying these criteria, the final sample comprised 472 children (245 girls, 227 boys; M_{age} = 102.6 months, SD_{age} = 4.7 months, range = 92–113 months). The sample size was determined to ensure that the number of children with potential poor academic performance in reading or mathematics is sufficient and comparable to that of previous studies (e.g., W. W. L. Chan & Wong, 2020; Fluss et al., 2009; Valdois et al., 2021). Importantly, the sample size was also selected to be suitable for conducting structural equation modeling (SEM) analyses (Nachtigall et al., 2003).

1.2. Procedure

Data collection for this thesis project took place between May 2022 and December 2023. Children were individually assessed in a quiet room at their school by trained research assistants or interns in psychology, speech therapy, or related disciplines. Assessments were conducted across four experimental sessions of approximately 30 minutes each, spaced on average one week apart. Session 1 assessed academic outcomes in reading and mathematics along with nonverbal IQ. Session 2 evaluated domain-general cognitive skills. Session 3 assessed reading-related domain-specific skills, while Session 4 measured mathematics-related domain-specific skills and emotional factors. Task order varied within each session. Children were informed that they could request breaks at any time and discontinue a testing session without providing justification. In addition, demographic and SES information was collected via a parental questionnaire. The experimental protocol for this thesis project was approved by the Ethics Committee of Université Paris Cité (CER; N° IRB: 00012023-42).

1.3. Measures

This research project included both academic, cognitive and emotional assessments administered to children, and SES information collected from parents. Academic and cognitive abilities were evaluated using validated paper-and-pencil tests and computerized tasks. Emotional factors were measured with validated questionnaires. Demographic and SES information was obtained through a parental questionnaire specifically developed for this project (see Appendix 1). An overview of the measures is provided in Table 1 below, and detailed descriptions of each measure are presented in the following subsections.

Variable	Measure	Description	Coding
		Academic achievement	
Reading			
Reading fluency	Text reading (BALE; Jacquier-Roux et al., 2010)	Participants read aloud a text passage for 1 min	Number of words correctly read / minute (max = 274)
	Word reading (BALE; Jacquier-Roux et al., 2010)	Participants read three lists of low-frequency words (irregular, regular, and pseudowords)	Number of words correctly read / minute (max = 20)
Reading comprehension	Written comprehension (BALE; Jacquier-Roux et al., 2010)	Participants read a sentence and select the matching picture	Total score (max = 10)
Mathematics			
Word problems	Word problems (ZAREKI-R; von Aster & Dellatolas, 2006)	Participants solve word problems presented orally	Total score (max = 12)
Calculation	Mental arithmetic (ZAREKI-R; von Aster & Dellatolas, 2006)	Participants solve a series of addition, subtraction, and multiplication problems presented orally	Total score (max = 44)
	Calculation (WJ-III; Woodcock et al., 2001)	Participants solve increasingly difficult written calculations	Number of calculations correctly solved (max = 45)
Math fluency	Math fluency (WJ-III; Woodcock et al., 2001)	Participants solve as many single-digit addition, subtraction, and multiplication problems as possible within 3 min	Number of calculations correctly solved (max = 160)

Cognitive abilities			
Domain-general cognitive abilities			
Working memory	Digit span (WISC-V; Wechsler, 2014)	Participants recall increasingly longer digit sequences in backward and ascending order	Number of sequences correctly recalled (max = 18)
	Spatial span (WNV; Wechsler & Naglieri, 2006)	Participants recall increasingly longer block-tapping sequences in backward order	Number of sequences correctly recalled (max = 16)
Inhibition	Inhibition (NEPSY-II; Korkman et al., 2007)	Participants name rows of black-and-white stimuli using opposite labels (e.g. “circle” for a square, and “square” for a circle)	Error-corrected-time score of inhibition condition (adjusted for naming speed)
Cognitive flexibility	Inhibition (NEPSY-II; Korkman et al., 2007)	Participants name rows of black-and-white stimuli using the correct label for black stimuli, and the opposite label for white stimuli	Error-corrected-time score of flexibility condition (adjusted for naming speed)
Selective attention	Cancellation (WISC-V; Wechsler, 2014)	Participants cross out as many animals as possible within a sheet featuring animals and objects in 45 s	Number of correct targets minus errors (max = 128)
Reading-specific cognitive abilities			
Oral language	Oral comprehension (BALE; Jacquier-Roux et al., 2010)	Participants hear a sentence and select the matching picture	Number of correct responses (max = 20)
	Vocabulary (ELO; Khomsi, 2001)	Participants hear a word and select the matching picture	Number of correct responses (max = 20)
Phonological awareness	Initial phoneme deletion (BALE; Jacquier-Roux et al., 2010)	Participants hear a word and repeat it, omitting the initial phoneme	Number of correct responses (max = 10)

	Final phoneme deletion (BALE; Jacquier-Roux et al., 2010)	Participants hear a word and repeat it, omitting the final phoneme	Number of correct responses (max = 10)
RAN	Rapid image naming (BALE; Jacquier-Roux et al., 2010)	Participants name five rows of five objects as quickly as possible	Total naming time (s)
Visual-attention span	Global report (Bosse et al., 2007)	Participants recall strings of five consonants displayed for 200 ms on a screen	Total number of letters correctly identified (max = 100)
Mathematics-specific cognitive abilities			
Transcoding	Number dictation (ZAREKI-R; von Aster & Dellatolas, 2006)	Participants write down Arabic numerals as they are dictated orally	Total score (max = 16)
	Number reading (ZAREKI-R; von Aster & Dellatolas, 2006)	Participants read aloud written Arabic numerals	Total score (max = 16)
Symbolic comparison	Number comparison (Numeracy Screener; Lafay et al., 2018; Nosworthy et al., 2013)	Participants select the larger Arabic numeral within pairs of single-digit Arabic numerals – time limit: 1 min	Number of correct responses (max = 56)
Ordering	Number ordering (Numeracy Screener; Hutchison et al., 2022; Nosworthy et al., 2013)	Participants indicate whether triplets of single-digit Arabic numerals are in ascending order or not – time limit: 1 min	Number of correct responses (max = 48)
Non-symbolic comparison of small quantities	Dot comparison (Numeracy Screener; Lafay et al., 2018; Nosworthy et al., 2013)	Participants select the array with more dots within pairs of dot arrays (ranging from 1 to 9 dots) – time limit: 1 min	Number of correct responses (max = 56)

ANS acuity	Panamath (Halberda et al., 2008)	Participants indicate which of two dot arrays (ranging from 5 to 21 dots) contains more dots	Weber fraction (*w*)
		Math anxiety	
MA	SEMA (Wu et al., 2012)	Participants indicate how nervous they would feel in various math-related situations	Total score (max = 100)
		Socioeconomic status	
Composite SES score	Parental questionnaire	Parents report their highest level of education (converted into years) and occupation (mapped to ISEI scores)	PCA-derived score based on the highest education and highest ISEI score from either parent

Table 1. Overview of measures. RAN = rapid automatized naming; ANS = approximate number system; MA = math anxiety; SES = socioeconomic status; ISEI = international socioeconomic index; PCA = principal component analysis.

1.3.1. Academic measures

1.3.1.1. Reading achievement

Reading performance was assessed through two subskills, namely reading fluency and reading comprehension.

Reading fluency was evaluated using the *Text Reading* and *Word Reading* subtests from the Batterie Analytique du Langage Écrit (BALE; Jacquier-Roux et al., 2010). In the *Text Reading* subtest, children had 1 minute to read a text passage aloud, and both the total number of words read and the number of errors were recorded. The *Word Reading* subtest consisted of three lists of 20 low-frequency words, including irregular words, regular words, and pseudowords. Children were instructed to read each list as accurately and quickly as possible, and for each list both accuracy and reading time were recorded. In both subtests (i.e., the text passage and the three word lists), the number of words correctly read per minute was calculated as an index of reading fluency.

Reading comprehension was assessed using the *Written Comprehension* subtest from the same battery (BALE; Jacquier-Roux et al., 2010). In this task, each item presented a sentence alongside four pictures on a paper sheet. Children were first asked to read the sentence while the pictures were covered, and then to select the picture corresponding to the sentence. For each of the 10 items, one point was awarded only if both the sentence was read correctly and the correct picture was chosen.

1.3.1.2. Mathematics achievement

Mathematical performance was assessed across three subskills, namely word problem-solving, calculation, and math fluency.

Word problem-solving was evaluated using the *Word Problems* subtest from the ZAREKI-R battery (von Aster & Dellatolas, 2006). In this test, the examiner orally presented six word problems, and children were required to respond verbally to each problem, with no time limit. Scoring awarded two points if the child answered correctly without requesting the problem to be repeated, one point if the correct response was given after a single repetition by the examiner, and zero points for an incorrect answer or failure to respond following the single allowed repetition.

Calculation abilities were assessed using the *Mental Calculation* subtest from the ZAREKI-R battery (von Aster & Dellatolas, 2006) and the *Written Calculation* subtest from the WJ-III battery (Woodcock et al., 2001). The *Mental Calculation* subtest included eight additions, eight subtractions, and six multiplications, presented orally by the examiner, and children had to respond verbally, without time constraints. Problems involved both single- and double-digit operations. Scoring awarded two points for a correct response without requesting a repetition, one point for a correct response after a single repetition, and zero points for an incorrect answer or failure to respond following the single allowed repetition. In the *Written Calculation* subtest, children completed a series of increasingly difficult written calculation problems, including single-, double-, and triple-digit operations. There was no time limit, and the subtest was discontinued after six consecutive errors. Each correct response was awarded one point.

Math fluency was measured using the *Math Fluency* subtest from the WJ-III battery (Woodcock et al., 2001). In this written test, children were given 3 minutes to complete as many single-digit addition, subtraction, and multiplication problems as possible. The total number of correctly solved problems within the time limit served as the outcome measure.

1.3.2. Cognitive measures

1.3.2.1. Domain-general cognitive abilities

Domain-general cognitive skills were assessed through measures of working memory, inhibition, cognitive flexibility, and selective attention.

Working memory was assessed using the *Digit Span* subtest from the WISC-V (Wechsler, 2014) for the verbal component and the *Spatial Span* subtest from the Wechsler Nonverbal Scale of Ability (Wechsler & Naglieri, 2006) for the visuospatial component. In the *Digit Span* subtest, children had to repeat progressively longer sequences of orally presented digits in three conditions: (i) same order (“forward” condition); (ii) reverse order (“backward” condition); and (iii) ascending numerical order (“ascending” condition). In the *Spatial Span* subtest, children had to replicate sequences of block touches on a 3D board with 10 blocks, either (i) in the same order (“forward” condition), or (ii) in reverse order (“backward” condition). For both subtests, each condition started with two practice trials and was discontinued after two consecutive errors at a given sequence length (e.g., four digits or four touches). Only scores from conditions requiring both storage and manipulation of information

(i.e., backward digit span, ascending digit span, and backward spatial span) were used as indices of working memory (Baddeley, 1992; Bunge et al., 2000).

Inhibition and cognitive flexibility were measured using the *Inhibition* subtest from the NEPSY-II battery (Korkman et al., 2007). In this subtest, children were presented with a paper sheet displaying 40 black-and-white stimuli (squares and circles in part 1, arrows in part 2) arranged in five rows of eight stimuli. In the first condition, measuring naming speed, children were instructed to name the stimuli as quickly as possible, regardless of their color (e.g., "square", "circle"). The second condition, assessing inhibition, required children to respond with the opposite label (e.g., say "square" for a circle, and "circle" for a square). The third condition, assessing cognitive flexibility, required children to give the correct label for black stimuli and the opposite label for white stimuli. Before each condition, children completed a practice row of eight stimuli. For all three conditions, both errors and response times were recorded. Corrected-time scores were computed by adding, for each error, twice the participant's average stimulus naming time to the total completion time (Klenberg et al., 2015). To account for individual differences in naming speed, inhibition and flexibility scores were calculated by subtracting the corrected-time score of the naming condition from the corrected-time scores of the inhibition and flexibility conditions, respectively (Hedge et al., 2022; Klenberg et al., 2015).

Selective attention was assessed using the *Cancellation* subtest from the WISC-V (Wechsler, 2014). Children were presented with an A3 paper sheet featuring animals and objects, first arranged in a disorganized layout (item 1) and then in an organized layout where stimuli were aligned in rows and columns (item 2). For each item, children had 45 seconds to cross out as many animals as possible. A practice trial on an A4 paper sheet preceded the actual test. The total score was computed as the sum of correctly identified animals across both items, minus any errors.

1.3.2.2. Domain-specific cognitive abilities related to reading

Domain-specific skills related to reading included measures of phonological awareness, RAN, oral language, and visual-attention span.

Phonological awareness was assessed using the *Initial Phoneme Deletion* and *Final Phoneme Deletion* subtests from the BALE battery (Jacquier-Roux et al., 2010). In these subtests, the examiner pronounced a word (ranging from one to three syllables), and children were asked to repeat it while omitting either the initial or the final phoneme. Two practice

trials preceded each subtest to ensure that instructions were fully understood. Accuracy was computed for each subtest as the number of correct responses out of 10 items.

RAN was assessed using the *Rapid Object Naming* subtest from the BALE battery (Jacquier-Roux et al., 2010). In this subtest, children were presented with a paper sheet containing five rows of five objects and were asked to name each object as quickly as possible, from left to right, row by row. Prior to the test, children had to name each object in isolation to ensure that object names were known. The total time, in seconds, required to name all objects was recorded as the outcome measure.

Oral language skills were assessed using the *Listening Comprehension* subtest from the BALE battery (Jacquier-Roux et al., 2010) and the *Receptive Vocabulary* subtest from the Evaluation of Oral Language (ELO) battery (Khomsi, 2001). In the *Listening Comprehension* subtest, the examiner read a sentence aloud, after which children were presented with a paper sheet containing four pictures and were asked to select the picture corresponding to the sentence. In the *Receptive Vocabulary* subtest, children had to select from four options presented on a paper sheet the picture that matched a word spoken by the examiner. Scores for both subtests were based on the number of correct responses out of 20 items.

Visual-attention span was assessed using the global report task described in Bosse et al. (2007) and provided by the task authors. This computerized task included 20 trials, each presenting a string of five consonants on the screen for 200 ms. For each trial, children were asked to recall as many letters as possible, regardless of order. The total score, out of 100, reflected the number of letters correctly reported across all trials. A training session with 10 different items preceded the main task. Following previous studies (e.g., Bosse et al., 2007; Bosse & Valdois, 2009), isolated letter processing speed was accounted for using a single-letter recognition task. In this control task, a single consonant appeared at the center of the screen for varying durations (33 ms, 50 ms, 67 ms, 84 ms, or 101 ms) followed by a visual mask. Children had to identify the letter displayed. Ten trials were presented for each duration, and the number of correct responses was weighted according to exposure duration, with shorter durations receiving higher weights. The total score was computed as the sum of all weighted scores (see Bosse & Valdois, 2009, for further details). To ensure that visual-attention span scores were not confounded by isolated letter recognition speed, performance on the global report task was controlled for single-letter recognition (Bosse & Valdois, 2009). Although visual-attention span is typically assessed using both global and partial report tasks (Bosse et

al., 2007; Bosse & Valdois, 2009; Frey & Bosse, 2018), time constraints led us to use only the global report task, consistent with prior research (van den Boer et al., 2015).

1.3.2.3. Domain-specific cognitive abilities related to mathematics

The assessment of domain-specific mathematical skills included both symbolic abilities – namely, transcoding, symbolic comparison, and number ordering – and non-symbolic abilities, including non-symbolic comparison of small (single-digit) and large (multi-digit) quantities.

Transcoding skills were assessed using the *Number Dictation* and the *Number Reading* subtests from the ZAREKI-R battery (von Aster & Dellatolas, 2006). In the *Number Dictation* subtest, children were asked to write down 2- to 4-digit numbers spoken aloud by the examiner. Each response was scored two points if the number was accurately written without having to be repeated by the examiner, one point if correctly written after a single repetition by the examiner, and zero points for an incorrect answer or failure to provide a response after the single allowed repetition. This subtest comprised eight items and one practice trial. The *Number Reading* subtest required children to read aloud 2- to 4-digit numbers presented in symbolic digit format on individual paper sheets. Two points were awarded for a correct response on the first attempt, one point for a self-corrected correct response, and zero points otherwise. This subtest also comprised eight items and one practice trial.

Symbolic comparison skills were measured using the *Number Comparison* subtest from the Numeracy Screener battery (Nosworthy et al., 2013; validated for use with French-speaking children by Lafay et al., 2018). This subtest included 56 pairs of single-digit Arabic numerals ranging from 1 to 9, presented on A4 paper sheets. Children were asked to cross out the numerically larger number in each pair. They had 1 minute to complete as many pairs as possible. Before the test, children completed 12 practice pairs to familiarize themselves with the procedure. The outcome measure was the number of correct responses within the time limit.

Number ordering skills were assessed using a subtest later added to the Numeracy Screener battery (Hutchison et al., 2022; Nosworthy et al., 2013). This *Number ordering* subtest consisted of 48 triplets of single-digit Arabic numerals, ranging from 1 to 9, presented on A4 paper sheets. Children were instructed to judge whether the numbers were in ascending order or not and to mark their response by crossing a check symbol for ordered triplets (e.g., 2–4–6) or a cross symbol for unordered triplets (e.g., 4–2–6). Children had 1 minute to

complete as many items as possible, following four practice trials. The outcome measure was the number of correct responses within the allotted time. Importantly, this subtest was introduced into the research protocol shortly after the beginning of data collection, resulting in 19% of missing data for this variable (i.e., N = 88 children).

Non-symbolic comparison of small quantities was evaluated with the *Dot Comparison* subtest from the Numeracy Screener (Lafay et al., 2018; Nosworthy et al., 2013). This subtest included 56 pairs of dot arrays, each containing between 1 and 9 dots, presented on A4 paper sheets, with dot stimuli controlled for area and density (Nosworthy et al., 2013). Children were instructed to cross out the array containing more dots, without counting. After 12 practice trials, they had 1 minute to complete as many items as possible. The outcome measure was the number of correct responses within the time limit.

Non-symbolic comparison of large quantities was assessed as an index of more complex non-symbolic magnitude processing (Mishra & Khan, 2023) and as a more precise measure of ANS acuity (Halberda et al., 2008). The task was administered with the Panamath software (version 1.22; Halberda et al., 2008). Each trial began with a central fixation cross, followed by two dot arrays – one containing blue dots and the other yellow dots – simultaneously presented on either side of the screen for 1506 ms. Numerosities ranged from 5 to 21 dots per array. Children were asked to indicate whether there were more blue or more yellow dots by pressing the corresponding colored keyboard keys (F = yellow, J = blue). Once a response was provided, the examiner pressed the space bar to initiate the next trial, thereby ensuring that each child had sufficient time to respond and consistent with standard Panamath administration procedures (Halberda et al., 2008). The task consisted of 112 trials equally distributed across four ratios (1.22, 1.37, 1.60, 2.60) and was preceded by two practice trials to familiarize children with the procedure and response format. ANS acuity was indexed by the Weber fraction (*w*) (Halberda et al., 2008), with smaller values reflecting more precise quantity representations.

1.3.3. Emotional measures

Math anxiety (MA) was assessed using the Scale for Early Mathematics Anxiety (SEMA; Wu et al., 2012), adapted into French (see Appendix 2). As no validated French version was available, the questionnaire was first translated by a bilingual laboratory member and then reviewed by the author of this thesis as a native French speaker to ensure clarity and understandability. The SEMA is a self-report questionnaire designed for use with primary

school children. It comprises 20 items depicting math-related situations (e.g., solving addition problems, doing math homework). Each item was read aloud to participants by the examiner while simultaneously being presented in written format on individual paper sheets. Children were asked to indicate how nervous they would feel in each math-related situation using a 5-point Likert scale with smiley faces, ranging from 1 (*not nervous at all*) to 5 (*very very nervous*). Two practice items unrelated to mathematics were administered beforehand to ensure understanding of the procedure. MA scores were calculated by summing responses across all items, with higher scores reflecting greater MA. Internal consistency of the scale in the current sample was good (Cronbach's $\alpha = .87$) and consistent with the reliability reported for the original English version (Wu et al., 2012).

General anxiety was included as a control measure for MA to rule out effects attributable to general rather than mathematics-specific anxiety (e.g., Doz et al., 2024; S. Song et al., 2023; Z. Wang et al., 2015; Wu et al., 2012). General anxiety was assessed using the French version of the Revised Children's Manifest Anxiety Scale (R-CMAS; Reynolds & Richmond, 1978; Castro, 1999), a self-report questionnaire designed for children and adolescents aged 6 to 19. The R-CMAS comprises 37 dichotomous items (*Yes* = 1, *No* = 0), including 28 items measuring anxiety symptoms and 9 items forming a "Lie subscale" to detect social desirability bias. The 28 anxiety items are distributed across three subscales – *Physiological Anxiety* (10 items), *Worry/Oversensitivity* (11 items), and *Social Concerns/Concentration* (7 items) – which together contribute to a total anxiety score. This total score, calculated by summing responses to the 28 anxiety items, served as the outcome measure. Internal consistency for the total anxiety scale in the current sample was good (Cronbach's $\alpha = .85$).

1.3.4. SES measures

Parental SES was assessed through the questionnaire completed by parents (see Appendix 1). The questionnaire included items on the highest educational degree and the occupation of both parents – variables consistently shown to effectively represent the SES construct (e.g., Avvisati, 2020; Duncan et al., 2015; Galobardes, 2006; J. Lee et al., 2019). Educational attainment was converted into years of education, ranging from 0 (no schooling) to 20 (e.g., PhD degree). Occupations were coded according to the International Standard Classification of Occupations (ISCO-08; International Labour Office, 2012) at the 4-digit level. These ISCO codes were subsequently mapped to International Socio-Economic Index (ISEI) scores from the ISEI-08 classification (Ganzeboom, 2010) using the R package occupar (Ferrari, 2019). Unlike ISCO codes, which are categorical, ISEI scores provide a continuous measure of

the socioeconomic position of occupations, ranging from 10 to 90, with higher scores reflecting higher-based occupations (i.e., higher SES). Following Avvisati (2020), parents without an occupation (e.g., unemployed, homemaker, student) were assigned an ISEI score of 17, corresponding to occupations generally classified as “elementary occupations”. For each child, the highest number of years of education and the highest ISEI score from either parent were retained as SES indicators, consistent with the procedure used by the OECD in PISA studies (Avvisati, 2020; OECD, 2023). When data were available for only one parent, that information was used. In our sample, 37 participants (8%) had missing data for parental education only, 7 (1%) for parental occupation only, and 51 (11%) for both. Missing values for a single SES indicator (i.e., either education or occupation) were imputed using linear regression based on the other available indicator (e.g., Chung et al., 2017; Y. Jiang et al., 2024; Noble et al., 2007). For participants with missing data on both indicators, the SES score was treated as missing. A composite SES score was then derived via principal component analysis (PCA) on the two SES indicators. The first component, accounting for 85% of the total variance, was extracted and individual factor coefficients were used as the SES score, consistent with procedures used in prior research (e.g., Chung et al., 2017; Y. Jiang et al., 2024; Maximino-Pinheiro et al., 2024; Noble et al., 2007).

1.4. Data processing

Data from the paper-and-pencil academic and cognitive tests, as well as from the emotional and parental questionnaires, were scored independently by two raters to minimize data entry errors. Discrepancies between raters were resolved by checking the original student forms, after which the correct score was entered into the database. For the reading fluency tasks, both text and word reading were audio-recorded during administration and subsequently evaluated by two independent raters, with at least one being a speech-language therapy intern. For the coding of parental occupations and the assignment of ISCO scores (International Labour Office, 2012), disagreements were resolved through discussion until consensus was reached. After all data were double-checked and the database finalized, analyses for each study were conducted using R (version 4.2.1., R Core Team, 2022). The following sections present the theoretical framework, methodological approach, results, and discussion for each of the four studies included in this thesis.

2. Study 1: SES and academic achievement in reading and mathematics: The mediating role of cognitive factors

This study led to a manuscript:

Taieb, E., Le Stanc, L., Borst, G., Houdé, O., Altarelli, I.*, & Iuculano, T.* (under review). Cognitive factors mediating socioeconomic influences on reading and mathematics achievement among primary school children.

This study examined the relationship between SES and various reading and mathematics outcomes in third-grade children. We hypothesized that cognitive factors may mediate the association between SES and academic performance in both domains. Using structural equation modeling (SEM), we investigated whether domain-specific, domain-general, or a combination of both types of cognitive factors contribute to SES-achievement gaps in reading and mathematics.

2.1. Introduction

Extensive research indicates that children's academic performance is significantly associated with parental socioeconomic status (SES) (J. Liu et al., 2022b; OECD, 2023; Selvitopu & Kaya, 2023; Sirin, 2005). This SES-achievement link is observed across all OECD countries, with SES accounting, on average, for 13% of the variance in reading comprehension and over 16% in mathematics performance among 15-year-old students (OECD, 2023). Importantly, such disparities are evident as early as preschool, affecting children's readiness for formal schooling (Buckingham et al., 2014; N. C. Jordan & Levine, 2009). Critically, the acquisition of reading and mathematical skills in the first years of elementary school constitutes an essential milestone, predicting both later educational success (Duncan et al., 2007) and longer-term outcomes such as quality of life (Carneiro & Gordon, 2013) and achieved SES in adulthood (Ritchie & Bates, 2013). It is therefore necessary to clarify the factors through which SES may shape reading and mathematics learning in order to address educational inequalities effectively. While environmental factors (e.g., home environment, parent-child interactions) have been shown to contribute to the SES-achievement relationship (Davis-Kean, 2005; L. Elliott & Bachman, 2018; Y. Jiang et al., 2024), increasing attention has turned to the potential mediating role of neurocognitive factors (Noble et al., 2007; Noble, Tottenham, et al., 2005; Romeo, Uchida, et al., 2022).

Notably, academic success in reading and mathematics is underpinned by a broad range of cognitive abilities. Domain-general cognitive skills such as executive functions and selective attention support multiple forms of learning and have been consistently linked to performance in both reading (Cartwright, 2012; Follmer, 2018; Franceschini et al., 2012; Hwang et al., 2024; Jacob & Parkinson, 2015; Ober et al., 2020; Spiegel et al., 2021) and mathematics (Commodari & Di Blasi, 2014; Cortés Pascual et al., 2019; Hohol et al., 2017; Jacob & Parkinson, 2015; Spiegel et al., 2021; Zhong et al., 2022). In addition, each academic domain also relies on domain-specific cognitive abilities. For reading, these include phonological awareness (Ehri et al., 2001; Melby-Lervåg et al., 2012), RAN (Araújo et al., 2015), oral language (Foorman et al., 2015; Hjetland et al., 2020; Ricketts et al., 2007), and visual-attention span (Bosse & Valdois, 2009; Valdois et al., 2019; van den Boer et al., 2015). In mathematics, symbolic processing skills – such as symbolic comparison (De Smedt et al., 2013; Hawes, Nosworthy, et al., 2019), number ordering (Lyons et al., 2014; Sasanguie & Vos, 2018), and transcoding (Banfi et al., 2022; Göbel et al., 2014; Habermann et al., 2020) – as well as non-symbolic processing skills (Chen & Li, 2014; Fazio et al., 2014) have been associated

with achievement. However, no study to date has examined the joint contribution of these domain-general and domain-specific factors in mediating the relationship between SES and academic performance in reading and mathematics.

2.1.1. SES and domain-general cognitive abilities

A substantial body of research has demonstrated that SES is related to domain-general cognitive skills, including executive functions (Lawson et al., 2018; Merz et al., 2019; Taylor et al., 2023) and selective attention (Schibli et al., 2017), with evidence for such effects even before children enter formal schooling (e.g., Conway et al., 2018; Hampton Wray et al., 2017). Furthermore, several studies have highlighted the mediating role of executive functions in the link between SES and academic performance (Deer et al., 2020; X. Ding et al., 2024; Hu et al., 2024; Perry et al., 2018). However, most of this research has conceptualized academic achievement as a unitary construct, leaving open the possibility that executive functions may differentially contribute to SES-related disparities across academic domains. Notably, Lawson & Farah (2017) found that executive functions mediated the association between SES and mathematics, but not between SES and reading. Other studies reported that while the mediating effect of executive functions was present for both domains, it was significantly stronger for mathematics than for reading (Albert et al., 2020; Nesbitt et al., 2013).

Yet, the majority of these studies have treated executive functions as a unitary latent construct, with relatively few examining the distinct mediating roles of individual executive function components (Albert et al., 2020; Z. T. Barnes et al., 2022; Morgan et al., 2024; Poon et al., 2022). Among the studies adopting a more differentiated perspective, evidence suggests that both working memory and cognitive flexibility mediate the link between SES and academic outcomes, with working memory generally exerting a stronger influence than cognitive flexibility (Z. T. Barnes et al., 2022; Morgan et al., 2024; Poon et al., 2022). Findings regarding inhibition, however, remain inconsistent, with some studies reporting a significant mediation effect (James-Brabham et al., 2023; Morgan et al., 2024), while others do not (Albert et al., 2020; Poon et al., 2022). Importantly, most prior work has investigated these mediation effects within isolated academic domains – focusing either on reading (Barnes et al., 2022), mathematics (Morgan et al., 2024; James-Brabham et al., 2023), or composite measures of academic achievement encompassing both (Poon et al., 2022) – rather than considering reading and mathematics concurrently, yet distinctively. To our knowledge, Albert et al. (2020) provide the only investigation into the mediating roles of various executive functions in both SES-reading and SES-mathematics associations. Their findings showed that while working

memory acted as a mediator in both domains, inhibition did not in either. However, their study did not assess cognitive flexibility, leaving a gap in understanding its potential mediating role in SES-related academic disparities. Overall, these findings highlight the need to further specify which domain-general skills mediate the SES-achievement link across both reading and mathematics. Moreover, given that performance in these domains also depends on domain-specific cognitive processes, jointly considering both domain-general and domain-specific mediators within the same analytical framework is essential.

2.1.2. SES and domain-specific cognitive abilities

2.1.2.1. SES and domain-specific abilities related to reading

Regarding reading-specific cognitive abilities, numerous studies have documented the effect of SES on oral language skills (see Hoff, 2013, for a review), with disparities even observable in infancy (Farkas & Beron, 2004; Fernald et al., 2013). SES has also been linked to phonological awareness across a range of languages (Alloway et al., 2014; Chung et al., 2017; Pace et al., 2017; Schiff & Lotem, 2011), including French (Rassel et al., 2021). Evidence concerning RAN, however, is less consistent. While some studies report SES-related differences in RAN (Dolean et al., 2019; Espinoza et al., 2022; Su et al., 2017), others do not, even within comparable age groups and linguistic contexts (Asadi et al., 2023; Lima et al., 2020; C. Liu & Georgiou, 2017). Crucially, no research to date has investigated the SES-RAN relationship in French-speaking children, particularly during the middle years of elementary school – a developmental period when RAN is thought to play an increasingly important role in predicting reading outcomes (Kirby et al., 2003).

Several domain-specific skills have also been found to mediate the link between SES and reading. In a recent meta-analysis, J. Li et al. (2023) demonstrated that both oral language and phonological awareness partially mediated SES-related disparities in reading accuracy, fluency, and comprehension. However, their model did not include other relevant domain-specific abilities such as RAN. Notably, Dolean et al. (2019) reported that RAN, but not phonological awareness, mediated the association between SES and growth in reading fluency among Romanian children aged 7 to 9, although oral language skills were not included. In addition, despite the well-established role of visual-attention span in reading acquisition (e.g., Bosse & Valdois, 2009; Valdois et al., 2019), no study has yet examined whether this ability is associated with SES and whether it may mediate the relationship between SES and reading performance. Together, these gaps underline the need for a more comprehensive approach

that considers various domain-specific abilities alongside domain-general skills to clarify their contributions to SES-related disparities in reading outcomes.

2.1.2.2. SES and domain-specific abilities related to mathematics

Compared to reading, substantially fewer studies have investigated the association between SES and domain-specific mathematical skills. Among those that have, some report links between SES and both symbolic and non-symbolic skills (Bachman et al., 2022; Fischer & Thierry, 2021), whereas others find an effect of SES only on symbolic skills (Sepúlveda et al., 2020; Slusser et al., 2019), or conversely, only on non-symbolic skills (Bonifacci et al., 2021; Braeuning et al., 2021). Notably, the relationship between SES and non-symbolic skills appears to weaken with age, in contrast to the more stable SES-symbolic skills association (Guzmán et al., 2021).

Moreover, only a limited number of studies have examined the relationship between SES and different symbolic abilities, and findings remain inconsistent. For instance, Meloni et al. (2023) reported that SES was related to performance on an Arabic number reading transcoding task, but not to symbolic number comparison, in 5-year-old children. By contrast, Bernabini et al. (2020) found no association between SES and transcoding in children of the same age. Finally, the link between SES and number ordering remains unexplored, despite strong evidence that number ordering significantly predicts mathematics achievement in elementary school (Lyons et al., 2014; Sasanguie & Vos, 2018).

To our knowledge, no study has investigated whether these domain-specific mathematical skills mediate the SES-mathematics relationship. Interestingly, however, one study on number-word and cardinality knowledge found that this skill mediated the link between SES and mathematics performance in kindergarten (Slusser et al., 2019). This finding suggests that other domain-specific processes may similarly play a mediating role, though this possibility remains largely untested. Importantly, no research to date has examined whether various domain-specific abilities mediate the SES-achievement association across distinct mathematical outcomes – such as word problem-solving, calculation, and math fluency – after the onset of formal schooling.

2.1.3. Current study

Thus far, research on the cognitive mediators of the SES-achievement relationship has focused mainly on domain-general and language-related factors. In addition, most studies

have relied on aggregate measures of academic performance, rarely differentiating between reading and mathematics and between finer-grained subskills within each domain. Moreover, prior studies have typically considered only a narrow set of mediators at a time, without integrating both domain-general and domain-specific factors within comprehensive multiple-mediation models.

The objective of the current study is to address these gaps by examining the mediating effects of both domain-general and domain-specific cognitive factors on the associations between SES and academic achievement in reading and mathematics. Additionally, given evidence that SES can differentially relate to specific subskills within the same academic domain (e.g., Pina et al., 2014), we adopt a detailed approach by distinguishing between reading fluency and reading comprehension in the reading domain, and between word problem-solving, calculation, and math fluency in the mathematics domain. Our focus is on third-grade children, a critical developmental period characterized by (i) the transition from basic skill acquisition to more complex academic tasks (Fuchs et al., 2006); (ii) the increasing differentiation of the cognitive processes underlying reading and mathematics (Fuchs et al., 2016); (iii) the widening of SES-related academic disparities (Kieffer, 2012); and (iv) heightened risk for significant learning difficulties among low-SES children (Morgan et al., 2016). Using structural equation modeling (SEM), we tested whether domain-general factors, domain-specific factors, or a combination of both mediated the SES-achievement relationship, considering reading and mathematics separately.

2.2. Methods

2.2.1. Participants

The sample of this study comprised all participants described in Section 1.1. of the General Methodology, totaling 472 third graders (245 girls, 227 boys; M_{age} = 102.6 months, SD_{age} = 4.7 months, range = 92 – 113 months) from elementary schools in Paris and surrounding areas. All participants had normal vision and hearing, no neurological or neurodevelopmental disorders, had not repeated or skipped a grade, demonstrated sufficient mastery of French, and a had nonverbal IQ greater than 2 *SD* below the age norm.

2.2.2. Procedure

The procedure for the current study is described in greater detail in Section 1.2. of the General Methodology. Notably, children were tested individually across four experimental sessions, each lasting approximately 30 minutes, with an average interval of one week between sessions. Assessments were conducted in the following order: academic performance (session 1), domain-general cognitive skills (session 2), domain-specific cognitive skills related to reading (session 3), and domain-specific cognitive skills related to mathematics (session 4). Additionally, demographic and SES information was collected using a parental questionnaire (see Appendix 1).

2.2.3. Measures

The current study included measures assessing academic achievement, cognitive abilities and SES. Detailed descriptions of these measures are provided in Section 1.3. of the General Methodology.

Academic achievement was assessed in both reading and mathematics. In the reading domain, we evaluated reading fluency and reading comprehension. Reading fluency was modeled as a latent variable (Bollen, 2002) based on text, irregular word, regular word, and pseudoword reading fluency. In mathematics, we assessed word problem-solving, calculation, and math fluency. Calculation was modeled as a latent variable based on mental and written calculation tasks.

Cognitive abilities were assessed across domain-general, reading-specific and mathematics-specific skills. For domain-general skills, we evaluated verbal and visual working memory (used as indicators of a latent working memory variable), inhibition, cognitive flexibility, and selective attention. Reading-specific skills included phonological awareness, RAN, oral language, and visual-attention span. Phonological awareness and oral language were modeled as latent variables based on initial and final phoneme deletion, and oral comprehension and vocabulary, respectively. Mathematics-specific skills comprised transcoding, symbolic comparison, number ordering, and non-symbolic comparison of small and large quantities. Transcoding was modeled as a latent variable representing Arabic number writing and Arabic number reading.

SES was assessed based on the highest educational and occupational level of either parent. A composite SES score was then derived from these two indicators using principal component analysis (PCA).

Finally, several **covariates** of no interest were included to account for potential confounding effects. Specifically, we controlled for sex (coded –0.5 for boys and 0.5 for girls) and age (coded continuously, in months). Furthermore, because children were tested at different times throughout the school year, the timing of assessment could have influenced performance beyond age effects (Morrison et al., 2019). To address this, the month of testing (coded from 1 = September to 11 = July) was included as a covariate. In addition, nonverbal IQ, assessed using the *Matrices* subtest of the WISC-V (Wechsler, 2014), was also controlled. In this subtest, children are required to select from five alternatives the visual pattern that completes a logical sequence. The test is discontinued after three consecutive errors.

2.2.4. Data analyses

Structural equation modeling (SEM) was used to examine the mediating effects of cognitive skills on the relationships between SES and reading (Model 1), and SES and mathematics (Model 2). SEM allows for a comprehensive assessment of mediation processes by simultaneously estimating multiple relationships and accounting for complex interdependencies among variables (Gunzler et al., 2013). Raw variables were standardized prior to inclusion in the SEM models to facilitate interpretation of the coefficients. Missing data and non-normality were addressed using a Full Information Maximum Likelihood (FIML) approach with robust standard errors (MLR). Model fit was evaluated using the χ^2 test, the Comparative Fit Index (CFI), the Root Mean Square Error of Approximation (RMSEA), and the Standardized Root Mean Square Residual (SRMR). Model fit was considered acceptable when CFI > .95, RMSEA < .08, and SRMR < .10 (Schermelleh-Engel et al., 2003).

Each model included both latent and observed variables. Consequently, confirmatory factor analyses (CFA) were first conducted to assess the fit of the measurement models and determine whether the latent variables adequately represented their observed indicators (Kline, 2016). The scaling of latent factors was unconstrained, allowing the model to freely estimate factor loadings. Following the CFA models, the two SEM mediation models were tested, as illustrated in Appendices 3 and 4. Indirect effects were evaluated using 95% percentile bootstrap confidence intervals (CIs) based on 5000 resamples, in line with the recommendations of Preacher and Hayes (2008). Indirect effects are considered significant when the CI does not include 0. Mediation effect sizes were evaluated by reporting the type of mediation (full or partial) and the magnitude of the indirect effects, as indicated by their standardized coefficients (Rucker et al., 2011).

Data analyses were conducted using R (version 4.2.1., R Core Team, 2022) and the packages lavaan (Rosseel, 2012), occupar (Ferrari, 2019), semhelpinghands (Cheung, 2024), and tidyverse (Wickham et al., 2019).

2.3. Results

2.3.1. Descriptive statistics

Descriptive statistics for the raw observed variables are reported in Table 2 below. Bivariate correlations among the observed variables included in the reading and mathematics models are provided in Appendices 5 and 6, respectively.

Variable	N	Mean	SD	Min	Max
Academic variables					
Text fluency	472	83.21	29.57	2	184
Irregular words fluency	472	22.05	17.92	0	109.09
Regular words fluency	472	39.20	19.39	0	103.64
Pseudowords fluency	472	28.15	13.43	0	72
Written comprehension	469	6.59	1.94	0	10
Word problems	472	6.45	3.24	0	12
Mental calculation	472	29.66	9.01	0	44
Written calculation	461	12.56	3.01	1	21
Math fluency	472	38.96	13.23	6	86
Cognitive variables					
Digit span backward	472	6.64	1.73	3	12
Digit span ascending	471	6.00	2.03	1	11
Spatial span backward	472	5.37	1.95	0	11
Inhibition	472	33.30	19.42	–17.80	123.80
Cognitive flexibility	470	102.11	40.98	5.20	403.10
Selective attention	471	53.44	13.60	9	107
Oral comprehension	469	15.63	2.43	7	20
Vocabulary	469	16.57	1.77	8	20

Initial phoneme deletion	469	7.03	2.72	0	10
Final phoneme deletion	469	7.39	2.64	0	10
RAN	469	23.30	6.62	13	64
Visual-attention span	469	80.43	11.55	43	100
Number dictation	461	13.78	2.64	4	16
Number reading	459	14.83	1.85	4	16
Symbolic comparison	461	39.41	8.08	16	56
Ordering	384	15.27	4.49	1	28
Non-symbolic comparison of small quantities	461	38.23	6.41	18	54
ANS acuity (*w*)	458	0.31	0.25	0.02	3.37
Socioeconomic variables					
Parental education	384	13.56	3.79	0	20
Parental occupation	414	45.50	23.14	14.21	88.70
SES composite (*z* score)	421	0	1	–2.70	1.99
Covariates					
Sex (% of girls)	472	51.91%	_	_	_
Age	472	102.61	4.70	92	113
Testing month	472	6.19	3.22	1	11
Nonverbal IQ	472	13.95	3.15	7	24
Single letter identification	468	98.86	27.51	13	150

Table 2. Descriptive statistics for the raw observed variables. For the cognitive measures, lower scores on the Weber fraction (*w*), RAN, inhibition, and flexibility tasks indicate better performance. In the inhibition task, scores are adjusted for processing speed using a baseline condition without interference; negative scores indicate that a participant performed better in the inhibition than in the baseline condition (observed in 3 participants). RAN = rapid automatized naming; ANS = approximate number system; SES = socioeconomic status.

2.3.2. Measurement models (CFA)

The observed variables corresponding to each latent construct exhibited high and significant factor loadings, indicating that the latent variables adequately represented their respective observed indicators (see Table 3). Both the reading measurement model ($\chi^2(38) = 125.02$, $p < .001$, CFI = .964, RMSEA = .069, SRMR = .032) and the mathematics measurement model ($\chi^2(11) = 14.28$, $p = .218$, CFI = .997, RMSEA = .024, SRMR = .019) demonstrated good model fit (Schermelleh-Engel et al., 2003).

Latent variable	Indicators	β	SE
	Reading CFA model		
Reading fluency	Text fluency	.92	0.03
	Irregular words fluency	.86	0.04
	Regular words fluency	.93	0.04
	Pseudowords fluency	.85	0.04
Working memory	Digit span backward	.57	0.05
	Digit span ascending	.62	0.05
	Spatial span backward	.54	0.06
Oral language	Oral comprehension	.76	0.07
	Vocabulary	.56	0.06
Phonological awareness	Initial phoneme deletion	.79	0.09
	Final phoneme deletion	.55	0.07
	Mathematics CFA model		
Calculation	Mental calculation	.87	0.05
	Written calculation	.76	0.05
Working memory	Digit span backward	.56	0.05
	Digit span ascending	.60	0.05
	Spatial span backward	.57	0.05
Transcoding	Number dictation	.77	0.07
	Number reading	.72	0.08

Table 3. Loadings of observed variables on latent variables. Coefficients are standardized coefficients and are all significant at $p < .001$. SE = standard error; CFA = confirmatory factor analysis.

2.3.3. Structural equation models examining mediation effects

2.3.3.1. SES and reading performance

The SEM model examining the effects of SES on reading outcomes (i.e., fluency and comprehension) through the tested cognitive mediators demonstrated a good fit ($\chi^2(131) = 306.22$, $p < .001$, CFI = .951, RMSEA = .052, SRMR = .036). The results of the model are depicted in Figure 4. Additional information regarding all path estimates, as well as variance and covariance estimates, is provided in Appendix 7.

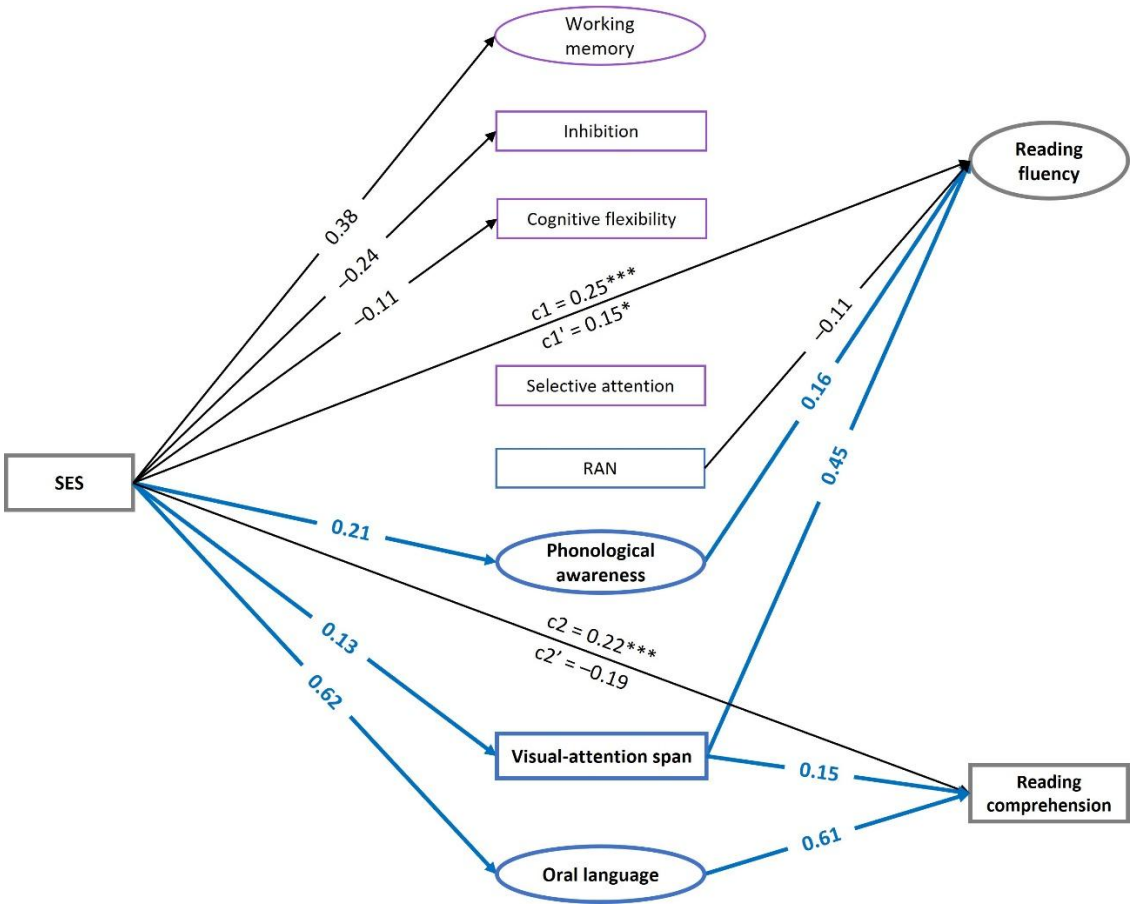

Figure 4. SEM mediation model representing the total, direct, and indirect effects of SES on reading outcomes. All coefficients are standardized coefficients. Latent variables are depicted by ovals, while observed variables are represented by squares. Domain-general factors are shown in purple (upper half) and domain-specific factors in blue (lower half). For clarity, nonsignificant paths, covariates, and covariances are omitted from the figure but are reported in Appendix 7. Total and direct effects are labeled c and c', respectively. Significant mediation effects are bolded. SES = socioeconomic status; RAN = rapid automatized naming. *$p < .05$; ***$p < .001$.

Bivariate associations

The results indicated that the total effect of SES on reading outcomes was significant for both reading fluency (path c1: β = .25, $p < .001$) and reading comprehension (path c2: β = .22, $p < .001$). Regarding domain-general cognitive abilities, SES was significantly associated with working memory (β = .38, $p < .001$), inhibition (β = –.24, $p < .001$), and cognitive flexibility (β = –.11, $p = .025$), but not selective attention (β = .10, $p = .056$). For domain-specific abilities, SES had a significant effect on oral language (β = .62, $p < .001$), phonological awareness (β = .21, $p = .001$), and visual-attention span (β = .13, $p = .011$), but not on RAN (β = –.08, $p = .138$). In terms of cognitive predictors of reading performance, domain-general abilities did not significantly contribute to reading outcomes, whereas domain-specific abilities played a key role. Reading fluency was significantly predicted by phonological awareness (β = .16, $p = .006$), visual-attention span (β = .45, $p < .001$), and RAN (β = –.11, $p = .009$), while reading comprehension was significantly predicted by oral language (β = .61, $p < .001$) and visual-attention span (β = .15, $p = .012$).

Mediation pathways

Examination of the indirect effects, presented in Table 4, revealed that both phonological awareness and visual-attention span significantly mediated the relationship between SES and reading fluency. The magnitude of these two mediation effects did not differ significantly (difference = –.026, 95% bootstrap CI [–0.082, 0.038]). Notably, the direct effect of SES on reading fluency (path c1': β = .15, $p = .035$) remained significant after accounting for the mediators, indicating partial mediation effects (Rucker et al., 2011). Regarding the SES-reading comprehension link, significant indirect effects were observed via both oral language and visual-attention span. The mediation effect of oral language was significantly larger than that of visual-attention span (difference = .355, 95% bootstrap CI [0.175, 1.940]), highlighting the predominance of oral language as a mediator in the association between SES and reading comprehension. Importantly, after accounting for the mediators, the direct effect of SES on reading comprehension (path c2': β = –.19, $p = .058$) was no longer significant, indicating full mediation effects (Rucker et al., 2011).

Mediation paths	Reading fluency		Reading comprehension	
	β	95% Boot CI	β	95% Boot CI
SES → Working memory → Reading	–.020	[–0.338, 0.084]	–.001	[–0.719, 0.105]
SES → Inhibition → Reading	–.010	[–0.035, 0.011]	–.008	[–0.040, 0.021]
SES → Flexibility → Reading	–.000	[–0.012, 0.012]	–.002	[–0.018, 0.015]
SES → Selective attention → Reading	.008	[–0.002, 0.025]	–.003	[–0.016, 0.015]
SES → Oral language → Reading	.029	[–0.170, 0.585]	**.375**	**[0.196, 1.990]**
SES → Phonological awareness → Reading	**.034**	**[0.004, 0.091]**	.034	[–0.006, 0.110]
SES → RAN → Reading	.008	[–0.003, 0.024]	–.001	[–0.016, 0.014]
SES → Visual-attention span → Reading	**.059**	**[0.016, 0.109]**	**.020**	**[0.001, 0.061]**

Table 4. Indirect effects of the SEM reading model. All coefficients are standardized coefficients. Significant mediation effects are bolded. CI = confidence interval; SES = socioeconomic status; RAN = rapid automatized naming.

2.3.3.2. SES and mathematics performance

With regard to mathematics, the SEM model examining the effects of SES on the three mathematical outcomes of interest (i.e., word problems, calculation, and math fluency) through the tested cognitive mediators demonstrated a good fit ($\chi^2(67) = 101.76$, $p = .004$, CFI = .989, RMSEA = .033, SRMR = .019). The results of the model are depicted in Figure 5. Additional details on all path estimates, as well as variance and covariance estimates, are provided in Appendix 8.

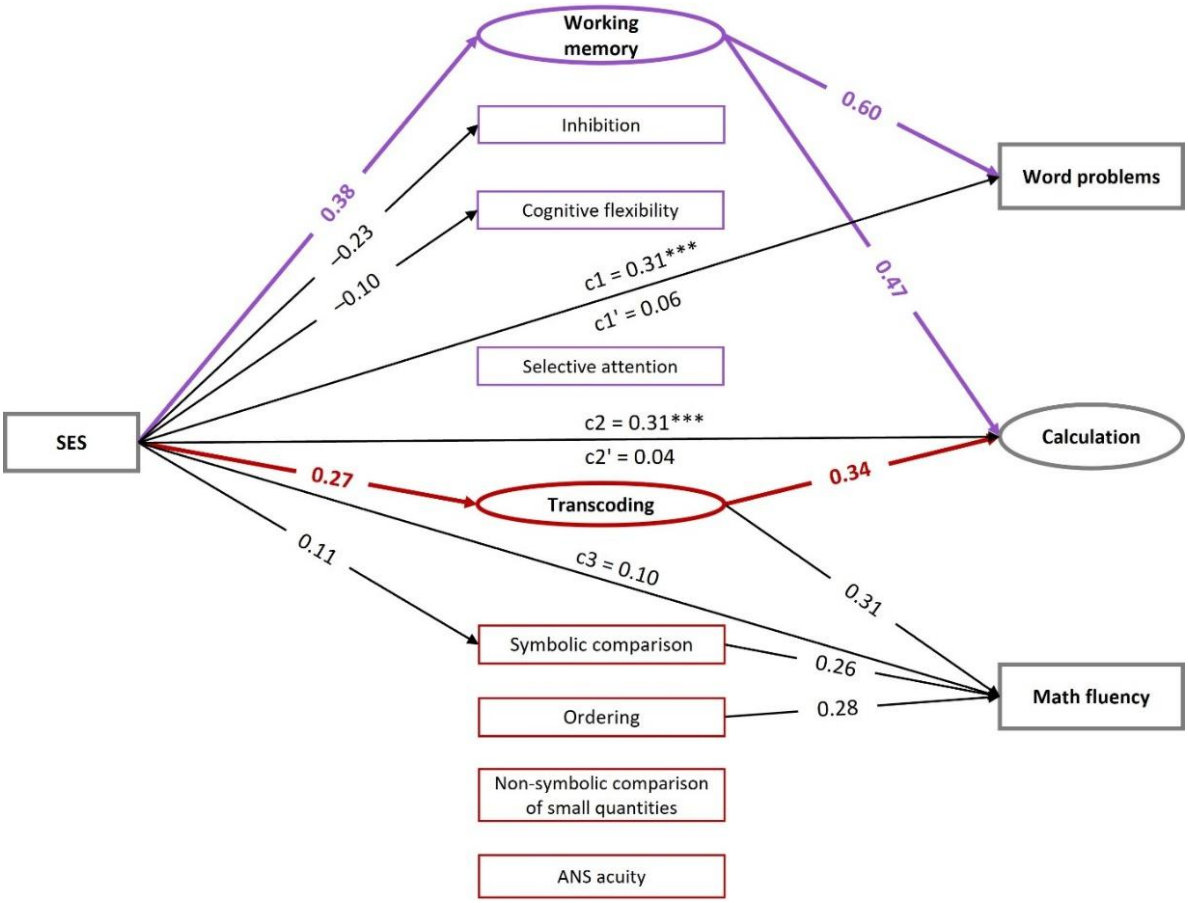

Figure 5. SEM mediation model representing the total, direct, and indirect effects of SES on mathematics outcomes. All coefficients are standardized coefficients. Latent variables are depicted by ovals, while observed variables are represented by squares. Domain-general factors are shown in purple (upper half) and domain-specific factors in red (lower half). For clarity, nonsignificant paths, covariates, and covariances are omitted from the figure but are reported in Appendix 8. Total and direct effects are labeled c and c', respectively. Significant mediation effects are bolded. SES = socioeconomic status; ANS = approximate number system. ***$p < .001$.

Bivariate associations

The results indicated that the total effect of SES on mathematics was significant for word problems (path c1: β = .31, $p < .001$) and calculation (path c2: β = .31, $p < .001$), but not for math fluency (path c3: β = .10, $p = .056$). Similar to the reading model, SES had significant effects on working memory (β = .38, $p < .001$), inhibition (β = –.23, $p < 0.001$), and cognitive flexibility (β = –.10, $p = .040$), but not on selective attention (β = .09, $p = .086$). Regarding domain-specific abilities, SES was associated with transcoding (β = .27, $p < .001$) and symbolic

comparison (β = .11, *p* = .032), but not with number ordering (β = .09, *p* = .100) or non-symbolic skills, including non-symbolic comparison of small quantities (β = .04, *p* = .451) and ANS acuity (β = –.03, *p* = .563). Mathematical outcomes were related to both domain-general and domain-specific abilities. Specifically, word problem-solving was predicted by working memory (β = .60, *p* < .001). Calculation skills were predicted by both working memory (β = .47, *p* = .001) and transcoding (β = .34, *p* < .001). Math fluency was predicted by transcoding (β = .31, *p* < .001), symbolic comparison (β = .26, *p* < .001), and number ordering (β = .28, *p* < .001).

Mediation pathways

Examination of the indirect effects, presented in Table 5, revealed that working memory significantly mediated the relationship between SES and word problem-solving. Additionally, the SES-calculation link was significantly mediated by both working memory and transcoding skills. The magnitudes of these two mediation effects did not differ significantly (difference = .089, 95% bootstrap CI [–0.042, 0.317]). Importantly, the direct effects of SES on word problem-solving (path c1': β = .06, *p* = .238) and calculation skills (path c2': β = .04, *p* = .513) were no longer significant after accounting for the mediators, indicating full mediation effects (Rucker et al., 2011). Mediation effects were not examined for math fluency, as the total effect of SES on this outcome was not significant.

Mediation paths	Word problems		Calculation	
	β	95% Boot CI	β	95% Boot CI
SES → Working memory → Math	**.227**	**[0.124, 0.452]**	**.179**	**[0.091, 0.366]**
SES → Inhibition → Math	–.019	[–0.045, 0.001]	–.010	[–0.035, 0.010]
SES → Flexibility → Math	.001	[–0.015, 0.012]	.003	[–0.008, 0.017]
SES → Selective attention → Math	–.004	[–0.019, 0.003]	–.004	[–0.019, 0.005]
SES → Transcoding → Math	.044	[–0.024, 0.098]	**.090**	**[0.029, 0.163]**
SES → Symbolic comparison → Math	–.002	[–0.020, 0.015]	.005	[–0.013, 0.030]
SES → Ordering → Math	.002	[–0.023, 0.019]	.003	[–0.018, 0.021]
SES → Non-symbolic comparison of small quantities → Math	.003	[–0.006, 0.016]	.003	[–0.007, 0.016]
SES → ANS acuity → Math	–.001	[–0.010, 0.003]	.001	[–0.003, 0.013]

Table 5. Indirect effects of the SEM mathematics model. All coefficients are standardized coefficients. Significant mediation effects are bolded. CI = confidence interval; SES = socioeconomic status; ANS = approximate number system.

2.4. Discussion

This study aimed to investigate the mediating roles of both domain-general and domain-specific cognitive factors in the relationship between SES and academic performance in reading and mathematics among primary school children. To this end, two comprehensive mediation models were developed within a SEM framework: one examining the cognitive mediators linking SES to reading outcomes, and the other analyzing those linking SES to mathematics outcomes. Our findings indicate that domain-specific factors mediate the association between SES and performance in both academic domains, whereas domain-general factors play a mediating role only in mathematics. Specifically, phonological awareness and visual-attention span mediated the relationship between SES and reading fluency, whereas oral language – and, to a lesser extent, visual-attention span – mediated the association between SES and reading comprehension. In mathematics, working memory emerged as a mediator of the relationship between SES and both word problem-solving and calculation, whereas transcoding skills mediated the link between SES and calculation only.

2.4.1. Cognitive mediators of the SES-reading relationship

Our results revealed that domain-specific – but not domain-general – cognitive factors mediated the relationship between SES and reading performance. More specifically, linguistic skills emerged as key mediators of the SES-reading link, consistent with the meta-analysis by J. Li et al. (2023), which demonstrated that both phonological awareness and oral language mediate this association across various reading subskills, including reading accuracy, fluency and comprehension. However, our findings suggest a more differentiated pattern, with phonological awareness mediating the relationship between SES and reading fluency, whereas oral language mediates the SES-reading comprehension link. This divergence may reflect methodological differences, as meta-analytic studies aggregate data from diverse samples and measures, potentially obscuring subtle distinctions in the role of linguistic skills across reading components at different developmental stages. Nonetheless, our results align with prior research indicating that phonological awareness is primarily related to reading decoding, whereas oral language is more strongly associated with reading comprehension (Bianco et al., 2012; Muter et al., 2004).

Furthermore, the present study is the first to provide evidence that visual-attention span mediates the relationship between SES and reading, for both reading fluency and reading comprehension. Although visual-attention span has previously been identified as an

independent predictor of reading ability beyond language-related domain-specific abilities (e.g., Bosse & Valdois, 2009; Valdois et al., 2021), our findings highlight, for the first time, its positive association with SES. This result aligns with studies suggesting SES-related disparities in visual short-term memory (Mooney et al., 2021), a subcomponent of visual-attention span (X. Ren et al., 2023). However, the mechanisms through which SES relates to visual-attention span remain largely unknown, warranting further investigation. Notably, this mediating effect appears specific to visual-attention span, as selective attention – assessed via a visual search task – was unrelated to both reading performance and SES (see Figure 4 and Appendix 7). This specific association between visual-attention span and reading is consistent with Cirino et al. (2022), who reported that among various visual attention measures, only visual-attention span showed a robust association with reading performance, whereas visual search did not. Moreover, our results are in line with those of Deer et al. (2020), who found no evidence of an association between SES and low-order executive functions, including visual search.

Our results further revealed that although RAN predicted reading fluency, it was not associated with SES and therefore did not mediate the SES-reading relationship. This contrasts with Dolean et al. (2019), who reported a mediating role of RAN in SES-related disparities in reading. This discrepancy may be explained by developmental differences, as our study focused exclusively on third graders, whereas theirs involved first-grade children. Notably, Espinoza et al. (2022) showed that while the association between SES and linguistic skills remained stable in early grades, the effect of SES on RAN declined over time, suggesting a compensatory developmental trajectory for this particular skill in low-SES children.

Finally, although SES was associated with domain-general abilities, including working memory, inhibition, and cognitive flexibility, none of these factors mediated the SES-reading relationship. This contrasts with previous studies reporting that executive functions mediate the link between SES and reading performance (Albert et al., 2020; Nesbitt et al., 2013). However, those studies did not account for domain-specific cognitive factors, which may explain the lack of predictive power of domain-general abilities observed in the present study. Indeed, when both domain-general and domain-specific abilities are examined simultaneously in relation to reading outcomes, domain-general skills either show no association with reading (Dolean et al., 2021) or exert an indirect influence through domain-specific factors, such as phonological awareness (Chung et al., 2017) or oral language (Spencer et al., 2020). It is also possible that executive functions play a more prominent role during earlier stages of reading development by supporting the acquisition and consolidation of grapheme-phoneme correspondences (Blair & Razza, 2007). Once these skills become automatized, their

contribution to reading may diminish, which could account for the absence of a significant association in our sample of third-grade children (X. Ding et al., 2024; Fuchs et al., 2016).

2.4.2. Cognitive mediators of the SES-mathematics relationship

In mathematics, our results underline the mediating role of both domain-general and domain-specific cognitive factors in the relationship between SES and mathematical performance. Among domain-general abilities, working memory emerged as the sole mediator, linking SES to both word problem-solving and calculation. This finding aligns with prior research indicating that working memory is a stronger predictor of mathematics achievement than other executive functions (Bull & Lee, 2014; Spiegel et al., 2021). Furthermore, while confirming the central role of working memory in the SES-mathematics relationship, our results extend previous studies (Albert et al., 2020; Morgan et al., 2024; Waters et al., 2021) by demonstrating that this effect persists even when domain-specific cognitive factors are simultaneously considered.

Among domain-specific skills, transcoding emerged as the only mediator of the SES-mathematics relationship, specifically linking SES to calculation performance. This finding is consistent with prior evidence showing that transcoding is a key predictor of arithmetic ability (Göbel et al., 2014; Habermann et al., 2020). Moreover, our results corroborate existing findings that SES is associated with transcoding abilities in early childhood (Meloni et al., 2023) and extend this evidence by demonstrating that this effect remains observable in older primary school children, even when domain-general cognitive factors are taken into account.

Furthermore, our results showed that, unlike symbolic processing, non-symbolic processing abilities were unrelated to both mathematical performance and SES. This finding aligns with prior research highlighting the stronger predictive power of symbolic over non-symbolic skills for mathematics achievement (see Amland et al., 2024; Fazio et al., 2014; Schneider et al., 2017, for meta-analytic reviews). It is also possible that non-symbolic processing contributes to mathematical performance indirectly, by influencing symbolic skills (Finke et al., 2020; Y. Li et al., 2018; Price & Fuchs, 2016), an effect that could not be captured in the present study due to the parallel mediation approach employed. Moreover, although SES has been shown to affect non-symbolic processing in preschoolers (e.g., Bachman et al., 2022; Bonifacci et al., 2021; Fischer & Thierry, 2021; Guzmán et al., 2021), the absence of such an effect in older primary school children is consistent with previous findings (Guzmán et al., 2021; Sepúlveda et al., 2020).

Lastly, it is important to note that, while SES predicted performance in both word problem-solving and calculation, it was not significantly associated with math fluency, although a trend was observed. This finding contrasts with Ayala et al. (2024), who reported SES-related differences across all three mathematical abilities, albeit less pronounced for math fluency. A possible explanation for this discrepancy may lie in age-related differences, as our sample included only third-grade children, whereas Ayala et al. (2024) focused on first graders.

2.4.3. Cognitive mediators across academic domains

The present findings highlight the role of cognitive factors in the association between SES and academic achievement in both reading and mathematics, and reveal distinct cognitive pathways underlying these relationships. Domain-general abilities mediated the SES-mathematics link, but not the SES-reading one, a pattern consistent with previous evidence (Lawson & Farah, 2017). Importantly, other studies have shown that although executive functions contribute to SES-related disparities in both academic domains, their mediating effect is stronger for mathematics than for reading (Albert et al., 2020; Nesbitt et al., 2013; Waters et al., 2021). The absence of such mediation in reading in the present study may also reflect the comprehensiveness of our model, which included both domain-general and domain-specific factors. In particular, prior research suggests that once language abilities are taken into account, executive functions no longer mediate the SES-reading relationship (Dilworth-Bart, 2012; Fitzpatrick et al., 2014).

Unlike domain-general abilities, domain-specific skills emerged as mediators in both academic domains, consistent with their well-documented role in reading (Hulme & Snowling, 2013; Valdois et al., 2004) and mathematics achievement (Ruiz et al., 2024). Crucially, the mediation pathways varied across academic subskills within each domain, emphasizing the need for a nuanced perspective when investigating the cognitive processes involved in the association between SES and educational outcomes.

2.4.4. Educational implications

Altogether, our findings provide valuable insights for education, highlighting the importance of both domain-specific and domain-general cognitive skills in addressing SES-related disparities in reading and mathematics. In particular, interventions aimed at strengthening linguistic abilities – such as oral language and phonological awareness – as well as visual-attention span may be especially effective in mitigating SES inequalities in reading. In

mathematics, our results suggest that training programs targeting working memory and transcoding skills hold promise for reducing SES effects on mathematics. Prior research has shown that training these cognitive abilities improves reading (Bianco et al., 2012; Valdois et al., 2025) and mathematics performance (DePascale et al., 2024). Implementing such interventions among children from low-SES backgrounds could therefore play a pivotal role in narrowing SES-related gaps across both academic domains.

2.4.5. Limitations and future directions

This study has several limitations that should be considered when interpreting the results. Most importantly, its correlational design precludes any causal inferences regarding the observed associations. Future research should adopt longitudinal designs to better capture the developmental dynamics of the cognitive mechanisms linking SES to academic performance throughout schooling. Moreover, our mediation models used a parallel mediation approach, simultaneously considering multiple mediators. While this choice was justified by the absence of a strong rationale for the sequential ordering of mediators, it precluded the detection of potential serial mediation pathways.

Furthermore, while our study included a broad range of domain-general and domain-specific cognitive factors, it was not exhaustive. Other cognitive abilities not assessed here, such as metacognition (Maximino-Pinheiro et al., 2024) or planning (Crook & Evans, 2014), may also mediate SES-related variations in academic achievement. Beyond cognitive factors, emotional (e.g., anxiety, attitudes toward learning) and environmental influences (e.g., home literacy and home math environments) – which have been linked to both SES (L. Elliott & Bachman, 2018; Evans & Schamberg, 2009; Y. Jiang et al., 2024) and academic performance (Brumariu et al., 2023; Daucourt et al., 2021; Nag et al., 2024) – should also be considered in future research to deepen our understanding of the mechanisms through which SES shapes cognitive and academic outcomes.

Future studies should also evaluate the efficacy of interventions targeting the cognitive mediators identified in the present study as a means to reduce educational inequalities. Finally, while our findings provide a detailed snapshot of a specific developmental stage – characterized by (i) widening SES disparities (Kieffer, 2012), (ii) the transition from basic skill acquisition to more complex learning (Fuchs et al., 2006), and (iii) increasing differentiation of the cognitive skills supporting reading and mathematics (Fuchs et al., 2016) – future studies should adopt a broader developmental perspective across multiple age groups. Such an

approach would help determine which cognitive factors are most critical for addressing SES-related disparities in reading and mathematics at different stages of development.

2.4.6. Conclusion

In conclusion, this study provides novel insights into the cognitive factors linking SES to academic achievement. In reading, domain-specific skills – including phonological awareness, oral language, and visual-attention span – were found to mediate the SES-reading relationship. In mathematics, both working memory and transcoding abilities mediated the link between SES and mathematical performance. These findings suggest that interventions aimed at reducing SES-related disparities should be tailored to each academic domain, prioritizing domain-specific skills for reading, while adopting a combined approach that targets both domain-general and domain-specific abilities for mathematics.

Overall, this first experimental study provides evidence that SES is significantly associated with various reading and mathematics outcomes in third-grade children, suggesting that children from low-SES backgrounds may be at greater risk of poor academic achievement than their higher-SES peers. The findings further indicate that cognitive factors may contribute to these SES-related achievement gaps, highlighting their potential as targets for interventions aimed at reducing educational inequalities.

Moreover, emotional factors, such as MA, have also been shown to negatively affect mathematics performance. However, it remains unclear whether such effect persists after accounting for SES, and whether cognitive factors may likewise mediate the relationship between MA and mathematics – questions that will be addressed in the subsequent study.

3. Study 2: Math anxiety and mathematics achievement: The mediating role of cognitive factors

This study led to a manuscript:

Taieb, E., Borst, G., Le Stanc, L., Houdé, O., Altarelli, I.*, & Iuculano, T.* (accepted). Domain-general and domain-specific cognitive factors mediating the relationship between math anxiety and mathematical performance in primary school children. *Scientific Reports*.

This study investigated the relationship between math anxiety (MA) and different mathematics outcomes in third-grade children, while accounting for SES. We hypothesized that MA would predict mathematics performance beyond the effects of SES, and that cognitive factors could serve as mediators in this relationship. Employing structural equation modeling (SEM), we examined whether domain-specific, domain-general, or a combination of both types of cognitive factors contribute to the link between MA and mathematics.

3.1. Introduction

Proficiency in mathematics is essential in modern society and constitutes a strong predictor of both academic and professional success (Duncan et al., 2007; Parsons & Bynner, 2005). Math anxiety (MA) – defined as feelings of tension, apprehension, or fear experienced during mathematical activities (Ashcraft, 2002) – represents a significant barrier to mathematical performance. A substantial body of research has demonstrated the detrimental impact of MA on mathematics across developmental stages (Barroso et al., 2021; Caviola et al., 2022; Namkung et al., 2019; J. Zhang et al., 2019) and cultural contexts (OECD, 2023). Nevertheless, the mechanisms through which MA interferes with different aspects of mathematical performance remain insufficiently understood. This issue is particularly relevant in the early years of formal schooling – a critical learning stage during which early mathematical difficulties can cascade into pervasive, long-term educational challenges (Andersson, 2010).

Prior research in primary school children has shown that MA can affect various mathematical outcomes, including word problem-solving (Wu et al., 2012), calculation (Commodari & La Rosa, 2021; Wu et al., 2012), and math fluency (Sorvo et al., 2017). However, these three mathematical skills have not been concurrently analyzed within a single cohort, leaving the specific contribution of MA to each mathematical outcome unclear. In adults, more comprehensive approaches indicate that MA negatively impacts math fluency but not word problem-solving (Braham & Libertus, 2018; Silver et al., 2022). Findings regarding calculation skills remain inconsistent, as some studies report an effect of MA on calculation (Silver et al., 2022), whereas others do not (Braham & Libertus, 2018). Importantly, previous studies often relied on separate statistical models for each mathematical outcome, thereby overlooking the covariance between mathematical variables and limiting the possibility to disentangle the unique effects of MA on each of these skills. Addressing these limitations by simultaneously analyzing multiple mathematical outcomes within an integrated framework is crucial for a more precise understanding of the MA-mathematics link and the cognitive processes that may contribute to it. Furthermore, applying this approach to primary school children constitutes a novel contribution, as such investigations have not previously been conducted within this developmental period.

3.1.1. MA and domain-general cognitive factors

Thus far, research investigating the links between MA and mathematical performance has predominantly focused on domain-general skills, particularly highlighting working memory

as a key mediator (Caviola et al., 2022; Finell et al., 2022). This finding is consistent with the Processing Efficiency Theory (Eysenck & Calvo, 1992), which posits that anxiety – as sometimes experienced in mathematical contexts – can impose an additional cognitive load on working memory resources, thereby hindering mathematical performance (Ashcraft, 2002). Evidence also indicates that adults with high MA may struggle to inhibit irrelevant information (Hopko et al., 2002; Núñez-Peña & Campos-Rodríguez, 2024; Suárez-Pellicioni et al., 2013; Van den Bussche et al., 2020), efficiently switch between different types of arithmetic problems (González-Gómez et al., 2023), and may display an attentional bias toward mathematical content (J. Liu et al., 2019; Rubinsten et al., 2015). However, only a few studies have comprehensively examined whether multiple domain-general skills – including working memory, inhibition, cognitive flexibility, and selective attention – could mediate the relationship between MA and mathematics. Among these, one study in adults found that working memory was the only executive function mediating the MA-mathematics link (Pelegrina et al., 2024), whereas research with adolescents identified cognitive flexibility as a key mediator (Živković et al., 2022). Moreover, Orbach et al. (2020) reported that, in fourth- and fifth-grade children, MA was associated with increased inattention, which negatively impacted working memory and, subsequently, mathematics achievement, suggesting a serial mediation pathway. Yet, no study to date has integrated all these domain-general skills into a single, unified mediation model.

3.1.2. MA and domain-specific cognitive factors

Research investigating domain-specific cognitive skills as potential mediators of the relationship between MA and mathematical performance remains limited. In adults, Skagerlund et al. (2019) reported that symbolic comparison abilities, together with working memory, mediated the link between MA and arithmetic calculation, although other cognitive skills were not examined. In contrast, research with first- to third-grade children found that the association between MA and overall mathematics achievement was not mediated by magnitude processing, whether symbolic or non-symbolic, but was solely mediated by working memory (Szczygieł, 2021). To date, the mediating role of a broad set of domain-specific skills in the relationship between MA and distinct mathematical outcomes – namely, word problem-solving, calculation, and math fluency – has not been thoroughly examined. Importantly, other domain-specific abilities shown to be significantly influenced by MA, such as number ordering (Colomé & Núñez-Peña, 2021; Dubinkina et al., 2023; Skagerlund et al., 2024) and ANS acuity (Guzmán et al., 2021; Lindskog et al., 2017), have not been considered

in previous research. Finally, the potential mediating role of transcoding skills – despite their established importance for successful mathematics development (Banfi et al., 2022; Göbel et al., 2014; Habermann et al., 2020) – remains unexplored.

3.1.3. Current study

Overall, to date, no study has comprehensively examined the cognitive factors mediating the link between MA and distinct mathematical outcomes using an integrated approach that simultaneously considers both domain-general and domain-specific pathways. Furthermore, although evidence suggests that the relationship between MA and mathematical performance may already be shaped by factors such as SES (Guzmán et al., 2021) and sex (Erturan & Jansen, 2015; Van Mier et al., 2019) as early as primary school, these influences have not been systematically accounted for as potential confounders in prior research. Moreover, distinguishing the effects specific to MA from those related to more general forms of anxiety is essential for better understanding how MA specifically relates to mathematical performance (Doz et al., 2024; S. Song et al., 2023; Z. Wang et al., 2015; Wu et al., 2012).

The present study aims to address these gaps in the literature by examining, for the first time and within a narrow age range of third graders: (i) the impact of MA on three core and distinct areas of mathematics – namely, word problem-solving, calculation, and math fluency; and (ii) the extent to which both domain-general and domain-specific cognitive skills mediate the relationship between MA and these mathematical outcomes. Focusing on third grade is particularly relevant, as this developmental stage marks both a key transition from basic to more complex mathematical learning (Qin et al., 2014) and a critical period in MA development (Wu et al., 2012), making it a pivotal window for investigating its cognitive correlates. Using structural equation modeling (SEM), we examined whether domain-general, domain-specific, or both types of cognitive factors mediate the link between MA and distinct mathematical outcomes, while accounting for various confounding factors including general anxiety, SES, sex, age, month within the academic year, and nonverbal IQ.

3.2. Methods

3.2.1. Participants

The sample of this study comprised all participants described in Section 1.1. of the General Methodology, totaling 472 third graders (245 girls, 227 boys; M_{age} = 102.6 months,

SD_{age} = 4.7 months, range = 92–113 months) from elementary schools in Paris and its surrounding areas. All participants had normal vision and hearing, no history of neurological or neurodevelopmental disorders, had not repeated or skipped a grade, demonstrated sufficient mastery of French, and a had nonverbal IQ greater than 2 *SD* below the age norm.

3.2.2. Procedure

The procedure for the current study is described in detail in Section 1.2. of the General Methodology. Importantly, children were tested individually across four experimental sessions, each lasting approximately 30 minutes, with an average interval of one week between sessions. With regard to the present study, mathematics performance was assessed in session 1, domain-general cognitive skills in session 2, and domain-specific cognitive skills together with MA and general anxiety in session 4. Demographic and SES information was additionally collected through a parental questionnaire (see Appendix 1).

3.2.3. Measures

The main measures used in the present study included assessments of mathematics achievement, cognitive abilities, and MA. Detailed descriptions of these measures are provided in Section 1.3. of the General Methodology.

Mathematics achievement was assessed using measures of word problem-solving, calculation, and math fluency. Calculation was modeled as a latent variable (Bollen, 2002), based on mental and written calculation tasks.

Cognitive abilities were assessed across both domain-general and domain-specific skills. For domain-general skills, we evaluated verbal and visual working memory (used as indicators of a latent working memory variable), inhibition, cognitive flexibility, and selective attention. Domain-specific skills comprised transcoding, symbolic comparison, number ordering, and non-symbolic comparison of small and large quantities. Transcoding was modeled as a latent variable, with Arabic number writing and Arabic number reading as indicators.

MA was assessed using a self-report questionnaire in which children indicated how nervous they would feel in different math-related situations.

Finally, several **covariates** were included to account for potential confounding effects, including sex, age, testing month, nonverbal IQ, SES, and general anxiety. Sex was coded as –0.5 for boys and 0.5 for girls. Age was coded continuously in months. Furthermore, because

children were tested at different time points throughout the school year, the timing of assessment could have influenced performance beyond age effects (Morrison et al., 2019). To address this, the month of testing (coded from 1 = September to 11 = July) was included as a covariate. Nonverbal IQ was assessed using the *Matrices* subtest of the WISC-V (Wechsler, 2014), in which children are required to select from five alternatives the visual pattern that completes a logical sequence. SES was computed as a composite PCA score derived from the highest educational and occupational level of either parent. Finally, to ensure that the observed associations were specific to MA (Doz et al., 2024; S. Song et al., 2023; Z. Wang et al., 2015; Wu et al., 2012), we also controlled for general anxiety, assessed via a self-report questionnaire in which children indicated whether different anxiety statements applied to them.

3.2.4. Data analyses

Structural equation modeling (SEM) was conducted to examine the mediating role of cognitive skills in the relationship between MA and mathematical outcomes. SEM enables a comprehensive evaluation of mediation effects by simultaneously estimating multiple relationships and accounting for interdependencies among variables (Gunzler et al., 2013). All variables were standardized prior to inclusion in the SEM model to facilitate interpretation of path coefficients. The Robust Maximum Likelihood (MLR) estimator was used to compute robust standard errors and address non-normality, while missing data were handled via the Full Information Maximum Likelihood (FIML) method. Model fit was assessed using the χ^2 statistic, the Comparative Fit Index (CFI), the Root Mean Square Error of Approximation (RMSEA), and the Standardized Root Mean Square Residual (SRMR), with thresholds for acceptable fit defined as CFI > .95, RMSEA < .08, and SRMR < .10 (Schermelleh-Engel et al., 2003).

The analysis proceeded in two stages. First, a confirmatory factor analysis (CFA) was performed to evaluate the measurement model and assess whether the latent variables adequately represented their observed indicators (Kline, 2016). Factor loadings were freely estimated without constraints on the scaling of latent factors. Second, the SEM mediation model was tested to investigate the relationships between MA and mathematical outcomes through both domain-general and domain-specific cognitive factors (see Appendix 9 for an illustration of the model). Indirect effects were evaluated using 95% percentile bootstrap confidence intervals (CIs) with 5000 iterations (Preacher & Hayes, 2008). Indirect effects are deemed significant when their CI does not include 0. Mediation effect sizes were reported in

terms of both the type of mediation (full or partial) and the magnitude of the indirect effects, as reflected in their standardized coefficients (Rucker et al., 2011).

Data analyses were conducted using R (version 4.2.1., R Core Team, 2022) and the packages lavaan (Rosseel, 2012), occupar (Ferrari, 2019), semhelpinghands (Cheung, 2024), and tidyverse (Wickham et al., 2019).

3.3. Results

3.3.1. Descriptive statistics

Descriptive statistics for all raw observed variables included in the analyses are summarized in Table 6. Bivariate correlations among these variables are reported in Appendix 10.

Variable	N	Mean	SD	Min	Max
Math anxiety					
SEMA score	461	39.37	13.53	20	86
Mathematics achievement					
Word problems	472	6.45	3.24	0	12
Mental calculation	472	29.66	9.01	0	44
Written calculation	461	12.56	3.01	1	21
Math fluency	472	38.96	13.23	6	86
Domain-general cognitive skills					
Digit span backward	472	6.64	1.73	3	12
Digit span ascending	471	6.00	2.03	1	11
Spatial span backward	472	5.37	1.95	0	11
Inhibition	472	33.30	19.42	–17.80	123.80
Cognitive flexibility	470	102.11	40.98	5.20	403.10
Selective attention	471	53.44	13.60	9	107
Domain-specific cognitive skills					
Number dictation	461	13.78	2.64	4	16
Number reading	459	14.83	1.85	4	16

Symbolic comparison	461	39.41	8.08	16	56
Ordering	384	15.27	4.49	1	28
Non-symbolic comparison of small quantities	461	38.23	6.41	18	54
ANS acuity (*w*)	458	0.31	0.25	0.02	3.37
Covariates					
Sex (% of girls)	472	51.91%	_	_	_
Age	472	102.61	4.70	92	113
Testing month	472	6.19	3.22	1	11
Nonverbal IQ	472	13.95	3.15	7	24
Parental education	384	13.56	3.79	0	20
Parental occupation	414	45.50	23.14	14.21	88.70
SES composite (*z* score)	421	0	1	–2.70	1.99
General anxiety	461	11.98	5.99	0	28

Table 6. Descriptive statistics for raw observed variables. For the cognitive measures, lower scores on the Weber fraction (*w*), inhibition, and flexibility tasks indicate better performance. In the inhibition task, scores are adjusted for processing speed using a baseline condition without interference; negative scores indicate that a participant performed better in the inhibition than in the baseline condition (observed in 3 participants). Parental education and occupation, reported here for descriptive purposes, were used solely to compute the SES composite score and were not included as individual covariates in the analyses. ANS = approximate number system; SES = socioeconomic status.

3.3.2. Measurement model (CFA)

A confirmatory factor analysis (CFA) was conducted to evaluate the measurement model and examine whether the latent variables adequately represented their observed indicators. All observed variables exhibited high and significant factor loadings, indicating that the latent variables reliably captured their respective indicators (Table 7). Fit indices for the measurement model suggested a good fit to the data ($\chi^2(11) = 14.283$, $p = .218$, CFI = .997, RMSEA = .024, SRMR = .019) (Schermelleh-Engel et al., 2003).

Latent variable	Indicator	β	SE
Calculation	Mental calculation	0.87	0.05
	Written calculation	0.76	0.05
Working memory	Digit span backward	0.56	0.05
	Digit span ascending	0.60	0.05
	Spatial span backward	0.57	0.05
Transcoding	Number dictation	0.77	0.07
	Number reading	0.72	0.08

Table 7. Loadings of observed variables on latent variables. All coefficients are standardized coefficients and are significant at $p < .001$. SE = standard error.

3.3.3. Structural equation model examining mediation effects

The SEM analysis assessing the influence of MA on the three mathematical outcomes of interest – word problem-solving, calculation, and math fluency – through the tested cognitive variables showed a good fit to the data ($\chi^2(75) = 106.627$, $p = .010$, CFI = .990, RMSEA = .029, SRMR = .017) (Schermelleh-Engel et al., 2003). The results of the model are presented in Figure 6. Comprehensive details regarding all path coefficients, as well as variance and covariance estimates, are provided in Appendix 11.

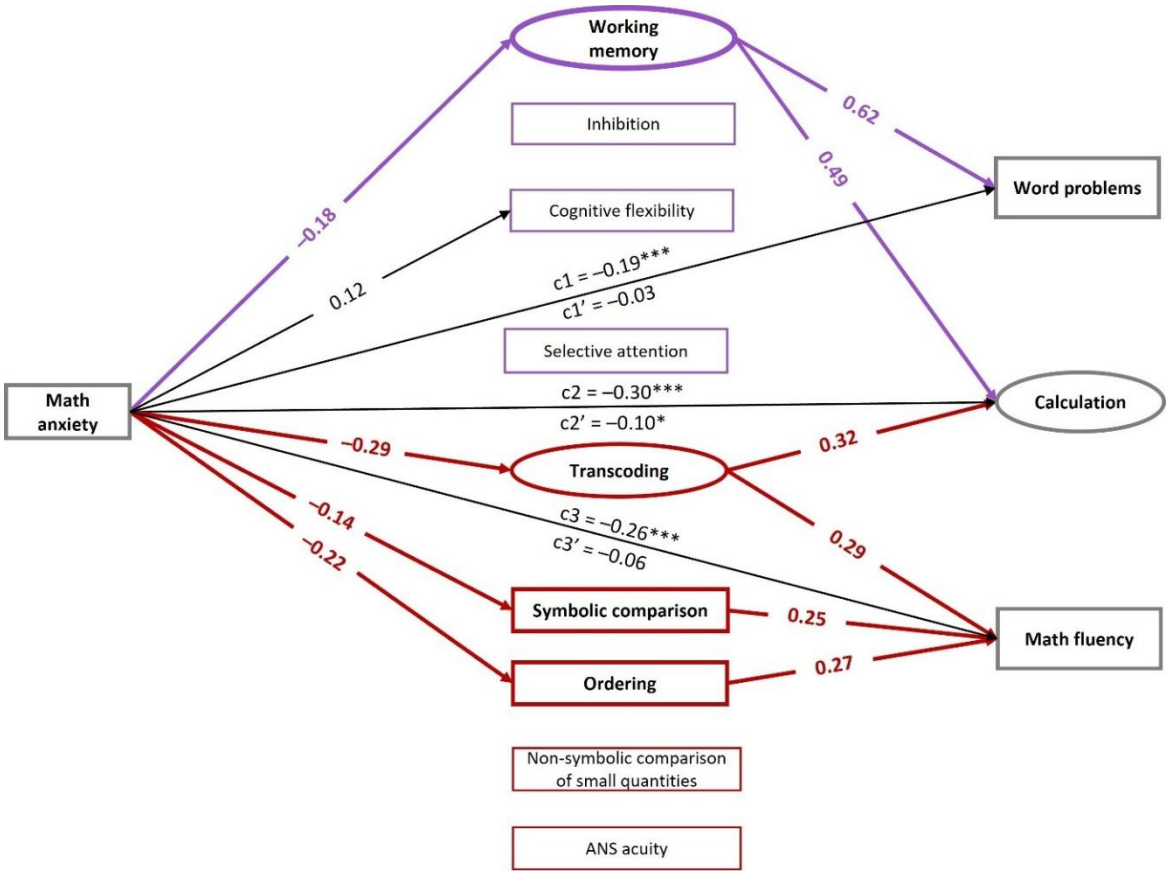

Figure 6. SEM mediation model representing the total, direct and indirect effects of MA on mathematics outcomes. All coefficients are standardized coefficients. Latent variables are shown as ovals and observed variables as squares. Domain-general factors are depicted in purple (upper half) and domain-specific factors in red (lower half). For clarity, covariances, nonsignificant paths, and covariates (including sex, age, testing month, nonverbal IQ, SES, and general anxiety) are not displayed. Total and direct effects are labeled c and c', respectively. Significant mediation effects are bolded. ANS = approximate number system. *p < .05; ***p < .001.

Bivariate associations

The results revealed that the total effect of MA on mathematical outcomes was significant across all three math abilities, including word problem-solving (path c1: β = –0.19, p < .001), calculation (path c2: β = –0.30, p < .001), and math fluency (path c3: β = –0.26, p < .001). Among domain-general cognitive skills, MA significantly predicted working memory (β = –0.18, p = .005) and cognitive flexibility (β = 0.12, p = .030), but not inhibition (β = –0.01, p = .853) or selective attention (β = –0.03, p = .576). Regarding domain-specific cognitive skills, MA

was significantly related to symbolic abilities, including transcoding (β = –0.29, p < .001), symbolic comparison (β = –0.14, p = .007), and number ordering (β = –0.22, p < .001). No significant effects were observed for non-symbolic skills, namely non-symbolic comparison of small quantities (β = –0.02, p = .711) and ANS acuity (β = 0.10, p = .062). With respect to cognitive predictors of mathematical performance, both domain-general and domain-specific skills emerged as significant contributors. Working memory predicted word problem-solving (β = 0.62, p < .001) and calculation (β = 0.49, p = .001). Transcoding was associated with calculation (β = 0.32, p = .001) and math fluency (β = 0.29, p < .001). Finally, symbolic comparison (β = 0.25, p < .001) and number ordering (β = 0.27, p < .001) also predicted math fluency.

Mediation pathways

The analysis of indirect effects (Table 8) indicated that the association between MA and word problem-solving was significantly mediated by working memory. For calculation, both working memory and transcoding skills emerged as significant mediators. In the case of math fluency, symbolic domain-specific skills – specifically transcoding, symbolic comparison, and number ordering – served as mediators. Notably, the direct effects of MA on word problem-solving (path c1': β = –0.03, p = .442) and math fluency (path c3': β = –0.06, p = .139) were no longer significant once the mediating variables were considered, providing evidence of full mediation effects (Rucker et al., 2011). The direct effect of MA on calculation (path c2': β = −0.10, p = .022) remained significant, indicating partial mediation for this outcome.

Mediation paths	Word problems		Calculation		Math fluency	
	β	95% Boot CI	β	95% Boot CI	β	95% Boot CI
MA → Working memory → Math	**–0.11**	**[–0.27, –0.03]**	**–0.09**	**[–0.21, –0.02]**	–0.03	[–0.09, 0.01]
MA → Inhibition → Math	–0.00	[–0.01, 0.01]	–0.00	[–0.01, 0.01]	–0.00	[–0.01, 0.01]
MA → Flexibility → Math	–0.00	[–0.01, 0.02]	–0.00	[–0.02, 0.01]	0.00	[–0.01, 0.02]
MA → Selective attention → Math	0.00	[–0.01, 0.01]	0.00	[–0.01, 0.01]	–0.00	[–0.01, 0.01]
MA → Transcoding → Math	–0.05	[–0.11, 0.03]	**–0.09**	**[–0.18, –0.02]**	**–0.09**	**[–0.16, –0.03]**
MA → Symbolic comparison → Math	0.00	[–0.02, 0.03]	–0.01	[–0.03, 0.02]	**–0.04**	**[–0.07, –0.01]**
MA → Ordering → Math	–0.00	[–0.04, 0.06]	–0.01	[–0.04, 0.05]	**–0.06**	**[–0.10, –0.02]**
MA → Non-symbolic comparison of small quantities → Math	–0.00	[–0.01, 0.01]	–0.00	[–0.02, 0.01]	0.00	[–0.01, 0.01]
MA → ANS acuity → Math	0.00	[–0.01, 0.02]	–0.00	[–0.02, 0.01]	0.00	[–0.01, 0.01]

Table 8. Indirect effects of the SEM mediation model. All coefficients reported are standardized coefficients. Significant mediation effects are bolded. CI = confidence interval; MA = math anxiety; ANS = approximate number system.

3.4. Discussion

The present study aimed at: (i) assessing the effects of MA on three core mathematical abilities, namely word problem-solving, calculation, and math fluency; and (ii) examining the mediating role of both domain-general and domain-specific cognitive skills in the relationship between MA and these outcomes. Crucially, the investigation was conducted within a narrow developmental window, as all participants were third graders, thereby reducing developmental variability and providing a unique snapshot of these associations during a critical stage of both formal math learning (Qin et al., 2014) and MA development (Wu et al., 2012). To address these objectives, we constructed a comprehensive multiple mediation model using SEM, which simultaneously tested the indirect contributions of cognitive skills to

the three mathematical outcomes of interest, while controlling for key covariates, including sex, age, testing month, nonverbal IQ, SES, and general anxiety.

The findings showed that MA negatively affected all three mathematical outcomes – i.e., word problems, calculation, and math fluency. Mediation analyses further revealed that both domain-general and domain-specific cognitive skills contributed to these associations, with mediators differing across outcomes. Specifically, the link between MA and word problem-solving was mediated by working memory. The relationship between MA and calculation was mediated by both working memory and transcoding. Lastly, the association between MA and math fluency was mediated by transcoding, symbolic comparison, and number ordering skills. Notably, non-symbolic skills did not emerge as significant mediators of the MA-mathematics link.

3.4.1. Domain-general mediators of the MA-mathematics relationship

Concerning domain-general cognitive skills, the present findings align with prior meta-analyses identifying working memory as a central mediator of the MA-mathematics relationship (Caviola et al., 2022; Finell et al., 2022). Importantly, this mediation effect emerged only for higher-order mathematical abilities – namely, word problem-solving and calculation – consistent with the Processing Efficiency Theory (Eysenck & Calvo, 1992). This theoretical framework posits that anxiety experienced during cognitively demanding tasks imposes an additional cognitive load on working memory, thereby impairing performance. In line with this interpretation, working memory mediated the link between MA and mathematics only for tasks that place high demands on working memory resources (Ashcraft, 2002; Dowker et al., 2016) – i.e., calculation and word problem-solving – but not for math fluency, which primarily relies on the retrieval of arithmetic facts from long-term memory, at least in typically developing children of this age (Gliksman et al., 2022).

Notably, other domain-general skills – such as inhibition, cognitive flexibility, and selective attention – did not emerge as mediators of the relationship between MA and mathematical outcomes. This pattern may partly reflect the predominant role of working memory among several domain-general skills in predicting mathematics achievement at this developmental stage (Spiegel et al., 2021; Van der Ven et al., 2012). Indeed, only working memory was significantly associated with mathematical performance – specifically, in word problems and calculation – whereas the other domain-general skills showed no significant relationships (see Figure 6 and Appendix 11). Nevertheless, inhibition and cognitive flexibility

may become more important at later stages of development, especially during more advanced mathematics learning, which requires the adoption of adaptive strategies and the ability to overcome potential biases induced by prior knowledge (Gómez et al., 2015; McGowen & Tall, 2013; Roell et al., 2017).

Such developmental dynamics could explain why cognitive flexibility – but not working memory – emerged as a mediator in the MA-mathematics relationship in adolescents aged 11 to 14 in a previous study (Živković et al., 2022). However, this contrasting finding may also reflect task differences, as the mathematics assessment in that study included an inference task which potentially placed greater demands on cognitive flexibility. Similarly, the absence of a relationship between MA and inhibition in the present study may be attributable to task-specific features, as our inhibition measure (opposite shape-naming) (Korkman et al., 2007) used non-numerical stimuli. Prior research shows that inhibitory deficits in math-anxious individuals are more pronounced with numerical compared to non-numerical stimuli (Hopko et al., 2002; Núñez-Peña & Campos-Rodríguez, 2024), a pattern consistent with the null effect observed in Živković et al. (2022), who employed the same task as ours.

3.4.2. Domain-specific mediators of the MA-mathematics relationship

Regarding the influence of domain-specific cognitive skills on the MA-mathematics relationship, the present findings indicate that all symbolic skills assessed – namely, transcoding, symbolic comparison, and number ordering – served as mediators, depending on the specific mathematical outcome considered. In contrast, non-symbolic skills did not play a mediating role. This pattern aligns with prior studies in adults, suggesting that MA primarily affects symbolic rather than non-symbolic processes (Dietrich et al., 2015; Szczygieł & Sarı, 2024; Zaleznik et al., 2023). One possible explanation is that high levels of MA may elicit fear or aversion toward mathematical symbols, thereby impairing performance on symbol-dependent tasks only. By contrast, non-symbolic processing appears less susceptible to such emotional interference (Barroso et al., 2021; Braham & Libertus, 2018). Notably, the mediating role of symbolic processing skills in the present study emerged only for mathematical tasks involving Arabic digit stimuli, including math fluency and calculation, but not for word problem-solving. This finding is consistent with previous research (Skagerlund et al., 2019) and supports the idea that basic number processing mainly underpins these aspects of arithmetic, whereas word problem-solving relies more strongly on working memory resources (Schneider et al., 2017; Skagerlund et al., 2019).

3.4.3. Combined contribution of domain-general and domain-specific mediators

Overall, our results indicate that the impact of MA on mathematical performance is mediated by both domain-general (i.e., working memory) and domain-specific (i.e., symbolic processing) cognitive factors. These findings align with research in adults reporting similar mediation effects (Skagerlund et al., 2019) and extend them by showing that these effects remain robust even when multiple other domain-general and domain-specific cognitive factors are considered. However, our results diverge from those of a previous study in primary school children, which found that while working memory mediated the relationship between MA and mathematics, domain-specific factors such as symbolic comparison did not (Szczygieł, 2021). A potential explanation for this discrepancy may lie in the mathematical measures used in that study, which did not differentiate between distinct mathematical outcomes (i.e., word problems, calculation, and math fluency), possibly obscuring the nuanced contributions of domain-specific skills.

3.4.4. Educational implications

The present study advances our understanding of how MA influences different aspects of mathematical performance during a critical phase of both formal math learning (Qin et al., 2014) and MA development (Wu et al., 2012). These findings indicate that the association between MA and mathematical performance is already evident by third grade and that cognitive factors contribute to this relationship. This underlines the importance of early interventions to prevent long-term negative academic and professional outcomes (Beilock & Maloney, 2015). Moreover, the results suggest that targeted cognitive interventions aimed at enhancing working memory and symbolic skills could help mitigate the adverse effects of MA on mathematics achievement (Sammallahti et al., 2023). For example, combined training in working memory and symbolic skills has been shown to significantly improve mathematical performance in children aged 5 to 7 (DePascale et al., 2024). Although that study did not assess MA, it raises the possibility that strengthening these domain-general and domain-specific cognitive skills may indirectly counteract the detrimental effects of MA on mathematical performance.

3.4.5. Limitations and future directions

The present study has several limitations that should be acknowledged. First and foremost, its correlational design precludes any causal interpretation of the observed relationships. Longitudinal studies are needed to clarify the causal pathways between MA and subsequent mathematical performance. Furthermore, the debated directionality of this relationship (i.e., whether MA influences mathematics or vice versa) (Carey et al., 2016) highlights the need to examine the reverse pathway as well. While the current study was not designed to robustly test bidirectional effects, future research should investigate whether children with lower domain-general or domain-specific skills are more likely to develop poorer mathematical proficiency and, in turn, higher MA. Interventional studies are also necessary to clarify causality and determine whether targeted training of working memory and symbolic skills can effectively mitigate the detrimental impact of MA on mathematical performance in primary school children. Moreover, although restricting the sample to third graders was a strength – providing a homogeneous developmental window and a precise snapshot of how MA relates to mathematics during a key transition in primary school (Qin et al., 2014; Wu et al., 2012) – it also limits the generalizability of the findings. Future cross-sectional or longitudinal research including multiple age groups is needed to examine how these relationships evolve across different developmental stages.

Furthermore, a limitation of the present study is that we did not assess the strategies that children used to solve the mathematical tasks. As a result, it remains unclear how high MA, in interaction with cognitive abilities, may shape the adoption of different or less effective approaches and thereby contribute to poorer mathematics performance (Caviola et al., 2017; Chang & Beilock, 2016; Ramirez et al., 2016). Future research incorporating detailed problem-solving protocols or think-aloud procedures would provide a more comprehensive mechanistic account of how MA influences mathematical performance, complementing the mediation pathways identified in the present study.

Lastly, the present study focused exclusively on cognitive mediators, leaving other potentially influential factors unexplored. Notably, the relationship between MA and calculation was only partially mediated by working memory and transcoding, suggesting that other factors may be involved. For example, emotional factors such as mathematics self-concept (Justicia-Galiano et al., 2017) and environmental influences such as participation in mathematical extracurricular activities (S. Song et al., 2023) are also likely to contribute to the link between MA and mathematics achievement. Considering these dimensions in future research would enable a more comprehensive understanding of the multifaceted pathways underlying the relationship between MA and mathematical outcomes.

3.4.6. Conclusion

In conclusion, the present study deepens our understanding of the association between MA and mathematics achievement in primary school children by demonstrating its pervasive impact on different key mathematical outcomes, including word problem-solving, calculation, and math fluency. Critically, the findings highlight the mediating roles of both domain-general skills – particularly working memory – and domain-specific skills – including symbolic processing – in this relationship. Together, these results underline the potential of targeted interventions designed to strengthen these cognitive skills to support children experiencing high MA during the early years of formal schooling.

Overall, this study demonstrated that MA significantly affects mathematics performance and that cognitive factors may contribute to this relationship. Importantly, the findings indicate that MA influences mathematics outcomes above and beyond the effects of SES. Consequently, when SES is held constant, children with higher levels of MA perform more poorly in mathematics than their peers with low MA. These results underline the importance of jointly considering environmental, emotional, and cognitive dimensions to build a more comprehensive understanding of the factors shaping academic achievement.

Thus far, the first two studies of this thesis have adopted a dimensional approach, examining the full sample of participants – including children with varying levels of achievement – to investigate the contribution of different types of factors to academic performance. The findings suggest that children from low-SES backgrounds and those experiencing high MA may be at heightened risk of poor academic outcomes, with cognitive factors potentially playing a role in these associations. Building on this, it is crucial to focus more closely on children with poor academic performance. Given that low-achieving children represent a heterogeneous group, particular attention should be paid to interindividual variability in their profiles. The next two studies of this thesis therefore adopt such an approach.

4. Study 3: Cognitive profiles of poor readers and poor mathematics achievers

This study examined the heterogeneity of cognitive profiles among children with poor academic performance in reading or mathematics. We hypothesized that distinct cognitive subtypes would emerge within each group. Using latent profile analysis (LPA), we investigated whether different combinations of domain-specific and domain-general weaknesses characterize subgroups of poor readers and poor mathematics achievers.

4.1. Introduction

Academic proficiency in reading and mathematics during elementary school represents a critical foundation for subsequent academic achievement (Duncan et al., 2007), as well as for broader life outcomes, including quality of life and socioeconomic attainment in adulthood (Mulcahy et al., 2016; Ritchie & Bates, 2013). Nevertheless, a substantial proportion of children experience poor academic performance, falling below age expectations in reading or mathematics. Recent large-scale international assessments, such as PIRLS 2021 and TIMSS 2023, reported that, on average, 22% of European fourth-grade students performed below proficiency levels in reading comprehension (Conceiçao et al., 2023) and 26% in overall mathematics (Cioldi & Raffy, 2024). Importantly, such difficulties are also evident earlier at the level of more foundational skills. For instance, national evaluations conducted in France in 2024 indicated that approximately 30% of second- and third-grade children demonstrated poor decoding abilities in reading, while up to 50% displayed weak calculation skills (Desclaux et al., 2025; Evrard et al., 2025). These findings are particularly concerning as such competencies constitute prerequisites for more advanced reading and mathematical learning (Fuchs et al., 2016). Furthermore, because most of these children do not meet diagnostic criteria for specific learning disorders – owing to the relatively less severe nature of their difficulties – they often fail to receive targeted support from which they may nonetheless benefit (Billard & Barbe, 2016; J. G. Elliott, 2020; X. Zhang et al., 2020).

It is therefore essential to deepen our understanding of the underlying sources of poor performance in foundational reading and mathematical skills during primary school. Among the factors associated with low achievement in these domains, cognitive processes have received particular attention. Notably, challenges in domain-specific abilities – such as phonological awareness and RAN in the reading domain (Hulme & Snowling, 2013), as well as symbolic and non-symbolic number processing in the mathematics domain (Geary, 2013) – are among the most consistently reported cognitive weaknesses in children with reading and mathematics difficulties, respectively. In addition to these domain-specific factors, impairments in domain-general processes, including executive functions, have also been observed in children struggling with reading (Booth et al., 2010; Peng et al., 2022) and mathematics (Peng, Wang, & Namkung, 2018). Yet, most studies to date have examined low-performing populations at the group level, typically contrasting poor readers or poor mathematics achievers with control groups of average-performing peers. While such an approach is valuable for identifying broad patterns of weaknesses, it fails to capture the

interindividual variability that characterizes struggling learners (Astle et al., 2024; Huijsmans et al., 2020). Indeed, evidence indicates that both poor readers and poor mathematics achievers do not constitute homogeneous groups but rather display marked heterogeneity in their cognitive profiles – even when they present comparable levels of poor reading or mathematics achievement.

4.1.1. Cognitive heterogeneity among poor readers

While previous research has consistently highlighted phonological deficits among children with reading difficulties (Melby-Lervåg et al., 2012), studies focusing on interindividual variability indicate that such impairments characterize only a subset of struggling readers, whereas others may primarily exhibit visual or visuo-attentional weaknesses (Bosse et al., 2007; J.-R. Cho & Ji, 2011; Valdois et al., 2021; White et al., 2006). For instance, Valdois et al. (2021) investigated the prevalence of deficits in phonological awareness, RAN, and visual-attention span among French sixth-grade poor readers. Their findings revealed that most struggling readers exhibited an isolated deficit in one of these three skills – 20% in phonological awareness, 15% in RAN, and 18% in visual-attention span – even though, at the group level, they scored significantly lower than average readers across all three abilities. Moreover, 23% of poor readers showed deficits in two of the three skills, while 4% presented impairments in all three. Notably, 20% did not display any weaknesses in these abilities, suggesting that their reading difficulties may be associated with other factors not assessed in this study.

Only a limited number of studies have examined the variability of cognitive profiles among poor readers considering domain-general factors. Some research using data-driven approaches, such as cluster analyses, has nonetheless identified subgroups of poor readers with working memory weaknesses, often accompanied by domain-specific impairments such as in phonological awareness or RAN (Willems et al., 2016). However, it remains unclear whether certain profiles of poor readers may also be characterized by weaknesses in other executive functions, including inhibition or cognitive flexibility. This underlines the importance of jointly integrating domain-specific and domain-general factors to better capture the cognitive heterogeneity of poor readers and achieve a more comprehensive understanding of potential cognitive subtypes within this population.

4.1.2. Cognitive heterogeneity among poor mathematics achievers

Similar to findings in reading, research indicates that children with poor mathematics performance do not constitute a homogeneous group, as diverse cognitive profiles have been observed in this population. Notably, cluster analyses conducted in primary school children with low mathematics achievement suggest that only about 10–15% exhibit deficits in ANS acuity, traditionally regarded as a core deficit underlying mathematical difficulties (Bartelet et al., 2014; W. W. L. Chan & Wong, 2020). Other subgroups have instead been characterized by weaknesses in symbolic number processing or visuospatial abilities (Bartelet et al., 2014; W. W. L. Chan & Wong, 2020). Interestingly, W. W. L. Chan and Wong (2020) identified a subgroup of second-grade students presenting solely working memory deficits, a profile that had not emerged in the same children a year earlier, when they were in first grade, indicating that domain-general weaknesses may become more apparent with development. Finally, some subtypes of poor mathematics achievers have been reported to display no apparent cognitive impairments (Bartelet et al., 2014; W. W. L. Chan & Wong, 2020), suggesting that their difficulties may be associated with other, unexplored, dimensions.

To our knowledge, no study has yet thoroughly examined the cognitive profiles of poor mathematics achievers while considering different executive function components. Nevertheless, research conducted on unselected samples of children with varying levels of mathematical performance indicates that poor mathematics achievement does not correspond to a single cognitive profile. Instead, it may manifest in profiles characterized by working memory weaknesses combined with deficits in either cognitive flexibility or inhibition (Carriedo et al., 2024). These findings highlight the importance of investigating various domain-general abilities alongside domain-specific processes when characterizing the cognitive profiles of children with poor mathematics achievement.

4.1.3. Current study

While a substantial body of research has examined the cognitive characteristics of children struggling with reading or mathematics at the group level, relatively few studies have investigated interindividual differences among poor readers and poor mathematics achievers. Furthermore, among the studies that have adopted such an approach, none has comprehensively integrated both domain-specific and domain-general cognitive factors to characterize the diversity of cognitive weaknesses within these populations.

Considering variability in the cognitive profiles of poor academic achievers is crucial for several reasons. First, if similar academic difficulties are associated with distinct cognitive

profiles, interventions should be tailored to each child's specific profile, as targeting a cognitive skill that is not impaired in a given child is unlikely to be effective (Carroll et al., 2016; Ouyang et al., 2024; Valdois et al., 2021; White et al., 2006). For example, Zhao et al. (2019) reported that visual-attention span training improved reading performance only in dyslexic children with a deficit in this ability, but not in those with a phonological awareness deficit. Second, understanding this heterogeneity is essential because interventions may need to differ depending on whether a child exhibits a deficit in a single cognitive skill or impairments across multiple skills. Children with broader cognitive weaknesses are likely to benefit more from interventions that comprehensively target multiple cognitive abilities. Finally, examining interindividual variability may help clarify the mechanisms underlying response to interventions, providing insight into why some children may fail to benefit from support that is effective for others (Carroll et al., 2016; Younger et al., 2024). Moreover, uncovering the diverse cognitive profiles associated with poor reading and mathematics achievement can shed light on the multiple fundamental cognitive building blocks that underpin learning in these domains.

Building on this perspective, the present study aims to investigate the existence of distinct cognitive profiles among third-grade poor readers and poor mathematics achievers. Importantly, the study adopts a comprehensive approach, integrating both domain-specific and domain-general cognitive factors to capture the aforementioned heterogeneity. Third grade was selected because academic difficulties in fundamental reading and mathematical skills, such as decoding and calculation, are likely to persist over time rather than reflecting mere developmental delays at this stage (Andersson, 2010; Billard et al., 2010; Smart et al., 2005), underlining the importance of identifying supports that may be most effective for specific subtypes of children at this age. To this end, latent profile analysis (LPA) – a person-centered approach allowing for the detection of homogeneous subgroups within a population based on shared characteristics across individuals (Gana et al., 2022; Spurk et al., 2020) – was employed to examine whether particular combinations of domain-specific and domain-general weaknesses define distinct profiles among poor readers and poor mathematics achievers.

4.2. Methods

4.2.1. Participants

The sample for this study comprised the participants described in Section 1.1 of the General Methodology, namely third-grade students enrolled in elementary schools in Paris and its surrounding areas. A total of 472 children met the project's inclusion criteria, which required normal vision and hearing, absence of neurological or neurodevelopmental disorders, no grade repetition or skipping, sufficient mastery of French, and a nonverbal IQ above 2 *SD* below the age norm. Of these, nine children were excluded from the present analyses due to missing data on all domain-specific cognitive variables, resulting from absence during the corresponding test sessions. Since LPA cannot be conducted with incomplete datasets, and imputing more than 50% of the missing values for these children would not have been reliable (Junaid et al., 2025), these participants were not retained. The current sample therefore consists of 461 participants (241 girls, 220 boys; M_{age} = 102.5 months, SD_{age} = 4.7 months, range = 92 – 113 months). Importantly, the nine excluded participants did not differ from children who completed all testing sessions in terms of sex, nonverbal IQ, and SES. The only difference was that the excluded participants were on average 3.5 months older ($t(10.43) = -2.43$, $p = .043$), likely because many of them missed testing sessions at the very end of the school year due to leaving early for summer holidays, making it impossible to complete the remaining testing sessions.

Two subgroups of poor readers and poor mathematics achievers were identified within this sample. Children were classified as poor readers if they scored at or below the 30th percentile of the total sample on a composite measure of reading fluency, adjusted for age and testing month. Similarly, poor mathematics achievers were defined as those scoring at or below the 30th percentile of the total sample on a composite measure of calculation skills, likewise adjusted for age and testing month. According to these criteria, 139 participants were classified as poor readers and 139 as poor mathematics achievers. Notably, 69 children (49.64%) met criteria for poor performance in both academic domains. These participants were included in both the analyses of poor readers and of poor mathematics achievers, with this overlap examined in the analyses and subsequently discussed. For each set of analyses, the remaining participants who did not meet the poor performance criterion served as control groups of average readers (N = 322) and average mathematics achievers (N = 322), respectively.

These methodological decisions were guided by several considerations. First, although classifying children into low-performing groups based on standardized test norms would have been ideal, this option was not retained because the standardizations for the reading and mathematics test batteries dated back approximately 15–20 years, relied on relatively small

samples of 50–100 participants per age group (Jacquier-Roux et al., 2010; von Aster & Dellatolas, 2006), and, for the *Calculation* and *Math Fluency* subtests of the WJ-III battery (Woodcock et al., 2001), were not available for French participants. Second, the choice of the 30th percentile as a selection threshold was deliberately liberal, consistent with the aim of this study to focus on poor performers rather than specifically on children with severe reading or mathematics difficulties (Grills et al., 2023; Mammarella et al., 2018; Matejko et al., 2023; Wanzek et al., 2021), and in line with prevalence estimates of low academic performance in France at this age (Desclaux et al., 2025). Finally, composite measures of reading and mathematics were based solely on foundational skills – namely, decoding and calculation – rather than incorporating higher-level abilities such as reading comprehension or word problem-solving. This decision was intended to enhance the homogeneity of academic difficulties within each low-performing group and is supported by evidence that the cognitive processes underlying decoding and calculation may differ from those supporting higher-order comprehension and problem-solving skills (Cadime et al., 2024; Fuchs et al., 2008, 2010; Johann et al., 2020; W. Zhang et al., 2025), a pattern also observed in Studies 1 and 2 of this thesis.

4.2.2. Procedure

The procedure for the current study is described in greater detail in Section 1.2. of the General Methodology. Notably, children were tested individually across four experimental sessions, each lasting approximately 30 minutes, with an average interval of one week between sessions. Regarding the present study, academic performance in reading and mathematics was assessed in Session 1. Domain-general cognitive skills were measured in Session 2, while domain-specific cognitive skills related to reading and mathematics were evaluated in Sessions 3 and 4, respectively. Additionally, sociodemographic information was collected via a parental questionnaire (see Appendix 1).

4.2.3. Measures

The current study included measures of academic achievement, cognitive abilities, as well as SES and demographic variables. Detailed descriptions of these measures are provided in Section 1.3. of the General Methodology.

Academic achievement was assessed in both reading and mathematics. In the reading domain, reading fluency was evaluated using four measures: text reading, irregular word

reading, regular word reading, and pseudoword reading fluency. A composite reading fluency score based on these four indicators was computed via principal component analysis (PCA) by extracting the individual factor loadings from the first component, which accounted for 84% of the total variance (see Appendix 12 for further details). In mathematics, calculation performance was assessed through measures of mental and written calculation, as well as math fluency. A composite calculation score was similarly derived from these three indicators using PCA by extracting the individual factor loadings from the first component, accounting for 76% of the total variance (see Appendix 12).

Regarding **cognitive abilities**, because the current study focused on smaller subsets of participants (139 poor readers and 139 poor mathematics achievers), we limited the number of cognitive factors included in the analyses to three domain-general and three domain-specific variables in each case. This choice was made to avoid overparametrization of the LPA models and is consistent with previous LPA studies conducted on comparable sample sizes (Kißler et al., 2021; Scalise et al., 2021). The selection of variables was guided by both theoretical and empirical considerations, which are detailed below.

For ***domain-general abilities***, we included measures of the three core executive functions – working memory, inhibition, and cognitive flexibility (Diamond, 2013; Friedman & Miyake, 2017) – because (i) they are the most consistently associated with both reading and mathematics outcomes (Cortés Pascual et al., 2019; Spiegel et al., 2021), and (ii) selective attention, as measured by a visual search task, was not related to any academic outcomes or predictors examined in Studies 1 and 2 of this thesis (see Figures 4–6).

For ***reading-related domain-specific abilities***, we selected phonological awareness, RAN, and visual-attention span, because (i) these skills are primarily associated with decoding – the reading component defining our group of poor readers – whereas oral language is more closely linked to reading comprehension (Araújo et al., 2015; Bianco et al., 2012; Bosse & Valdois, 2009; Muter et al., 2004; Valdois et al., 2019), a pattern also observed in Study 1 of this thesis (see Figure 4); and (ii) they are the most frequently used variables in studies investigating cognitive subtypes of poor decoders (Dębska et al., 2022; Valdois et al., 2021), while oral language is predominantly examined in research on poor comprehenders (Capin et al., 2021; James et al., 2023).

For ***mathematics-related domain-specific abilities***, we included transcoding, symbolic comparison, and ANS acuity, because (i) deficits in these skills are among the most consistently reported in children struggling with mathematics (De Smedt et al., 2013; Haberstroh & Schulte-

Körne, 2022; Kivirähk-Koor & Kiive, 2025; Schwenk et al., 2017), and (ii) non-symbolic comparison of small quantities and number ordering were highly correlated with symbolic comparison (*r* = .76 and .56, respectively) – likely reflecting task format similarities within the Numeracy Screener battery (Hutchison et al., 2022; Lafay et al., 2018; Nosworthy et al., 2013) – which could have introduced instability or bias in the LPA parameter estimates (Nylund-Gibson & Choi, 2018; Sinha et al., 2021).

Among these cognitive variables, composite PCA scores were computed for constructs assessed by multiple subtests – namely, working memory, phonological awareness, and transcoding (see Appendix 12).

Finally, **demographic and SES variables**, along with **nonverbal IQ**, were used to describe the groups of poor readers and poor mathematics achievers, and to examine potential differential characteristics between the profiles emerging within each group. These variables included sex, age (in months), nonverbal IQ, and SES. Nonverbal IQ was assessed using the *Matrices* subtest of the WISC-V (Wechsler, 2014), in which children are required to select from five alternatives the visual pattern that completes a logical sequence. SES was operationalized as a PCA composite score based on the highest educational and occupational level of either parent (see Appendix 12).

4.2.4. Data analyses

Within the study sample (N = 461), nine participants (1.95%) had missing data on one cognitive variable due to technical issues during testing. As LPA requires complete datasets, these missing values were imputed using the missForest package in R (Stekhoven & Bühlmann, 2012). This non-parametric method, based on random forests, predicts missing values from all other available data without imposing distributional assumptions (Stekhoven & Bühlmann, 2012; Zugarramurdi et al., 2022). To avoid bias in the imputation of cognitive data, academic performance variables were excluded from the imputation procedure (Lavelle-Hill et al., 2024; Zugarramurdi et al., 2022). Following imputation, all academic and cognitive variables were regressed on age and testing month (Morrison et al., 2019), and residuals were extracted for use in the analyses to ensure that observed effects were not confounded by age or timing within the school year (Hart et al., 2016; Valdois et al., 2019; Van Bergen et al., 2017)[1]. All variables were then standardized – with higher *z* scores reflecting better performance – in

[1] Performance on the global report task assessing visual-attention span was additionally residualized on isolated letter recognition to control for potential confounding effects (Bosse & Valdois, 2009; Saksida et al., 2016).

order to limit scale-related effects in LPA estimation (Sinha et al., 2021). Finally, composite indices for reading fluency, calculation, working memory, phonological awareness, and transcoding were derived using PCA (see Appendix 12) and subsequently restandardized (Keenan et al., 2014; Willcutt et al., 2013).

Following data processing, LPA analyses were conducted using the tidyLPA package in R (Rosenberg et al., 2018) to examine the heterogeneity of cognitive profiles within poor readers (Model 1) and poor mathematics achievers (Model 2). LPA is a person-centered approach that, unlike other methods such as cluster analysis, relies on a probabilistic model accounting for uncertainty in profile membership and provides indices of model fit, enabling the selection of the solution that best represents the data (Gana et al., 2022; Nylund-Gibson & Choi, 2018; Sinha et al., 2021; Spurk et al., 2020; Weller et al., 2020). For each model, solutions with one to six latent profiles were evaluated, consistent with previous studies conducted on similar sample sizes (N. Ding et al., 2024; Kim et al., 2021; Scalise et al., 2021).

The optimal number of profiles was determined based on multiple criteria, including the Bayesian Information Criterion (BIC)**,** Akaike Information Criterion (AIC)**,** Bootstrap Likelihood Ratio Test (BLRT), entropy, minimum posterior probability of profile membership, proportion of participants per profile, and theoretical interpretability (Nylund et al., 2007; Sinha et al., 2021; Spurk et al., 2020; Weller et al., 2020). Specifically, lower BIC and AIC values indicate better model fit (Sinha et al., 2021; Weller et al., 2020). The BLRT evaluates whether a model with *k* profiles fits the data significantly better than a model with *k-1* profiles (Nylund et al., 2007). To ensure reliability, it is further recommended that entropy – reflecting classification accuracy – exceeds .60, that the minimum posterior probability of profile membership is at least .80, and that each profile comprises at least 5% of the sample (Weller et al., 2020). Finally, theoretical interpretability of profiles was also considered in model selection (Nylund-Gibson & Choi, 2018; Weller et al., 2020).

Model selection further involved comparing different parameterizations of the variance-covariance matrix of profile indicators, which cannot be determined a priori, to identify the specification that best fits the data (Ford et al., 2023; Holzer et al., 2025; Kißler et al., 2021; Vanbinst et al., 2015). We compared parameterizations allowing variances to vary or remain equal across profiles, and covariances to vary, remain equal, or be fixed to 0 (Ford et al., 2023; Rosenberg et al., 2018).

For each LPA model, once the optimal number of profiles had been determined, the profiles were interpreted based on the patterns of cognitive weaknesses they exhibited and

by comparing their scores on the different cognitive indicators (Capin et al., 2021; Orbach & Fritz, 2022b). Within each profile, a cognitive weakness was defined as a mean score on a given skill that significantly differed from the overall sample mean (Orbach & Fritz, 2022b). The profiles of poor readers and poor mathematics achievers were then compared with each other, as well as with the respective control groups of average readers or average mathematics achievers, on academic performance, nonverbal IQ, demographic variables, and SES, to examine differences between profiles and contextualize their characteristics relative to average achievers. Finally, for both analyses, we examined whether the proportion of children with difficulties in both reading and mathematics versus those with difficulties limited to a single domain differed across the identified profiles.

4.3. Results

Descriptive statistics and bivariate correlations for the study variables, computed on the total sample, are reported in Appendices 13 and 14, respectively.

4.3.1. Cognitive profiles of poor readers

4.3.1.1. Descriptive statistics and comparison between poor and average readers

Descriptive statistics and results of group comparisons between poor and average readers are presented in Table 9.

Variable	Poor readers (*n* = 139) Mean (*SD*)	Average readers (*n* = 322) Mean (*SD*)	*t*	Cohen's *d*
Demographics, SES, and nonverbal IQ				
Sex (% of girls)	55.40%	50.93%	_	_
Age	102.83 (4.88)	102.39 (4.58)	0.91	–0.09
Testing month	6.50 (3.19)	6.02 (3.20)	1.50	–0.15
SES	–0.32 (0.98)	0.13 (0.98)	–4.28***	0.46
Nonverbal IQ	–0.32 (0.92)	0.14 (1.00)	–4.80***	0.48
Reading				
Reading fluency	–1.09 (0.37)	0.47 (0.80)	–28.47***	2.49
Domain-general cognitive variables				
Working memory	–0.45 (0.87)	0.19 (0.99)	–6.97***	0.69
Inhibition	–0.24 (1.14)	0.10 (0.92)	–3.10**	0.33
Cognitive flexibility	–0.29 (1.13)	0.12 (0.91)	–3.82***	0.40
Domain-specific cognitive variables				
Phonological awareness	–0.28 (1.05)	0.12 (0.95)	–3.88***	0.40
RAN	–0.40 (1.15)	0.17 (0.88)	–5.22***	0.56
Visual-attention span	–0.70 (0.94)	0.30 (0.87)	–10.68***	1.10

Table 9. Group comparisons between poor and average readers. All variables, except sex, age, and testing month, are expressed as *z* scores. Reading and cognitive variables were adjusted for age and testing month; higher *z* scores indicate better performance. Welch's *t* tests were conducted to account for unequal variances and group sizes. Significant group differences remained after Bonferroni correction ($p < .0045$). SES data were missing for 47 participants (18 poor readers and 29 average readers). SES = socioeconomic status; RAN = rapid automatized naming. **$p < .01$; ***$p < .001$.

Poor readers did not differ from average readers in age, testing month, or sex distribution ($\chi^2(1) = 0.61$, $p = .436$). On average, poor readers came from lower SES backgrounds and exhibited lower nonverbal IQ scores. By construction, poor readers showed substantially lower reading fluency. Across cognitive measures, they performed worse than average readers in

both domain-general and domain-specific skills, with a large effect size (Cohen, 1988) observed for visual-attention span.

4.3.1.2. Latent profile analysis among poor readers

A LPA was conducted to examine the heterogeneity of cognitive profiles among poor readers, based on both domain-general (working memory, inhibition, cognitive flexibility) and domain-specific (phonological awareness, RAN, visual-attention span) skills. The results of this analysis, including the selection of the optimal model and the characterization of the identified profiles, are presented below.

Selection of the latent profile solution

Based on model fit indices, the two-profile LPA model – with varying variances and covariances fixed to 0 – was identified as the best-fitting solution, as reflected by the lowest BIC value (Nylund et al., 2007). Table 10 summarizes the profile solutions for this variance-covariance specification (see Appendix 15 for a complete overview of all tested models). The two-profile solution yielded a significant BLRT, indicating a better fit than the one-profile model, whereas this improvement was not significant for the three-profile model. Furthermore, the two-profile model showed good classification accuracy, with an entropy of 0.75 and a minimum profile membership probability of 0.93, and had a satisfactory smallest-profile proportion of 45% (Weller et al., 2020). Therefore, the two-profile model was retained.

Number of profiles	AIC	BIC	Entropy	Minimum probability	Smallest *n* (%)	BLRT (*p*)
1	2449.15	2484.36	1.00	1.00	1.00	_
2	**2323.22**	**2396.58**	**0.75**	**0.93**	**0.45**	**0.010**
3	2333.35	2444.86	0.88	0.91	0.09	0.861
4	2325.22	2474.87	0.74	0.83	0.09	0.069
5	2298.85	2486.66	0.77	0.70	0.12	0.010
6	2306.67	2532.63	0.78	0.72	0.09	0.604

Table 10. Model fit indices for one- to six-profile solutions among poor readers. AIC = Akaike information criterion; BIC = Bayesian information criterion; BLRT = bootstrapped likelihood ratio test. The selected model is bolded.

Description of the profiles

Figure 7 depicts the two cognitive profiles identified among poor readers based on the LPA. Corresponding descriptive statistics and between-profile comparisons are reported in Table 11.

Profile 1 (*n* = 76; 55% of poor readers) was characterized, on average, by cognitive weaknesses across all abilities, with mean *z* scores ranging from –0.67 to –0.90, all significantly below the overall sample mean. Accordingly, this profile was labeled *Broad cognitive weaknesses*.

Profile 2 (*n* = 63; 45% of poor readers) was characterized, on average, by a selective cognitive weakness in visual-attention span. This weakness was moderate, with a mean *z* score of –0.47, significantly below the overall sample mean. Accordingly, this profile was labeled *Specific visual-attention span weakness*.

The two profiles of poor readers differed significantly across all cognitive variables, with Profile 1 showing more pronounced cognitive weaknesses than Profile 2. Notably, while both profiles exhibited a weakness in visual-attention span, this was greater in Profile 1 than in Profile 2 (see Table 11).

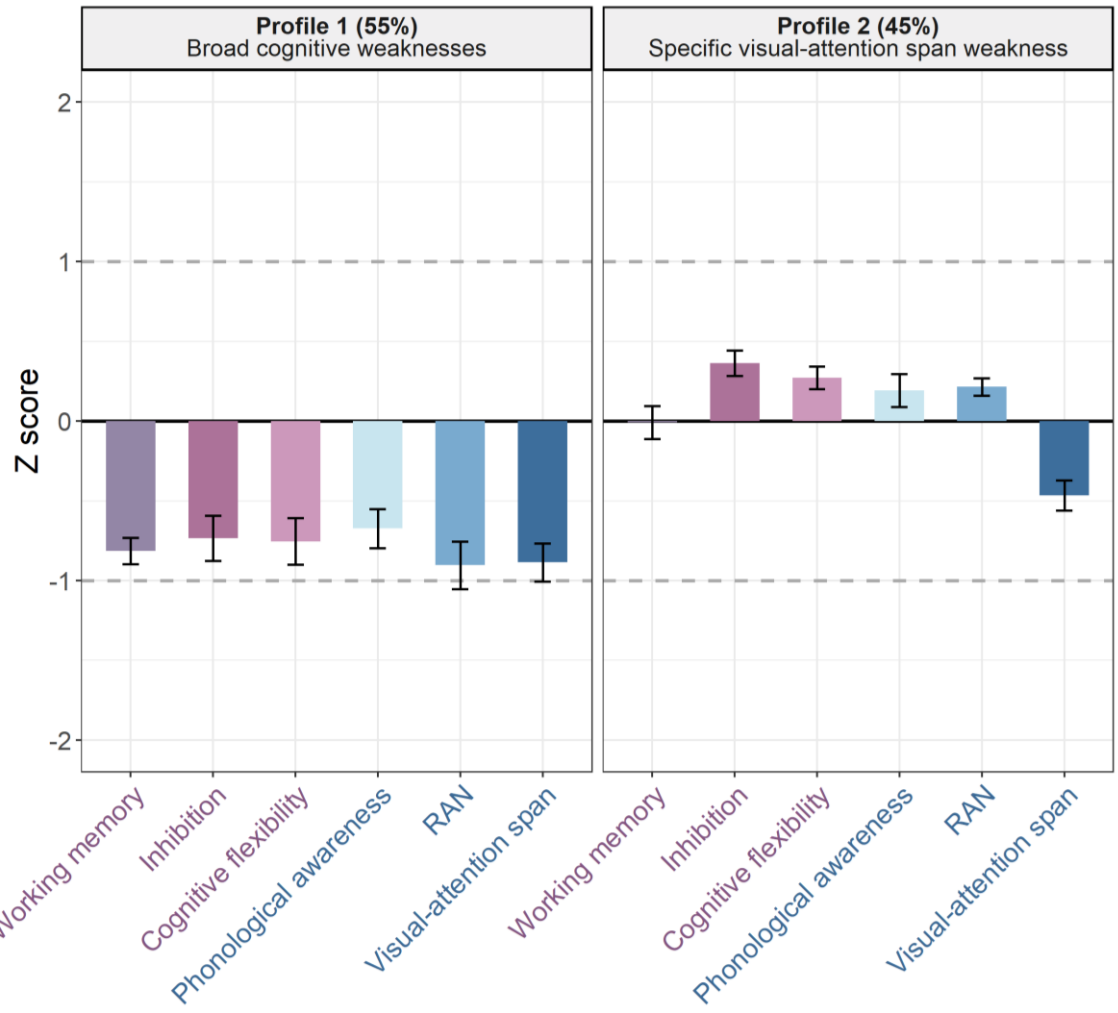

Figure 7. Cognitive profiles of poor readers. Bars represent mean *z* scores for each cognitive variable, with error bars indicating standard errors of the mean. Domain-general variables are shown in purple and domain-specific variables in blue. Higher *z* scores indicate better performance. RAN = rapid automatized naming.

Variable	Profile 1 (*n* = 76, 55%) Mean (*SD*)	Profile 2 (*n* = 63, 45%) Mean (*SD*)	*t*	*p*	Cohen's *d*
Domain-general variables					
Working memory	–0.81 (0.73)***	–0.01 (0.82)	–6.07	< .001	1.04
Inhibition	–0.73 (1.23)***	0.36 (0.63)	–6.78	< .001	1.12
Cognitive flexibility	–0.75 (1.27)***	0.27 (0.56)	–6.33	< .001	1.04
Domain-specific variables					
Phonological awareness	–0.67 (1.06)***	0.19 (0.82)	–5.44	< .001	0.92
RAN	–0.90 (1.30)***	0.21 (0.43)	–7.05	< .001	1.16
Visual-attention span	–0.89 (1.04)***	–0.47 (0.75)***	–2.77	.038	0.46

Table 11. Descriptive statistics and between-profile comparisons for cognitive indicators among poor readers. All variables are expressed as *z* scores, with higher scores reflecting better performance, and were adjusted for age and testing month. Welch's *t* tests were conducted to compare profile means, and *p* values were Bonferroni-corrected. Asterisks further indicate *z* scores significantly lower than the total sample mean (*z* = 0) after Bonferroni correction. RAN = rapid automatized naming. ***$p < .001$.

Comparison of profiles on external variables

The two profiles of poor readers were subsequently compared with each other and with the group of average readers on external variables not included in the LPA, encompassing demographic characteristics, SES, nonverbal IQ, and reading performance (see Table 12).

Variable	Profile 1 (n = 76) Mean (SD)	Profile 2 (n = 63) Mean (SD)	Average readers (n = 322) Mean (SD)	F	η^2_p
Demographics, SES, and nonverbal IQ					
Sex (% of girls)	64.47%	44.44%	50.93%	_	_
Age	103.11 (5.00)[a]	102.51 (4.74)[a]	102.39 (4.58)[a]	0.71	0.00
Testing month	6.41 (3.20)[a]	6.62 (3.20)[a]	6.02 (3.20)[a]	1.19	0.01
SES	–0.47 (0.81)[a]	–0.14 (1.14)[ab]	0.13 (0.98)[b]	10.84***	0.05
Nonverbal IQ	–0.36 (0.96)[a]	–0.28 (0.87)[a]	0.14 (1.00)[b]	10.86***	0.05
Reading					
Reading fluency	–1.15 (0.41)[a]	–1.01 (0.30)[a]	0.47 (0.80)[b]	240.42***	0.51

Table 12. Comparisons of poor reader profiles with each other and with average readers on external variables. All variables, except sex, age, and testing month, are expressed as *z* scores. Nonverbal IQ and reading performance were adjusted for age and testing month; higher *z* scores indicate better performance. Groups sharing the same superscript do not differ significantly based on ANOVA post hoc pairwise comparisons with Bonferroni correction. SES = socioeconomic status. ***p < .001.

The two profiles of poor readers did not differ from each other or from average readers in age or testing month. Regarding sex distribution, a significant overall effect was observed ($\chi^2(2) = 6.31$, $p = .043$); however, none of the Bonferroni-corrected post hoc pairwise comparisons reached significance, indicating that differences were not strong enough to be detected after correction. For nonverbal IQ, the two profiles of poor readers did not differ significantly, with both showing lower IQ scores than average readers. In terms of SES, poor readers in Profile 1 (*Broad cognitive weaknesses*) came from significantly lower SES backgrounds than average readers. Finally, although Profile 1 exhibited broader and more pronounced cognitive weaknesses than Profile 2 (*Specific visual-attention span weakness*), both profiles displayed comparable reading performance.

Distribution of poor readers with and without mathematics difficulties across profiles

Lastly, given that the current sample of poor readers included children with varying levels of mathematics performance, we conducted exploratory analyses to examine the distribution of children with isolated reading difficulties versus those with co-occurring reading and mathematics difficulties across profiles (see Figure 8).

Results indicated that the distribution of children with isolated reading difficulties versus those with co-occurring poor mathematics achievement differed across profiles ($\chi^2(1) = 8.94$, p = .003). Specifically, Profile 1 (*Broad cognitive weaknesses*) was characterized by an overrepresentation (62%) of children with co-occurring reading and mathematics difficulties, whereas children with isolated reading difficulties were overrepresented (65%) in Profile 2 (*Specific visual-attention span weakness*).

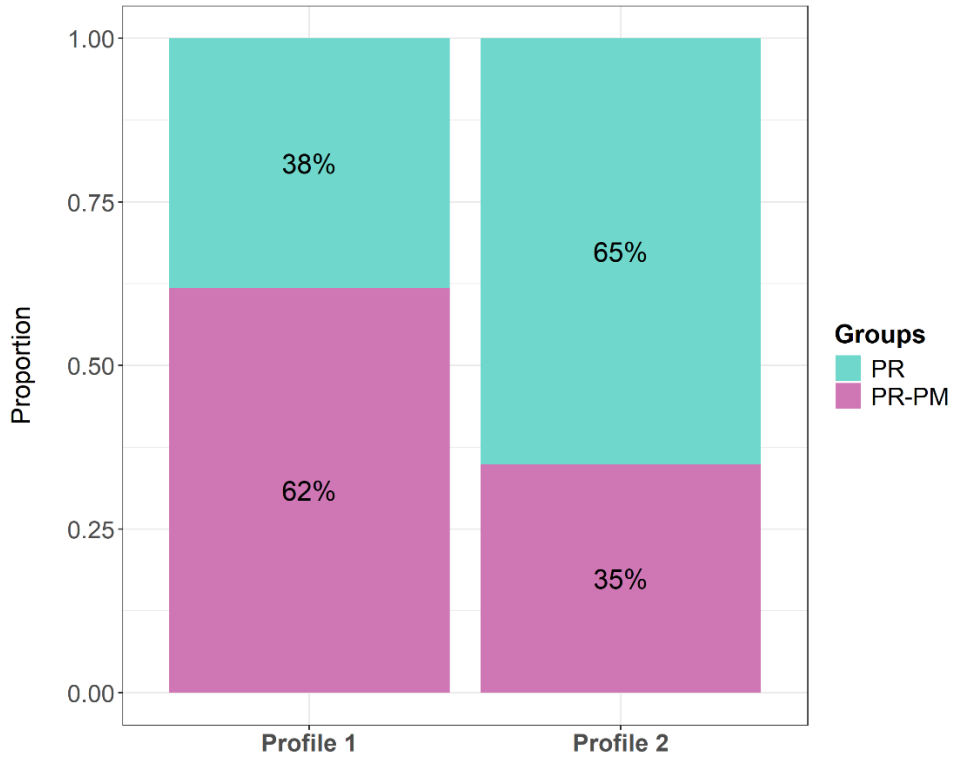

Figure 8. Distribution of poor readers with and without mathematics difficulties across profiles. Profile 1 (n = 76): *Broad cognitive weaknesses*; Profile 2 (n = 63): *Specific visual-attention span weakness*. PR (n = 70): poor readers only; PR-PM (n = 69): poor readers with co-occurring poor mathematics achievement.

4.3.2. Cognitive profiles of poor mathematics achievers

4.3.2.1. Descriptive statistics and comparison between poor and average mathematics achievers

Descriptive statistics and results of group comparisons between poor and average mathematics achievers are reported in Table 13.

Variable	Poor mathematics achievers (*n* = 139) Mean (*SD*)	Average mathematics achievers (*n* = 322) Mean (*SD*)	*t*	Cohen's *d*
Demographics, SES, and nonverbal IQ				
Sex (% of girls)	64.03%	47.20%	_	_
Age	102.68 (4.70)	102.46 (4.67)	0.45	–0.05
Testing month	6.20 (3.31)	6.15 (3.16)	0.16	–0.02
SES	–0.44 (0.97)	0.19 (0.95)	–6.00***	0.65
Nonverbal IQ	–0.36 (0.97)	0.15 (0.97)	–5.19***	0.53
Mathematics				
Calculation	–1.20 (0.66)	0.52 (0.59)	–26.22***	2.72
Domain-general cognitive variables				
Working memory	–0.68 (0.81)	0.29 (0.93)	–11.39***	1.12
Inhibition	–0.36 (1.09)	0.16 (0.92)	–4.90***	0.51
Cognitive flexibility	–0.49 (1.13)	0.21 (0.86)	–6.61***	0.71
Domain-specific cognitive variables				
Transcoding	–0.72 (1.30)	0.31 (0.62)	–8.85***	1.00
Symbolic comparison	–0.51 (0.96)	0.22 (0.93)	–7.60***	0.78
ANS acuity	–0.26 (1.04)	0.11 (0.96)	–3.64***	0.38

Table 13. Group comparisons between poor and average mathematics achievers. All variables, except sex, age, and testing month, are expressed as *z* scores. Mathematics and cognitive variables were adjusted for age and testing month; higher *z* scores indicate better

performance. Welch's *t* tests were used to account for unequal variances and group sizes. Significant group differences remained after Bonferroni correction ($p < .0045$). SES data were missing for 47 participants (15 poor mathematics achievers and 32 average mathematics achievers). SES = socioeconomic status; ANS = approximate number system. ***$p < .001$.

Poor mathematics achievers did not differ from average mathematics achievers in age or testing month. However, sex distribution significantly differed between the two groups ($\chi^2(1) = 10.40$, $p = .001$), with girls being overrepresented among poor mathematics achievers. In addition, poor mathematics achievers tended to come from lower SES backgrounds and displayed lower nonverbal IQ scores than their average-achieving peers. As expected by design, poor mathematics achievers performed substantially worse on calculation. Regarding cognitive skills, poor mathematics achievers showed weaker performance across both domain-general and domain-specific abilities, with particularly large effect sizes (Cohen, 1988) for working memory and transcoding.

4.3.2.2. Latent profile analysis among poor mathematics achievers

A LPA was conducted to examine the heterogeneity of cognitive profiles among children with poor mathematics performance, incorporating both domain-general (working memory, inhibition, and cognitive flexibility) and domain-specific (transcoding, symbolic comparison, and ANS acuity) skills. The results of this analysis, including model selection and characterization of the identified profiles, are presented below.

Selection of the latent profile solution

Based on model fit indices, the two-profile LPA model – with varying variances and covariances fixed to 0 – provided the best fit to the data, as indicated by the lowest BIC (Nylund et al., 2007). The different profile solutions for this variance-covariance specification are presented in Table 14 (see Appendix 16 for a complete overview of all tested models). The two-profile solution also yielded a significant BLRT, indicating a better fit than the single-profile model (Nylund et al., 2007), whereas the three-profile solution did not result in a significant improvement. Moreover, the two-profile model demonstrated good classification accuracy, with high entropy (0.74) and minimum profile membership probability (0.88), and had an adequate smallest-profile proportion (43%) (Weller et al., 2020). Therefore, the two-profile model was retained as the optimal solution.

Number of profiles	AIC	BIC	Entropy	Minimum probability	Smallest n (%)	BLRT (*p*)
1	2458.72	2493.93	1.00	1.00	1.00	_
2	**2314.76**	**2388.13**	**0.74**	**0.88**	**0.43**	**0.010**
3	2319.40	2430.91	0.75	0.78	0.17	0.475
4	2282.14	2431.80	0.73	0.79	0.10	0.010
5	2263.77	2451.58	0.79	0.83	0.09	0.030
6	2261.17	2487.13	0.81	0.75	0.06	0.050

Table 14. Model fit indices for one- to six-profile solutions among poor mathematics achievers. AIC = Akaike information criterion; BIC = Bayesian information criterion; BLRT = bootstrapped likelihood ratio test. The selected model is bolded.

Description of the profiles

Figure 9 illustrates the two cognitive profiles identified among poor mathematics achievers via the LPA. Corresponding descriptive statistics and results of between-profile comparisons are presented in Table 15.

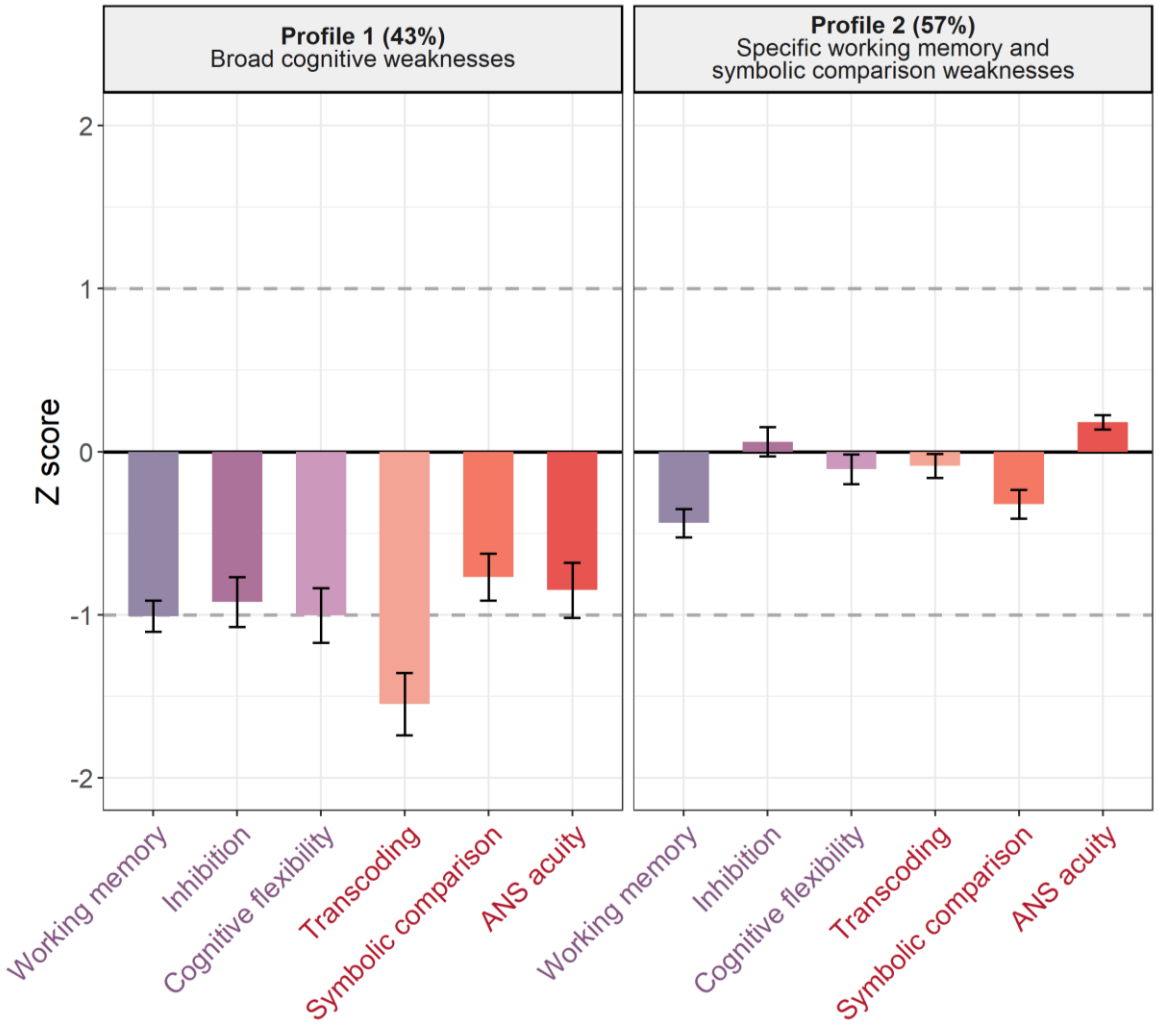

Figure 9. Cognitive profiles of poor mathematics achievers. Bars represent mean *z* scores for each cognitive variable, with error bars indicating standard errors of the mean. Domain-general variables are shown in purple and domain-specific variables in red. Higher *z* scores indicate better performance. ANS = approximate number system.

Profile 1 (*n* = 60; 43% of poor mathematics achievers) was characterized, on average, by widespread cognitive weaknesses across all abilities, with mean *z* scores ranging from −0.77 to –1.55, all significantly below the overall sample mean. Accordingly, this profile was labeled *Broad cognitive weaknesses*.

Profile 2 (*n* = 79; 57% of poor mathematics achievers) was characterized, on average, by moderate cognitive weaknesses in working memory and symbolic comparison, with mean *z* scores of –0.44 and –0.32, respectively. These were the only abilities significantly below the

overall sample mean. Accordingly, this profile was labeled *Specific working memory and symbolic comparison weaknesses*.

The two profiles of poor mathematics achievers differed significantly on all cognitive variables except symbolic comparison, with Profile 1 exhibiting more pronounced cognitive weaknesses than Profile 2.

Variable	Profile 1 (*n* = 60, 43%) Mean (*SD*)	Profile 2 (*n* = 79, 57%) Mean (*SD*)	*t*	*p*	Cohen's *d*
Domain-general variables					
Working memory	–1.01 (0.74)***	–0.44 (0.77)***	–4.43	< .001	0.76
Inhibition	–0.92 (1.19)***	0.06 (0.79)	–5.54	< .001	0.97
Cognitive flexibility	–1.00 (1.29)***	–0.11 (0.81)	–4.72	< .001	0.83
Domain-specific variables					
Transcoding	–1.55 (1.48)***	–0.09 (0.65)	–7.15	< .001	1.28
Symbolic comparison	–0.77 (1.12)***	–0.32 (0.78)**	–2.64	.057	0.46
ANS acuity	–0.85 (1.31)***	0.18 (0.40)	–5.88	< .001	1.06

Table 15. Descriptive statistics and between-profile comparisons for cognitive indicators among poor mathematics achievers. All variables are expressed as *z* scores, with higher scores reflecting better performance, and were adjusted for age and testing month. Welch's *t* tests were conducted to compare profile means, and *p* values were Bonferroni-corrected. Asterisks further indicate *z* scores significantly lower than the total sample mean (*z* = 0) after Bonferroni correction. ANS = approximate number system. **$p < .01$; ***$p < .001$.

Comparison of profiles on external variables

The two profiles of poor mathematics achievers were subsequently compared with each other and with the group of average mathematics achievers on external variables not included in the LPA, including demographic characteristics, SES, nonverbal IQ, and mathematics performance (see Table 16).

Variable	Profile 1 (n = 60) Mean (SD)	Profile 2 (n = 79) Mean (SD)	Average mathematics achievers (n = 322) Mean (SD)	F	η^2_p
Demographics, SES, and nonverbal IQ					
Sex (% of girls)	70.00%	59.49%	47.20%	_	_
Age	102.52 (4.63)[a]	102.80 (4.77)[a]	102.46 (4.67)[a]	0.16	0.00
Testing month	6.12 (3.48)[a]	6.27 (3.20)[a]	6.15 (3.16)[a]	0.05	0.00
SES	–0.55 (0.88)[a]	–0.35 (1.04)[a]	0.19 (0.95)[b]	18.94***	0.08
Nonverbal IQ	–0.38 (0.94)[a]	–0.34 (1.00)[a]	0.15 (0.97)[b]	13.44***	0.06
Mathematics					
Calculation	–1.47 (0.73)[a]	–0.99 (0.53)[b]	0.52 (0.59)[c]	403.40***	0.64

Table 16. Comparisons of poor mathematics achiever profiles with each other and with average mathematics achievers on external variables. All variables, except sex, age, and testing month, are expressed as z scores. Nonverbal IQ and mathematics performance were adjusted for age and testing month; higher z scores indicate better performance. Groups sharing the same superscript do not differ significantly based on ANOVA post hoc pairwise comparisons with Bonferroni correction. SES = socioeconomic status. ***$p < .001$.

The two profiles of poor mathematics achievers did not differ from each other or from average mathematics achievers in age or testing month. Regarding sex distribution, a significant overall effect was observed ($\chi^2(2) = 12.50$, $p = .002$), with Bonferroni-corrected post hoc pairwise comparisons indicating that girls were overrepresented in Profile 1 (*Broad cognitive weaknesses*) relative to average mathematics achievers ($p = .006$). For nonverbal IQ and SES, the two profiles of poor mathematics achievers did not differ significantly, with both showing lower IQ scores and lower SES than average mathematics achievers. Finally, Profile 1 exhibited poorer mathematics performance than Profile 2 (*Specific working memory and symbolic comparison weaknesses*).

Distribution of poor mathematics achievers with and without reading difficulties across profiles

Lastly, as the current sample of poor mathematics achievers included children with varying levels of reading performance, we conducted exploratory analyses to examine the distribution of children with isolated mathematics difficulties versus those with co-occurring mathematics and reading difficulties across profiles (see Figure 10).

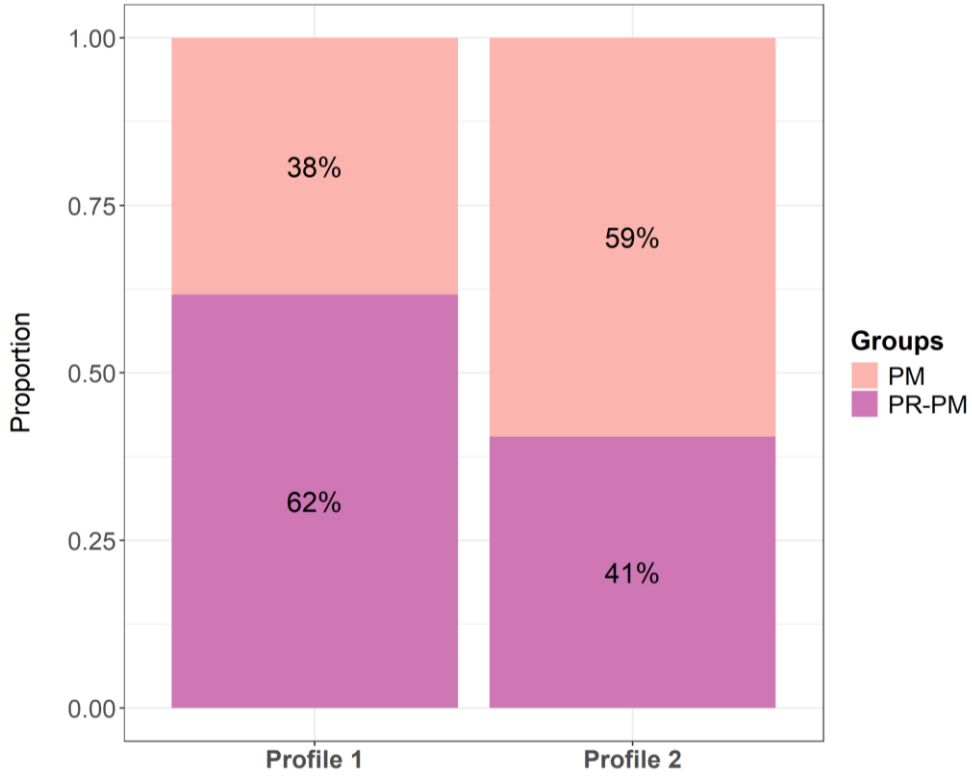

Figure 10. Distribution of poor mathematics achievers with and without reading difficulties across profiles. Profile 1 (*n* = 60): *Broad cognitive weaknesses*; Profile 2 (*n* = 79): *Specific working memory and symbolic comparison weaknesses*. PM (*n* = 70): poor mathematics achievers only; PR-PM (*n* = 69): poor mathematics achievers with co-occurring poor reading.

Results indicated that the distribution of children with isolated mathematics difficulties versus those with co-occurring mathematics and reading difficulties differed across profiles ($\chi^2(1) = 5.29$, $p = .021$). Specifically, Profile 1 (*Broad cognitive weaknesses*) was characterized by an overrepresentation (62%) of children with co-occurring mathematics and reading

difficulties, whereas children with isolated mathematics difficulties were overrepresented (59%) in Profile 2 (*Specific working memory and symbolic comparison weaknesses*).

4.4. Discussion

The present study aimed to examine the heterogeneity of cognitive profiles among third-grade children exhibiting poor achievement in foundational reading or mathematical skills – specifically, reading fluency or calculation. For each academic domain, both domain-specific and domain-general cognitive abilities were assessed to provide a comprehensive account of potential correlates of low performance. To this end, LPA was employed as a data-driven approach to determine whether distinct combinations of domain-specific and domain-general cognitive weaknesses characterized different subtypes of poor readers and poor mathematics achievers.

The results revealed the emergence of two distinct cognitive profiles within each group of low-performing children. Among poor readers, the first profile was characterized by broad and pronounced weaknesses across both domain-general (i.e., working memory, inhibition, cognitive flexibility) and domain-specific skills (i.e., phonological awareness, RAN, and visual-attention span). The second profile, by contrast, showed moderate, selective weaknesses in visual-attention span. Despite these cognitive differences, both profiles displayed comparable levels of poor reading performance and similar sociodemographic characteristics, although children in Profile 1 (*Broad cognitive weaknesses*) came on average from lower SES backgrounds than average readers. Likewise, among poor mathematics achievers, two distinct profiles emerged. The first profile exhibited broad and pronounced weaknesses across both domain-general (i.e., working memory, inhibition, cognitive flexibility) and domain-specific skills (i.e., transcoding, symbolic comparison, and ANS acuity), whereas the second profile was characterized by moderate weaknesses confined to working memory and symbolic comparison. In this case, Profile 1 (*Broad cognitive weaknesses*) displayed poorer mathematical performance than Profile 2 (*Specific working memory and symbolic comparison weaknesses*) and included an overrepresentation of girls compared to average mathematics achievers.

4.4.1. Cognitive profiles among poor readers

The present findings are consistent with previous research showing that poor readers do not form a homogeneous group but instead display diverse cognitive profiles (Carroll et al.,

2016; J.-R. Cho & Ji, 2011; S. Song et al., 2020; Valdois et al., 2021; Willems et al., 2016). Notably, the current results corroborate earlier evidence that specific weaknesses in visual-attention span characterize a subset of children with reading difficulties, independently of deficits in other domain-specific cognitive skills such as phonological awareness or RAN (Bosse et al., 2007; Valdois et al., 2021; Zoubrinetzky et al., 2014). Importantly, this study extends prior work by demonstrating that such isolated visual-attention span weaknesses can be detected using a data-driven approach that jointly considers both domain-specific and domain-general cognitive abilities.

Furthermore, unlike previous studies (Bosse et al., 2007; J.-R. Cho & Ji, 2011; S. Song et al., 2020; Valdois et al., 2021; Zoubrinetzky et al., 2014), the present study did not identify profiles characterized by isolated impairments in phonological awareness or RAN. Instead, one profile exhibited concurrent weaknesses across all domain-specific abilities, including phonological awareness, RAN, and visual-attention span. Several factors may account for this discrepancy. First, poor readers in the present study were defined using relatively liberal criteria, whereas prior research typically applied more stringent thresholds to identify children with dyslexia. Consequently, isolated phonological or RAN deficits may not have emerged here, as such profiles could be more characteristic of specific dyslexia subtypes (Bosse et al., 2007; K. Chan et al., 2023; Heim et al., 2008; White et al., 2006; Zoubrinetzky et al., 2014). In addition, methodological differences may have contributed to this divergence. Notably, few previous studies have examined all three domain-specific skills simultaneously, and none has done so within a data-driven framework. The LPA approach employed here may therefore have more effectively captured the multidimensional structure of cognitive weaknesses in poor readers, revealing a profile characterized by cumulative deficits. Finally, the relatively modest size of the current sample of poor readers might also have limited the detection of less prevalent cognitive subtypes within this population (Kißler et al., 2021; Nylund-Gibson & Choi, 2018).

Importantly, although Profile 1 (*Broad cognitive weaknesses*) exhibited more extensive and pronounced weaknesses than Profile 2 (*Specific visual-attention span weakness*), the two profiles did not differ in reading performance. This finding suggests that distinct cognitive pathways may lead to similar observable levels of reading difficulty. In this respect, Profile 2 is particularly noteworthy: despite preserved phonological awareness and RAN, children with a specific visual-attention span weakness still showed reading difficulties comparable to those of children with broader cognitive weaknesses. This result reinforces prior evidence that visual-attention span constitutes an important independent contributor to reading

performance (Bosse et al., 2007; Bosse & Valdois, 2009; Valdois et al., 2019, 2021) and suggests that even a selective deficit in this skill may substantially affect reading proficiency.

Moreover, this study highlights the importance of considering domain-general factors when examining the heterogeneity of cognitive profiles among poor readers. Specifically, poor readers who exhibited weaknesses across all domain-specific skills also showed impairments across all assessed executive functions. These findings are consistent with prior research identifying subgroups of children with reading difficulties characterized by combined domain-specific and working memory deficits (K. Chan et al., 2023; Willems et al., 2016) and extend this evidence by demonstrating that weaknesses in other executive functions – such as inhibition and cognitive flexibility – can co-occur alongside working memory weaknesses.

Finally, it is noteworthy that children in the *Broad cognitive weaknesses* profile had a lower average SES compared with average readers, whereas this was not observed for the profile characterized by a specific visual-attention span weakness. These findings suggest that low-SES poor readers may be at heightened risk of exhibiting widespread impairments across both domain-general and domain-specific cognitive skills (Willems et al., 2016). This pattern underlines the potential need for more comprehensive support for this subgroup, although future research directly comparing the cognitive profiles of low- and high-SES poor readers is necessary to clarify this issue (Noble & Mccandliss, 2005; Romeo, Perrachione, et al., 2022).

4.4.2. Cognitive profiles among poor mathematics achievers

Regarding poor mathematics achievers, our findings are consistent with previous research highlighting cognitive heterogeneity within this population (Bartelet et al., 2014; W. W. L. Chan & Wong, 2020; Costa et al., 2018; Ouyang et al., 2024). Specifically, they align with the study by Chan & Wong (2020), which identified a profile of children with deficits in symbolic processing and working memory across grades among poor mathematics achievers followed from first to second grade. In addition, the second profile in the present study exhibited broad cognitive weaknesses across various domain-specific and domain-general skills, corroborating earlier evidence of a subtype of children with pervasive cognitive deficits (Kißler et al., 2021; Ouyang et al., 2024; von Aster, 2000). Importantly, this study extends previous work by demonstrating that such broad cognitive weaknesses also encompass executive functions, including inhibition and cognitive flexibility, which had not been previously examined.

Notably, the present study did not identify any subtypes of poor mathematics achievers with isolated weaknesses in a single cognitive skill, in contrast to previous studies reporting profiles characterized by selective deficits in ANS (Bartelet et al., 2014; W. W. L. Chan & Wong, 2020), symbolic processing (Bartelet et al., 2014; Ouyang et al., 2024), or working memory (W. W. L. Chan & Wong, 2020). As with poor readers, this discrepancy may reflect sample characteristics, as our study included a relatively broad spectrum of poor mathematics achievers, whereas isolated deficits in ANS or symbolic processing may be more typical of children with severe mathematical difficulties (Bartelet et al., 2014; Ouyang et al., 2024; von Aster, 2000). The modest sample size may also have limited the detection of less prevalent subtypes (Kißler et al., 2021; Nylund-Gibson & Choi, 2018). Age-related factors could further contribute, since the predictive influence of domain-general skills, such as working memory, on mathematics performance has been found to increase across elementary school (Caviola et al., 2020; Geary, 2011), potentially explaining the emergence of profiles combining domain-specific and domain-general weaknesses in our third-grade sample. Finally, both profiles included children with lower SES relative to average mathematics achievers, which may have contributed to the presence of profiles with combined cognitive weaknesses, a pattern previously observed in this population (Costa et al., 2018).

4.4.3. Cross-domain similarities and differences in the cognitive profiles of poor academic achievers

Interestingly, the present study revealed comparable patterns of cognitive heterogeneity among children with poor reading and poor mathematics achievement. In each academic domain, two distinct profiles emerged: one characterized by selective, moderate cognitive weaknesses, and another by broad, pronounced weaknesses. In both domains, the broad-weaknesses profile exhibited impairments across both domain-specific and domain-general skills. By contrast, the profiles with limited weaknesses differed across domains: among poor readers, weaknesses were restricted to a domain-specific skill (visual-attention span), whereas among poor mathematics achievers, weaknesses encompassed both domain-general (working memory) and domain-specific skills (symbolic comparison). These findings may partly reflect that mathematics difficulties are influenced by both domain-specific and domain-general factors, whereas reading difficulties may be more strongly driven by domain-specific factors (Slot et al., 2016). This pattern may further explain why, in poor mathematics achievers, the broad-weaknesses profile showed lower mathematics performance than the limited-weaknesses profile, whereas in poor readers, both

profiles performed comparably despite markedly different levels of cognitive weaknesses. This suggests that the domain-general weaknesses observed in the broad-weaknesses profile among poor readers might not be primarily related to reading difficulties, but rather reflect the overrepresentation of children with co-occurring mathematics difficulties in this profile.

Indeed, in both academic domains, the broad-weaknesses profile included a higher proportion of children with co-occurring reading and mathematics difficulties. This suggests that these children may exhibit particular cognitive characteristics. These findings align with Brandenburg et al. (2021), who applied LPA to children with various learning difficulties and found that those with co-occurring reading and mathematics difficulties were more likely to belong to the most comprehensively impaired cognitive profile, characterized by deficits in domain-general skills and phonological awareness (though domain-specific mathematical skills were not assessed). Nevertheless, in both Brandenburg et al. (2021) and the present study, a substantial proportion of children with co-occurring difficulties were also observed in profiles with selective cognitive weaknesses, indicating that cognitive heterogeneity likely exists even among children with difficulties in both domains (Starling-Alves et al., 2025), a finding that warrants further investigation.

4.4.4. Educational implications

Overall, this study demonstrates the presence of heterogeneous cognitive profiles among children with poor reading and poor mathematics achievement, highlighting the importance of adopting a differential, person-centered approach rather than relying on group averages when investigating the factors underlying academic difficulties (Astle et al., 2024; Starling-Alves et al., 2025). Specifically, interventions targeting visual-attention span (e.g., Valdois et al., 2025) or working memory and symbolic processing skills (e.g., DePascale et al., 2024) may be effective for certain subgroups of children with reading or mathematics difficulties, respectively. Other subgroups, however, may require more comprehensive support addressing a broader range of domain-specific and domain-general skills. These findings underline the importance of systematically assessing multiple cognitive domains in poor readers and poor mathematics achievers, and tailoring interventions to individual cognitive profiles (Bartelet et al., 2014; Carroll et al., 2016; Ouyang et al., 2024; Valdois et al., 2021; Willems et al., 2016). Adopting such an interindividual perspective also provides insight into the heterogeneity observed in responses to interventions among children with comparable academic difficulties (Younger et al., 2024; Zhao et al., 2019).

4.4.5. Limitations and future directions

This study has several limitations that should be considered when interpreting the findings. First, its correlational design precludes any causal inference regarding the relationship between the observed cognitive weaknesses and academic difficulties. Moreover, the study focused exclusively on third-grade children – a developmental stage at which difficulties in foundational reading and mathematical skills are likely to persist over time (Andersson, 2010; Billard et al., 2010; Smart et al., 2005). Nonetheless, different cognitive profiles may emerge among children with poor reading or poor mathematics achievement at other developmental stages (W. W. L. Chan & Wong, 2020). Longitudinal research is therefore needed to examine the stability of these cognitive profiles over time and to investigate the heterogeneity of the cognitive mechanisms underlying developmental changes in academic performance, rather than performance at a single point in time.

Furthermore, interventional studies are needed to determine whether training programs tailored to each child's cognitive profile can effectively enhance academic performance. In this context, it would also be valuable to compare interventions targeting a single cognitive skill versus multiple skills simultaneously, to identify which cognitive abilities are necessary and/or sufficient to target for improving the academic outcomes of low-achieving children. Notably, despite marked differences in the number and severity of cognitive weaknesses between the two profiles of poor readers identified in this study, both groups exhibited comparably low reading performance. This raises the possibility that, although children with broader cognitive weaknesses may require more intensive remediation, interventions specifically targeting visual-attention span – impaired in both profiles – might suffice to improve reading performance across both groups. Indeed, as profiles reflect the average features of their members, substantial variability may persist within a given profile (Astle et al., 2022; Huijsmans et al., 2020). In this context, the domain-general weaknesses observed on average in Profile 1 among poor readers may primarily reflect the higher proportion of children with co-occurring mathematics difficulties. Because these domain-general abilities may be more strongly related to mathematics than to reading difficulties (Slot et al., 2016), the overrepresentation of children with co-occurring difficulties in this profile may have lowered the profile's average for these skills, without necessarily indicating that such weaknesses are characteristic of reading difficulties, whether isolated or co-occurring.

As mentioned, the present study did not distinguish between children with co-occurring reading and mathematics difficulties and those with isolated difficulties within the LPA models conducted for each domain. This methodological decision reflects the view that children with co-occurring difficulties represent a genuine part of the broader population of poor readers and poor mathematics achievers, and excluding them could have artificially reduced the natural variability within these groups. Nevertheless, future research should examine whether children with co-occurring reading and mathematics difficulties constitute a distinct cognitive subtype compared to those with isolated difficulties (Brandenburg et al., 2021; but see Astle et al., 2019), and whether cognitive heterogeneity also exists within each group – poor readers only, poor mathematics achievers only, and children with co-occurring difficulties (Starling-Alves et al., 2025).

Finally, future studies should include larger samples and broaden the range of cognitive factors considered, for instance by examining letter knowledge (Willems et al., 2016) or spatial abilities (Bartelet et al., 2014) – which may help identify additional subtypes of low-performing children. Moreover, extending this approach to children who struggle with more complex academic outcomes, such as reading comprehension or word problem-solving, could provide valuable insights into the cognitive diversity underlying higher-order reading and mathematics difficulties (e.g., James et al., 2023).

4.4.6. Conclusion

In conclusion, using a data-driven and person-centered approach, this study revealed that both poor readers and poor mathematics achievers constitute heterogeneous groups, each characterized by distinct cognitive profiles combining different patterns of domain-general and/or domain-specific weaknesses. These findings underline the importance of individualized interventions tailored to each child's cognitive profile to foster more effective support. Moreover, the results suggest that children with co-occurring difficulties in reading and mathematics are more likely to display broad cognitive impairments, emphasizing the need to jointly consider both academic domains and to further investigate the cognitive characteristics of children with co-occurring versus isolated difficulties.

Taken together, this study focused on children with poor reading or poor mathematics achievement, adopting a differential approach that allowed for the examination of interindividual variability in their cognitive weaknesses. A limitation, however, is that children with difficulties in both academic domains were not analyzed separately from those with isolated difficulties, leaving open the possibility that some of the observed variability may reflect whether difficulties occur in isolation or concurrently (Moll et al., 2019). Furthermore, in the first three studies of this thesis, reading and mathematics were treated separately, leaving unexplored the potential involvement of factors typically considered specific to one domain in the other. The final study of this thesis therefore addresses these questions by examining the cognitive factors associated with difficulties in reading only, mathematics only, and both domains, while simultaneously considering domain-general, reading-specific, and mathematics-specific cognitive abilities.

5. Study 4: Cognitive correlates of isolated and co-occurring difficulties in reading and mathematics

This study led to a manuscript in preparation:

Taieb, E., Borst, G., Le Stanc, L., Houdé, O., Iuculano, T.*, & Altarelli, I.* (in prep.). Cognitive correlates of isolated and co-occurring difficulties in reading and mathematics among primary school children.

This study examined how domain-general, reading-specific, and mathematics-specific cognitive factors predict poor performance in reading, mathematics, or both domains, and explored cognitive variability within each group of poor achievers. We hypothesized that each group may exhibit distinct cognitive characteristics, while also showing interindividual variability. Using multinomial logistic regression, we investigated the cognitive predictors of group membership across the three groups. Furthermore, by examining the prevalence of cognitive weaknesses within each group, we explored the extent of heterogeneity among poor academic achievers.

5.1. Introduction

Difficulties in reading and mathematics are among the most prevalent forms of academic challenges in elementary school and are associated with long-term adverse effects on later academic achievement (Duncan et al., 2007; McNamara et al., 2011; Morgan et al., 2011), psychological well-being (Morgan et al., 2012), and socioeconomic attainment (Ritchie & Bates, 2013). Although these difficulties are often studied separately, poor reading and poor mathematics performance frequently co-occur, with overlapping rates exceeding those expected by chance (Dirks et al., 2008; Moll et al., 2014, 2019). Indeed, research indicates that up to half of the children who struggle in one domain also experience difficulties in the other (Ashkenazi et al., 2013; Grigorenko et al., 2020; Koponen et al., 2018), though prevalence estimates vary depending on the threshold criteria and assessment measures used (Dirks et al., 2008; Moll et al., 2014, 2019).

Despite its high prevalence, the co-occurrence of reading and mathematics difficulties has received surprisingly little attention (Ashkenazi et al., 2013; Starling-Alves et al., 2025). Most studies examining the cognitive factors underlying reading or mathematics difficulties have investigated these domains in isolation, often without considering children's performance in the other academic area (L. Peters & Ansari, 2019). Consequently, it remains unclear to what extent the cognitive sources of poor reading and poor mathematics performance overlap or diverge, and whether children with co-occurring difficulties across both domains need supports that differ from those of children with isolated difficulties (Espinas & Fuchs, 2025).

5.1.1. Theoretical accounts of co-occurring reading and mathematics difficulties

Various theoretical accounts have been proposed to explain the potential origins of co-occurring difficulties in reading and mathematics (see Figure 3 of the Theoretical Background section). One prominent framework is the Additive model, which posits that the co-occurrence of reading and mathematics difficulties results from the cumulative effect of cognitive deficits independently associated with each domain (Ashkenazi et al., 2013; L. Peters & Ansari, 2019; Starling-Alves et al., 2025). Specifically, while phonological deficits have been observed in children with isolated reading difficulties and deficits in magnitude processing or executive functions in children with isolated mathematics difficulties, children with co-occurring difficulties have been found to exhibit both sets of deficits, reflecting the

combination of weaknesses characteristic of each single-difficulty group (Landerl et al., 2009; Moll et al., 2015; Schwenck et al., 2015; van der Sluis et al., 2004).

A second theoretical account is the Three Independent Disorders model, which posits that co-occurring difficulties in reading and mathematics are associated with distinct or more pronounced cognitive deficits than those observed in isolated reading or mathematics difficulties (Moll, 2022; Viesel-Nordmeyer et al., 2023). In particular, impairments in domain-general skills, such as executive and attentional abilities that support learning across multiple domains, have been suggested to underlie the emergence of co-occurring difficulties (Ashkenazi et al., 2013; L. Peters & Ansari, 2019; Starling-Alves et al., 2025). Consistent with this view, some studies have reported greater executive function deficits among children with co-occurring difficulties, indicating that these domain-general impairments may not simply reflect an additive combination of single-domain deficits (De Weerdt et al., 2013; Willcutt et al., 2013).

Finally, a third theoretical account is the Increased Risk model, which proposes that phonological deficits present in children with reading difficulties may increase the likelihood of developing concurrent difficulties in mathematics (L. Peters & Ansari, 2019; Starling-Alves et al., 2025). This effect may occur: (i) directly, through the involvement of phonological processes in specific mathematical tasks such as word problem-solving or arithmetic fact retrieval (De Smedt et al., 2010; Starling-Alves et al., 2025); or (ii) indirectly, by affecting verbally mediated cognitive skills relevant to mathematics, such as transcoding (Batista et al., 2023; Lopes-Silva et al., 2014). Consistent with this view, several studies have identified phonological awareness as a shared risk factor for both reading and mathematics difficulties (Fuchs et al., 2025; Mingozzi et al., 2024; Slot et al., 2016).

Thus, several theoretical frameworks have been proposed to account for the co-occurrence of reading and mathematics difficulties, yet no single hypothesis has received unequivocal empirical support, leaving the underpinnings of co-occurring difficulties poorly understood (L. Peters & Ansari, 2019). Importantly, these hypotheses are not mutually exclusive. Some studies have shown that children with co-occurring difficulties may exhibit both unique deficits and deficits shared with children with isolated difficulties, suggesting that both independent and additive processes may operate (Andersson, 2010; Marks et al., 2024; Starling-Alves et al., 2025). Nevertheless, few studies have considered a comprehensive set of cognitive factors encompassing reading-specific, mathematics-specific, and domain-general skills, which is deemed necessary to provide a more thorough understanding of the cognitive

underpinnings of co-occurring difficulties (L. Peters et al., 2020; Starling-Alves et al., 2025; Willcutt et al., 2013). Notably, such an integrative approach could also help clarify whether factors traditionally seen as domain-specific may contribute to difficulties across domains, potentially representing shared risk factors.

5.1.2. Cross-domain cognitive contributions to reading and mathematics difficulties

In line with the Increased Risk hypothesis, some studies suggest that cognitive factors typically associated with reading may also contribute to difficulties in mathematics. For instance, Jordan et al. (2010) found that children with phonological deficits at age 5 showed poorer mathematics performance at age 7 compared to children without such deficits. Moreover, other studies have reported deficits in RAN among children with mathematical difficulties (Mingozzi et al., 2024; Swanson & Jerman, 2006; T.-Y. T. Wong & Ho, 2021), indicating that certain mathematical tasks may require efficient lexical access to phonological representations stored in long-term memory (Cui et al., 2017; X. Yang et al., 2022). Notably, no study to date has examined whether a reduced visual-attention span may be associated with mathematical difficulties.

Similarly, certain domain-specific mathematical abilities may also be involved in reading difficulties. For example, several studies have reported that struggling readers exhibit impairments in mathematics-specific cognitive skills that rely on verbal processes, such as transcoding (De Clercq-Quaegebeur et al., 2018; Moll et al., 2015; Raddatz et al., 2017; Teixeira & Moura, 2020) and symbolic comparison (Moll et al., 2015; Träff et al., 2017). In contrast, nonverbal domain-specific skills, such as non-symbolic comparison, generally appear unaffected in children with reading difficulties (Moll et al., 2015; Träff et al., 2017).

Overall, these findings underline that a comprehensive approach integrating domain-general, reading-specific, and mathematics-specific cognitive factors is essential not only for achieving a better understanding of co-occurring difficulties, but also for clearly delineating the cognitive challenges faced by children with isolated reading or mathematics difficulties.

5.1.3. Within-group cognitive variability

While examining the general cognitive patterns of different groups of poor academic achievers – namely, children with poor reading skills only, children with poor mathematics

skills only, and children with difficulties in both domains – is important for delineating the cognitive characteristics of each group and informing adapted interventions (Espinas & Fuchs, 2025; S. R. Powell et al., 2020), it is equally crucial to account for interindividual variability within each group, which may be obscured by group-level analyses (Astle et al., 2024; Starling-Alves et al., 2025). Previous studies have shown that both poor readers and poor mathematics achievers are heterogeneous populations, comprising subtypes with distinct cognitive profiles (e.g., Bartelet et al., 2014; W. W. L. Chan & Wong, 2020; Ouyang et al., 2024; Valdois et al., 2021; Willems et al., 2016; see also Study 3). However, these studies have focused on a single academic domain and have not differentiated between children with isolated difficulties and those with co-occurring difficulties. Consequently, it remains unclear whether the observed variability in cognitive profiles may reflect the presence of co-occurring difficulties or whether distinct cognitive profiles may exist within each subgroup, including children with isolated reading difficulties, isolated mathematics difficulties, and co-occurring difficulties in both domains.

5.1.4. Current study

To date, research on co-occurring reading and mathematics difficulties remains limited, with only few studies considering a comprehensive range of cognitive factors. Moreover, most existing studies have focused on children with severe reading and/or mathematics difficulties, typically within the context of dyslexia or dyscalculia (Mingozzi et al., 2024; L. Peters et al., 2020; Willcutt et al., 2013; T.-Y. T. Wong & Ho, 2021), even though these children represent only a subset of those experiencing academic difficulties in these domains (Billard & Barbe, 2016; Dowker, 2024). Furthermore, important covariates, such as sex, nonverbal IQ, and SES, have generally not been controlled for, despite evidence that they may differentially affect children with isolated or co-occurring difficulties in reading and mathematics (Archibald et al., 2013; M. A. Barnes et al., 2020; Connors et al., 2025; N. C. Jordan & Levine, 2009; Landerl & Moll, 2010; Moll et al., 2014; Schwenck et al., 2015; Swanson, Jerman, et al., 2009). Finally, to our knowledge, no study has yet investigated whether interindividual variability exists among children with co-occurring or isolated difficulties in these academic domains.

Addressing these gaps in the literature, the present study aims to examine, in a sample of low-achieving third graders: (i) the unique contributions of domain-general, reading-specific, and mathematics-specific cognitive factors to poor performance in reading only, mathematics only, and both domains, while controlling for age, sex, nonverbal IQ, and SES; and (ii) whether cognitive heterogeneity exists within each group. Third graders were

targeted because reading and mathematics difficulties, and particularly their co-occurrence (Koponen et al., 2018), tend to be stable at this stage (Andersson, 2010; Smart et al., 2005), emphasizing the need to understand how to adequately support children whose challenges are unlikely to resolve spontaneously (Aubrey et al., 2006). Using multinomial logistic regression, we first examined whether different combinations of domain-general and/or domain-specific factors predicted membership in each of the three poor achiever groups (i.e., reading difficulties only, mathematics difficulties only, and difficulties in both domains). We then assessed the prevalence of cognitive weaknesses within each group to explore interindividual variability.

5.2. Methods

5.2.1. Participants

The sample for this study comprised the participants described in Section 1.1 of the General Methodology, namely third-grade students enrolled in elementary schools in Paris and its surrounding areas. A total of 472 children met the project's inclusion criteria, which required normal vision and hearing, no history of neurological or neurodevelopmental disorders, no grade repetition or skipping, sufficient mastery of French, and a nonverbal IQ above 2 *SD* below the age norm. Of these, nine children were excluded from the present analyses due to missing data on all domain-specific cognitive variables, resulting from absence during the corresponding test sessions. As multinomial logistic regression requires complete datasets, and imputing more than 50% of the missing values would not have been reliable (Junaid et al., 2025), these participants were not retained. The current sample for this study therefore consists of 461 children (241 girls, 220 boys; M_{age} = 102.5 months, SD_{age} = 4.7 months, range = 92 – 113 months). Importantly, the nine excluded participants did not differ from those who completed all testing sessions in terms of sex, nonverbal IQ, and SES. The only difference was that the excluded participants were on average 3.5 months older ($t(10.43) = -2.43$, $p = .043$), partly because a high proportion of them missed testing sessions at the very end of the school year, just before summer break.

Three subgroups of poor academic achievers were identified within this sample, based on their scores on composite measures of reading and mathematics – specifically, reading fluency and calculation – previously adjusted for age and testing month. Children were classified as poor readers only (PR) if they scored at or below the 30th percentile of the total sample in reading and above the 30th percentile in mathematics. Poor mathematics achievers

only (PM) were defined as those scoring at or below the 30th percentile in mathematics and above the 30th percentile in reading. Finally, children were identified as having co-occurring reading and mathematics difficulties (PR-PM) if they scored at or below the 30th percentile in both reading and mathematics. According to these criteria, 70 participants were classified as PR, 70 as PM, and 69 as PR-PM. The remaining 252 participants, who scored above the 30th percentile in both domains, constituted the control group of average achievers.

These methodological decisions were guided by several considerations. First, although classifying children into low-performing groups based on standardized test norms would have been ideal, this approach was not adopted because the standardizations for the reading and mathematics batteries dated back approximately 15–20 years, were based on relatively small samples of 50–100 participants per age group (Jacquier-Roux et al., 2010; von Aster & Dellatolas, 2006), and, for the *Calculation* and *Math Fluency* subtests of the WJ-III battery (Woodcock et al., 2001), were not available for French participants. Second, the 30th percentile was deliberately chosen as a liberal threshold, consistent with the aim of this study to target poor performers rather than specifically children with severe reading or mathematics difficulties, and in line with previous research using this criterion (Grills et al., 2023; Mammarella et al., 2018; Matejko et al., 2023; Wanzek et al., 2021). Finally, the composite measures of reading and mathematics were based solely on foundational skills – namely, decoding and calculation – rather than higher-level abilities such as reading comprehension or word problem-solving. This decision was motivated by evidence that the cognitive processes underlying decoding and calculation may differ from those supporting higher-order comprehension and problem-solving skills (Cadime et al., 2024; Fuchs et al., 2008, 2010; Johann et al., 2020; W. Zhang et al., 2025), as also observed in Studies 1 and 2 of this thesis. Moreover, it ensured methodological consistency with previous research on co-occurring difficulties, which has predominantly classified children based on fundamental reading and mathematical skills such as word reading and calculation (e.g., Landerl et al., 2009; Mingozzi et al., 2024; Moll et al., 2015; Willcutt et al., 2013).

5.2.2. Procedure

The procedure for the present study is described in detail in Section 1.2. of the General Methodology. Notably, children were tested individually across four experimental sessions, each lasting approximately 30 minutes, with an average interval of one week between sessions. Specifically, academic performance in reading and mathematics was assessed in Session 1. Domain-general cognitive skills were measured in Session 2, and domain-specific

cognitive skills related to reading and mathematics were evaluated in Sessions 3 and 4, respectively. Sociodemographic information was additionally collected through a parental questionnaire (see Appendix 1).

5.2.3. Measures

The current study included measures of academic achievement, cognitive abilities, as well as SES and demographic variables. Detailed descriptions of these measures are provided in Section 1.3. of the General Methodology.

Academic achievement was assessed in both reading and mathematics. In the reading domain, four measures evaluated reading fluency: text reading, irregular word reading, regular word reading, and pseudoword reading fluency. A composite reading fluency score based on these four indicators was computed using PCA by extracting the individual factor loadings from the first component, which accounted for 84% of the total variance (see Appendix 12 for further details). In mathematics, calculation performance was measured via mental and written calculation tasks, as well as math fluency. A composite calculation score was similarly derived from these three indicators using PCA and extracting the individual factor loadings from the first component, accounting for 76% of the total variance (see Appendix 12).

Regarding **cognitive abilities**, because the current study focused on smaller subgroups of participants (around 70 participants per group of poor achievers), the number of cognitive factors included in the analyses was limited to three domain-general, three reading-specific, and three mathematics-specific variables. This decision was made to ensure adequate performance of the multinomial logistic regression model (Pate et al., 2023; Vittinghoff & McCulloch, 2007). The selection of variables was guided by both theoretical and empirical considerations, which are detailed below.

For ***domain-general abilities***, we included measures of the three core executive functions – working memory, inhibition, and cognitive flexibility (Diamond, 2013; Friedman & Miyake, 2017) – because (i) they are the most consistently associated with reading and/or mathematics difficulties (Swanson, 2012; van der Sluis et al., 2004; Willcutt et al., 2013), and (ii) selective attention, as measured by a visual search task, was not related to any academic outcomes or predictors examined in Studies 1 and 2 of this thesis (see Figures 4–6).

For ***reading-specific abilities***, we selected phonological awareness, RAN, and visual-attention span, because (i) these skills are primarily associated with reading decoding –

the component used to define reading difficulties in the present study – whereas oral language is more closely linked to reading comprehension (Araújo et al., 2015; Bianco et al., 2012; Bosse & Valdois, 2009; Muter et al., 2004; Valdois et al., 2019), a pattern also observed in Study 1 of this thesis (see Figure 4), (ii) phonological awareness and RAN may constitute shared risk factors for co-occurring reading and mathematics difficulties (Fuchs et al., 2025; Mingozzi et al., 2024; Slot et al., 2016), and (iii) visual-attention span has not yet been investigated in relation to mathematics difficulties.

For ***mathematics-specific abilities***, we included transcoding, symbolic comparison, and ANS acuity, because (i) deficits in these skills are among the most consistently reported in children struggling with mathematics (De Smedt et al., 2013; Haberstroh & Schulte-Körne, 2022; Kivirähk-Koor & Kiive, 2025; Schwenk et al., 2017), (ii) transcoding and symbolic comparison may also be involved in reading difficulties (Moll et al., 2015; Raddatz et al., 2017; Träff et al., 2017), and (iii) non-symbolic comparison of small quantities and number ordering were highly correlated with symbolic comparison (r = .76 and .56, respectively) and no prior evidence suggests that they may provide additional information beyond the ANS and symbolic comparison tasks in the context of studying co-occurring difficulties.

Among these cognitive variables, composite scores were computed using PCA for constructs assessed by multiple subtests – namely, working memory, phonological awareness, and transcoding (see Appendix 12).

Finally, several **covariates** were included to account for potential confounding effects, including sex, age, testing month, nonverbal IQ, and SES. Sex was coded as –0.5 for boys and 0.5 for girls. Age was coded continuously in months. Because children were tested at different time points throughout the school year, the timing of assessment could have influenced performance beyond age effects (Morrison et al., 2019). To address this, the month of testing (coded from 1 = September to 11 = July) was included as a covariate. Nonverbal IQ was assessed using the *Matrices* subtest of the WISC-V (Wechsler, 2014), which requires children to select the visual pattern that completes a logical sequence from five alternatives. SES was operationalized as a PCA composite score based on the highest educational and occupational level of either parent (see Appendix 12).

5.2.4. Data analyses

Within the study sample (N = 461), nine participants (1.95%) had missing data on a single cognitive variable due to technical issues during testing. Because multinomial logistic

regression requires complete datasets, these missing values were imputed using the missForest package in R (Stekhoven & Bühlmann, 2012), a non-parametric method based on random forests that predicts missing values from all other available data without imposing distributional assumptions (Stekhoven & Bühlmann, 2012; Zugarramurdi et al., 2022). To avoid bias, academic performance variables were excluded from the imputation procedure (Lavelle-Hill et al., 2024; Zugarramurdi et al., 2022). Following imputation, all academic and cognitive variables were regressed on age and testing month (Morrison et al., 2019), and residuals were extracted and used in the analyses to ensure that effects were not confounded by age or timing within the school year (Hart et al., 2016; Valdois et al., 2019; Van Bergen et al., 2017)[2]. All variables were then standardized – with higher *z* scores reflecting better performance – to facilitate interpretation of the model estimates. Finally, composite indices for reading fluency, calculation, working memory, phonological awareness, and transcoding were derived via PCA (see Appendix 12) and subsequently restandardized (Keenan et al., 2014; Willcutt et al., 2013).

Following data processing, a multinomial logistic regression was conducted using the nnet package in R (Venables & Ripley, 2002) to examine the cognitive factors uniquely associated with difficulties in reading only, mathematics only, and both domains. This approach allowed the simultaneous modeling of the probability of membership in one of the three low-achieving groups (i.e., PR, PM, and PR-PM) relative to the reference group of average achievers, while including multiple predictor variables – namely domain-general, reading-specific, and mathematics-specific factors. Covariates such as sex, age, testing month, nonverbal IQ, and SES were also included to control for potential confounding effects. In multinomial logistic regression, the model estimates the relative odds of belonging to each outcome category compared to the reference group (V. M. T. De Jong et al., 2019; Kwak & Clayton-Matthews, 2002). Results are expressed as odds ratios (OR), obtained by exponentiating the regression coefficients. An OR indicates how the odds of belonging to a specific group, relative to the reference group, change for a one-unit increase in a given predictor (Kwak & Clayton-Matthews, 2002). An OR different from 1 indicates that the predictor contributes to the odds of group membership (De Weerdt et al., 2013; Pek & Flora, 2018). Specifically, in the present study, an OR less than 1 indicates that a 1 *SD* increase in a cognitive predictor (i.e., better performance) decreases the odds of belonging to the respective poor achiever group, whereas an OR greater than 1 indicates the opposite (i.e., increased likelihood of group membership with higher predictor values). The statistical

[2] Performance on the global report task, which assessed visual-attention span, was additionally residualized on isolated letter recognition to control for potential confounding effects (Bosse & Valdois, 2009; Saksida et al., 2016).

significance of each OR was evaluated by whether its 95% CI excluded 1, with the magnitude of the OR providing an index of effect size (Kallogjeri & Piccirillo, 2023; Pek & Flora, 2018).

Finally, after identifying the cognitive factors associated with group membership, we examined the heterogeneity within each group of poor achievers. To this end, we analyzed the prevalence of cognitive weaknesses within the PR, PM, and PR-PM groups. A cognitive weakness was defined as a score below the 10th percentile of the control group distribution (Valdois et al., 2021). Although a data-driven approach such as LPA would have been preferable, the sample sizes within each group were too small to reliably implement such models (Wurpts & Geiser, 2014). Therefore, we examined the prevalence and combination of cognitive weaknesses among poor achievers, an approach commonly used in the literature (e.g., Carroll et al., 2016; W. W. L. Chan & Wong, 2020; J.-R. Cho & Ji, 2011; Valdois et al., 2021).

5.3. Results

Descriptive statistics and bivariate correlations for all study variables, computed on the entire sample, are reported in Appendices 13 and 14, respectively.

5.3.1. Descriptive statistics and group comparisons

Descriptive statistics and results of group comparisons between PR, PM, PR-PM, and average achievers are presented in Table 17.

Variable	PR (n = 70) Mean (SD)	PM (n = 70) Mean (SD)	PR-PM (n = 69) Mean (SD)	Average achievers (n = 252) Mean (SD)	F	η^2_p
Demographics, SES, and nonverbal IQ						
Sex (% of girls)	45.71%	62.86%	65.22%	47.62%	_	_
Age	102.60 (4.74)[a]	102.29 (4.34)[a]	103.07 (5.03)[a]	102.42 (4.65)[a]	0.42	0.00
Testing month	6.53 (3.07)[a]	5.93 (3.30)[a]	6.48 (3.33)[a]	6.04 (3.18)[a]	0.77	0.01
SES	–0.11 (0.94)[ab]	–0.35 (0.97)[a]	–0.52 (0.98)[a]	0.26 (0.94)[b]	15.21***	0.10
Nonverbal IQ	–0.19 (0.90)[ab]	–0.26 (1.01)[a]	–0.46 (0.93)[a]	0.25 (0.97)[b]	13.45***	0.08
Academic achievement						
Reading	–0.99 (0.29)[a]	0.20 (0.72)[b]	–1.18 (0.42)[a]	0.54 (0.81)[b]	169.80***	0.53
Mathematics	0.23 (0.50)[a]	–1.07 (0.59)[b]	–1.33 (0.71)[b]	0.60 (0.59)[c]	272.97***	0.64
Domain-general cognitive variables						
Working memory	–0.08 (0.83)[a]	–0.54 (0.86)[ab]	–0.83 (0.73)[b]	0.40 (0.93)[c]	46.72***	0.24
Inhibition	–0.09 (1.06)[ab]	–0.34 (0.99)[a]	–0.39 (1.20)[a]	0.22 (0.86)[b]	11.23***	0.07
Cognitive flexibility	0.05 (0.82)[ab]	–0.36 (0.93)[bc]	–0.63 (1.29)[c]	0.26 (0.86)[a]	20.13***	0.12
Reading-specific cognitive variables						
Phonological awareness	0.07 (0.81)[a]	–0.25 (1.04)[ab]	–0.64 (1.15)[b]	0.22 (0.91)[a]	16.66***	0.10
RAN	–0.35 (1.16)[a]	–0.14 (0.90)[ab]	–0.44 (1.14)[a]	0.26 (0.86)[b]	14.52***	0.09
Visual-attention span	–0.61 (0.87)[a]	–0.01 (0.94)[b]	–0.78 (1.00)[a]	0.39 (0.83)[b]	45.61***	0.23
Mathematics-specific cognitive variables						
Transcoding	–0.02 (0.88)[a]	–0.38 (0.97)[ab]	–1.06 (1.50)[b]	0.40 (0.49)[c]	58.79***	0.28
Symbolic comparison	–0.01 (0.83)[ab]	–0.47 (0.91)[a]	–0.56 (1.02)[a]	0.29 (0.95)[b]	21.77***	0.13
ANS acuity	–0.10 (0.88)[ab]	–0.11 (0.76)[ab]	–0.42 (1.25)[a]	0.17 (0.97)[b]	7.40***	0.05

Table 17. Descriptive statistics and group comparisons between PR, PM, PR-PM, and average achievers. All variables, except sex, age, and testing month, are expressed as z scores. Academic and cognitive variables were adjusted for age and testing month; higher z scores indicate better performance. Groups sharing the same superscript do not differ significantly based on ANOVA post hoc pairwise comparisons with Bonferroni correction. SES data were missing for 47 participants (10 PR, 7 PM, 8 PR-PM, and 22 average achievers). PR = poor readers only; PM = poor mathematics achievers only; PR-PM = co-occurring poor readers and poor mathematics achievers; SES = socioeconomic status; RAN = rapid automatized naming; ANS = approximate number system. ***p < .001.

The four groups of poor academic achievers did not differ from each other or from average achievers in age or testing month. Regarding sex distribution, a significant overall effect was observed ($\chi^2(3) = 11.20$, $p = .011$); however, none of the Bonferroni-corrected post hoc pairwise comparisons reached significance, indicating that differences were not strong enough to be detectable after correction. Regarding nonverbal IQ and SES, both PM and PR-PM had lower IQ scores and came from lower SES backgrounds than average achievers, whereas PR did not significantly differ from average achievers.

For academic performance, both PR and PR-PM underperformed relative to average achievers in reading, while PM did not differ significantly from average achievers in reading. In mathematics, all three groups of poor achievers performed significantly lower than average achievers. Yet, PR outperformed both PM and PR-PM in mathematics, while scoring within the average range (mean *z* score = 0.23).

Regarding cognitive abilities, PR scored significantly lower than average achievers on working memory, RAN, visual-attention span, and transcoding. PM scored significantly lower than average achievers on working memory, inhibition, cognitive flexibility, transcoding, and symbolic comparison. Finally, PR-PM scored significantly lower than average achievers across all domain-general, reading-specific, and mathematics-specific variables.

5.3.2. Multinomial logistic regression

To examine the cognitive factors uniquely predicting membership to each of the three groups of poor achievers relative to the reference group of average achievers, a multinomial logistic regression model was performed. Results of the model are illustrated in Figure 11 and detailed in Table 18.

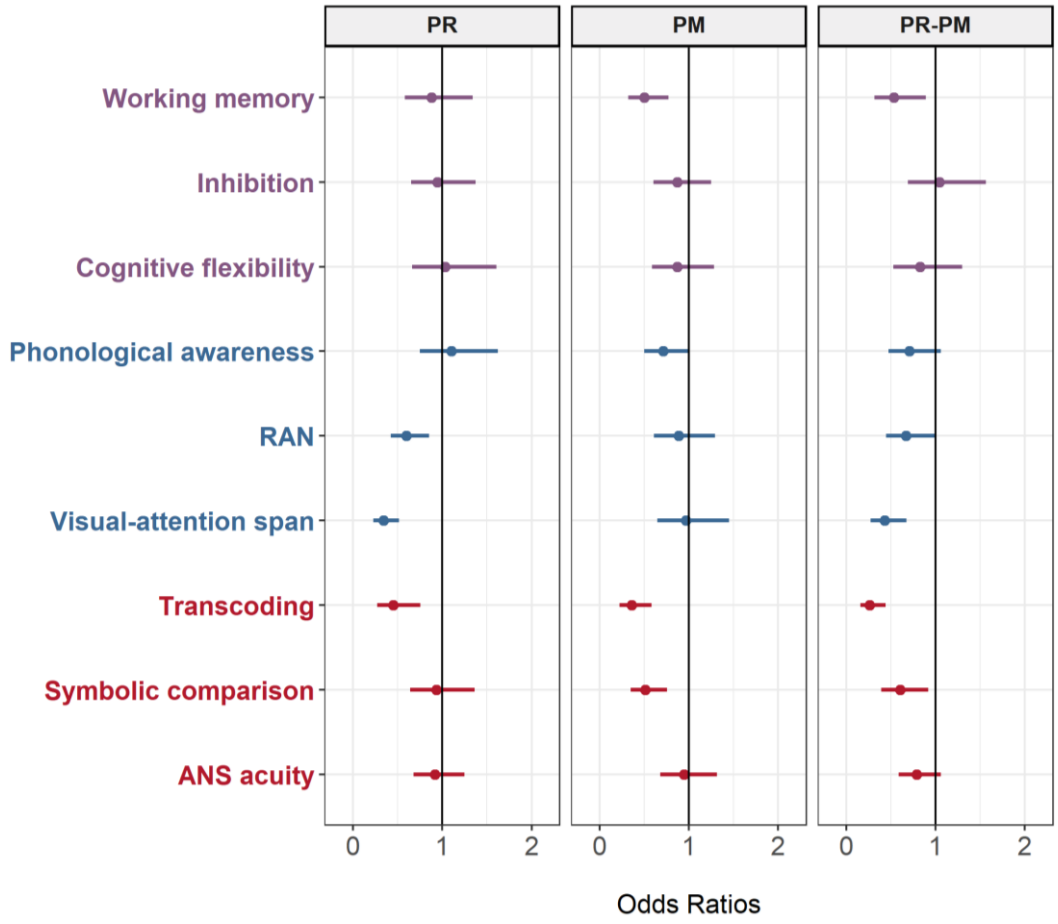

Figure 11. Cognitive predictors of group membership. Odds ratios and their 95% CI from the multinomial logistic regression model are shown. A predictor is considered to significantly contribute to group membership when the 95% CI of its odds ratio does not include 1. The average achievers group served as the reference category. Domain-general variables are shown in purple, reading-specific variables in blue, and mathematics-specific variables in red. Covariates were included in the model (see Table 18) but are not displayed in the figure to aid clarity. PR = poor readers only; PM = poor mathematics achievers only; PR-PM = co-occurring poor readers and poor mathematics achievers; RAN = rapid automatized naming; ANS = approximate number system; CI = confidence interval.

The results indicated that, among domain-general cognitive factors, working memory significantly predicted membership in the PM (OR = 0.50, 95% CI [0.32,0.77], p = .002) and PR-PM groups (OR = 0.53, 95% CI [0.32,0.89], p = .017). Specifically, an increase in working memory performance was associated with decreased odds of belonging to these groups. In contrast, inhibition and cognitive flexibility did not significantly predict group membership.

For reading-specific cognitive factors, both RAN and visual-attention span significantly predicted membership in the PR (RAN: OR = 0.60, 95% CI [0.42, 0.85], p = .004; Visual-attention span: OR = 0.34, 95% CI [0.23, 0.51], p < .001) and PR-PM groups (RAN: OR = 0.67, 95% CI [0.45, 0.99], p = .049; Visual-attention span: OR = 0.43, 95% CI [0.27, 0.67], p < .001). Specifically, increased RAN and visual-attention span were associated with decreased odds of belonging to these groups. In contrast, phonological awareness did not significantly predict group membership.

For mathematics-specific cognitive factors, symbolic comparison significantly predicted membership in the PM (OR = 0.51, 95% CI [0.35, 0.75], p < .001) and PR-PM groups (OR = 0.60, 95% CI [0.39, 0.92], p = .019), whereas transcoding was a significant predictor across all three groups, including PM (OR = 0.36, 95% CI [0.22, 0.58], p < .001), PR-PM (OR = 0.26, 95% CI [0.16, 0.44], p < .001), and PR (OR = 0.45, 95% CI [0.27, 0.75], p = .002). Specifically, increased performance in symbolic comparison and transcoding were associated with decreased odds of belonging to the respective low-achieving groups. ANS acuity did not significantly predict group membership.

Variables	PR			PM			PR-PM		
	β (SE)	OR	95% CI	β (SE)	OR	95% CI	β (SE)	OR	95% CI
Cognitive variables									
Working memory	–0.13 (0.21)	0.88	[0.58, 1.34]	–0.70 (0.22)**	0.50	[0.32, 0.77]	–0.63 (0.26)*	0.53	[0.32, 0.89]
Inhibition	–0.06 (0.19)	0.94	[0.65, 1.37]	–0.14 (0.18)	0.87	[0.60, 1.25]	0.04 (0.21)	1.04	[0.69, 1.57]
Cognitive flexibility	0.03 (0.23)	1.03	[0.66, 1.60]	–0.14 (0.20)	0.87	[0.59, 1.28]	–0.19 (0.23)	0.83	[0.53, 1.30]
Phonological awareness	0.10 (0.20)	1.10	[0.75, 1.62]	–0.34 (0.18)	0.71	[0.50, 1.01]	–0.35 (0.21)	0.71	[0.47, 1.06]
RAN	–0.52 (0.18)**	0.60	[0.42, 0.85]	–0.12 (0.19)	0.89	[0.61, 1.29]	–0.40 (0.21)*	0.67	[0.45, 0.99]
Visual-attention span	–1.08 (0.21)***	0.34	[0.23, 0.51]	–0.03 (0.21)	0.97	[0.64, 1.45]	–0.85 (0.23)***	0.43	[0.27, 0.67]
Transcoding	–0.80 (0.26)**	0.45	[0.27, 0.75]	–1.03 (0.25)***	0.36	[0.22, 0.58]	–1.33 (0.26)***	0.26	[0.16, 0.44]
Symbolic comparison	–0.07 (0.19)	0.93	[0.64, 1.36]	–0.67 (0.20)***	0.51	[0.35, 0.75]	–0.51 (0.22)*	0.60	[0.39, 0.92]
ANS acuity	–0.09 (0.16)	0.92	[0.68, 1.25]	–0.06 (0.17)	0.94	[0.68, 1.31]	–0.24 (0.15)	0.79	[0.59, 1.06]
Covariates									
Sex	–0.07 (0.35)	0.93	[0.47, 1.85]	0.70 (0.36)	2.02	[0.99, 4.12]	0.53 (0.41)	1.70	[0.76, 3.80]
Age	–0.04 (0.22)	0.96	[0.62, 1.48]	0.06 (0.23)	1.06	[0.67, 1.67]	0.08 (0.26)	1.09	[0.66, 1.79]
Testing month	0.23 (0.22)	1.26	[0.81, 1.94]	–0.09 (0.23)	0.91	[0.58, 1.44]	0.26 (0.26)	1.29	[0.77, 2.16]
Nonverbal IQ	–0.38 (0.19)*	0.68	[0.47, 0.99]	–0.34 (0.19)	0.71	[0.49, 1.04]	–0.57 (0.22)*	0.57	[0.36, 0.88]
SES	–0.14 (0.19)	0.87	[0.60, 1.25]	–0.25 (0.19)	0.78	[0.54, 1.12]	–0.37 (0.22)	0.69	[0.45, 1.05]

Table 18. Results of the multinomial logistic regression model examining predictors of group membership. The average achievers group served as the reference category. PR = poor readers only; PM = poor mathematics achievers only; PR-PM = co-occurring poor readers and poor mathematics achievers; SE = standard error; OR = odds ratio; CI = confidence interval; RAN = rapid automatized naming; ANS = approximate number system; SES = socioeconomic status. *p < .05; **p < .01; ***p < .001.

5.3.3. Prevalence of cognitive weaknesses

To investigate interindividual variability within each group of poor achievers, we examined the prevalence and combination of cognitive weaknesses in the PR, PM, and PR-PM groups (see Valdois et al., 2021, for a similar approach). For clarity and interpretability, we focused on the prevalence of weaknesses in the five cognitive factors that emerged as significant predictors of group membership in the multinomial logistic regression (i.e., working memory, RAN, visual-attention span, transcoding, and symbolic comparison). An overview of the prevalence of cognitive weaknesses across all variables is provided in Appendix 17. Moreover, for reference, the prevalence of cognitive weaknesses in the five variables considered for the average achievers group is presented in Appendix 18.

5.3.3.1. Prevalence of cognitive weaknesses within PR

The prevalence and combination of cognitive weaknesses within the PR group is presented in Figure 12. Among PR, the most prevalent weaknesses were observed in reading-specific skills, namely visual-attention span (47%) and RAN (26%), either in isolation or in combination with weaknesses in other cognitive abilities. Weaknesses in mathematics-specific skills, including transcoding (23%) and symbolic comparison (23%), were also present, whereas working memory weaknesses were the least frequent (13%).

Regarding the combination of cognitive weaknesses, 41% of PR exhibited isolated weaknesses, most often in visual-attention span (19%) or RAN (7%). Additionally, 37% showed multiple weaknesses, typically involving two cognitive skills – for instance, visual-attention span combined with mathematics-specific skills (14%), RAN combined with mathematics-specific skills (7%), or visual-attention span combined with RAN (4%) were the most frequent combinations. Weaknesses in more than two cognitive skills were relatively rare (13%). Finally, 21% of PR showed no weaknesses among the five cognitive skills considered.

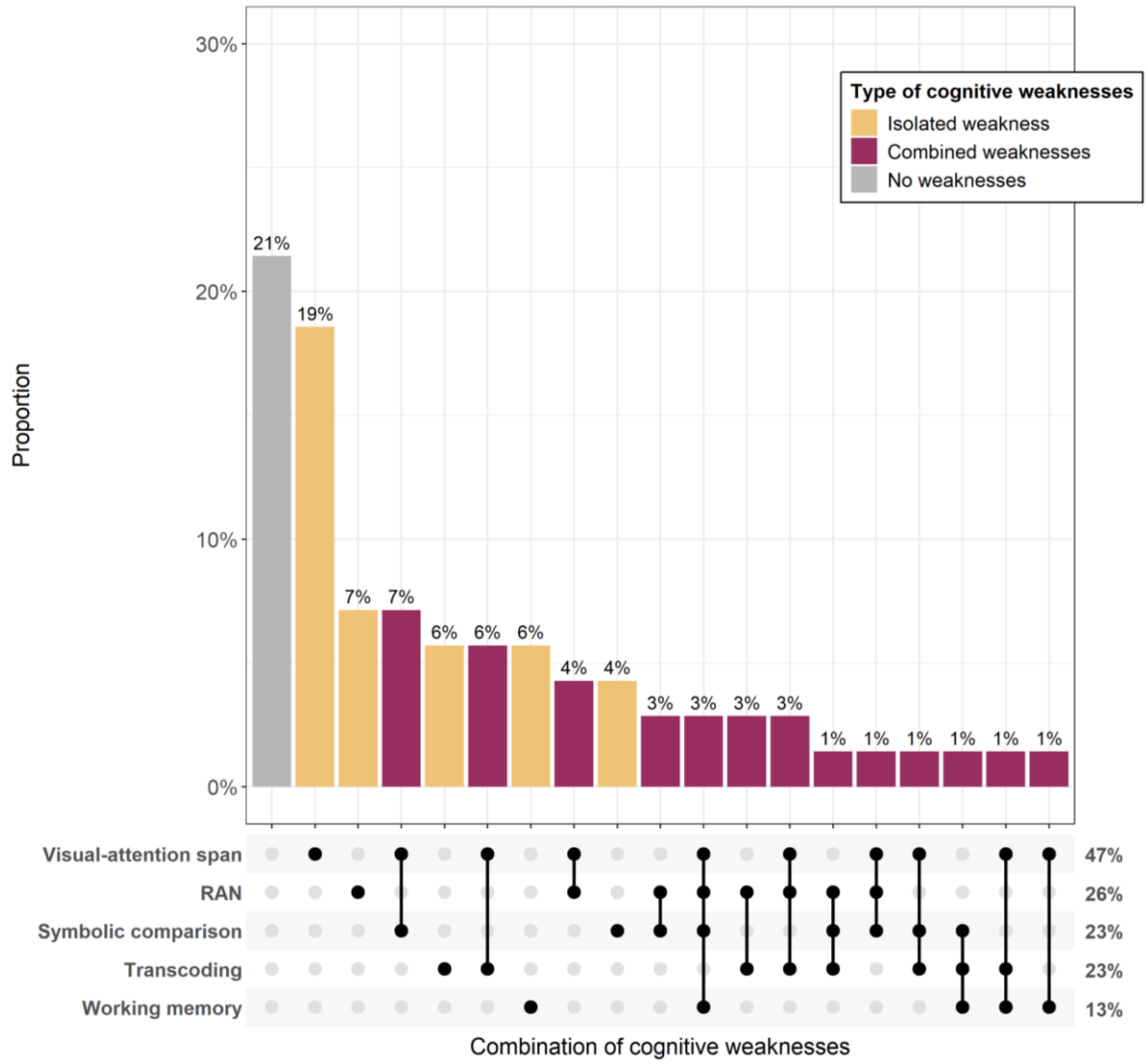

Figure 12. Prevalence and combination of cognitive weaknesses in the PR group. Percentages above bars indicate the proportion of children exhibiting a given combination of cognitive weaknesses. Percentages at the right end of each row indicate the total proportion of children showing a weakness in that cognitive ability. A cognitive weakness was defined as a score at or below the 10th percentile of the average achievers group. Minor discrepancies between percentages reported in the text and those shown in the figure may occur due to rounding. RAN = rapid automatized naming; PR = poor readers only.

5.3.3.2. Prevalence of cognitive weaknesses within PM

The prevalence and combination of cognitive weaknesses within the PM group is presented in Figure 13.

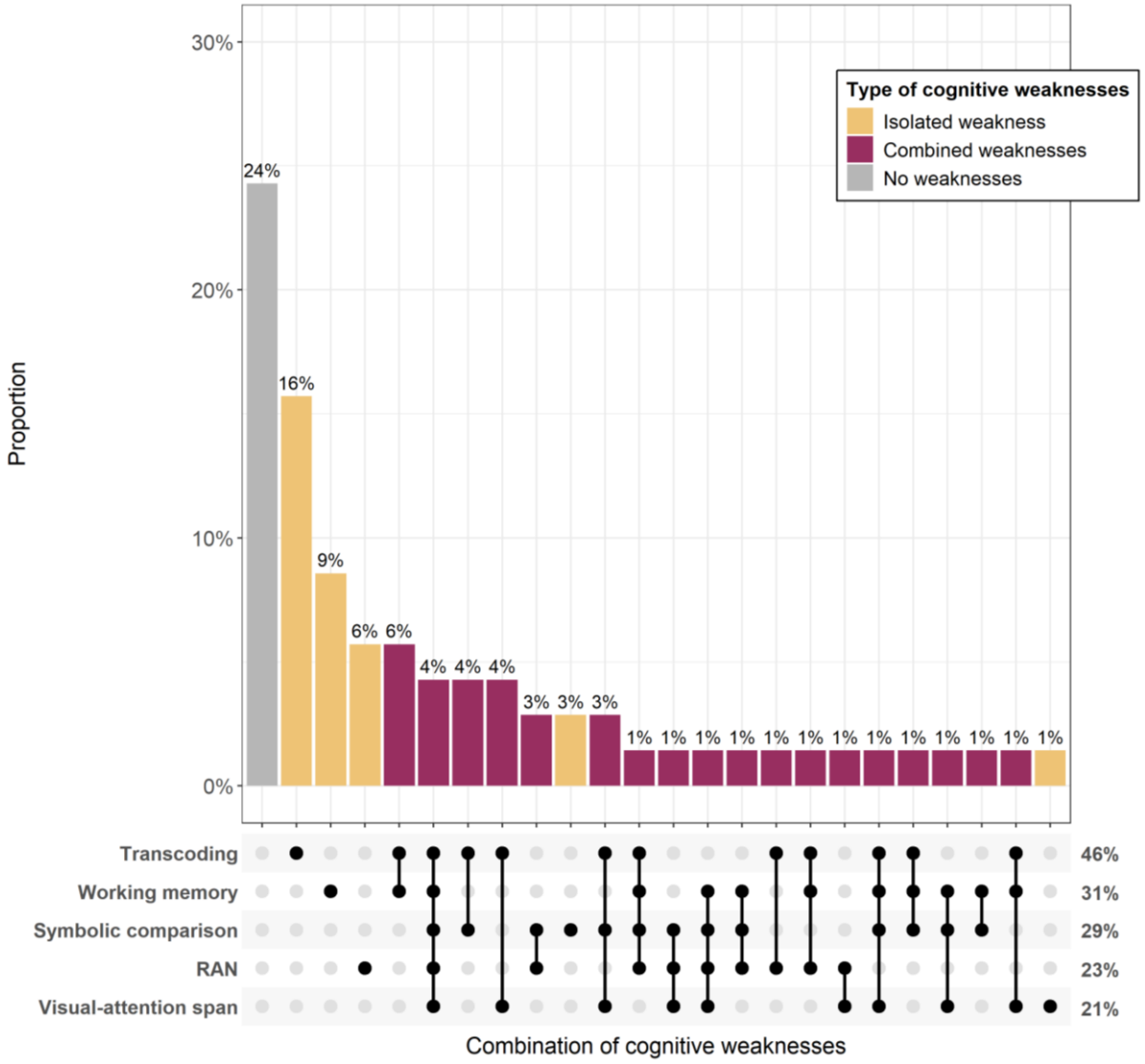

Figure 13. Prevalence and combination of cognitive weaknesses in the PM group. Percentages above bars indicate the proportion of children exhibiting a given combination of cognitive weaknesses. Percentages at the right end of each row indicate the total proportion of children showing a weakness in that cognitive ability. A cognitive weakness was defined as a score at or below the 10th percentile of the average achievers group. Minor discrepancies between percentages reported in the text and those shown in the figure may occur due to rounding. RAN = rapid automatized naming; PM = poor mathematics achievers only.

Among PM, the most prevalent cognitive weaknesses were observed in transcoding (46%), working memory (31%), and symbolic comparison (29%). Weaknesses in

reading-specific skills, including RAN (23%) and visual-attention span (21%), were also present, though less frequent.

Regarding the combination of cognitive weaknesses, 34% of PM exhibited isolated weaknesses, most often in transcoding (16%) or working memory (9%), but also in RAN (6%). Additionally, 41% of PM displayed multiple cognitive weaknesses, with almost half showing weaknesses in two cognitive skills – most frequently in transcoding combined with working memory (6%), symbolic comparison (4%), or visual-attention span (4%) – and the other half showing weaknesses in more than two cognitive skills. Finally, 24% of PM showed no cognitive weaknesses in the five cognitive skills considered.

5.3.3.3. Prevalence of cognitive weaknesses within PR-PM

The prevalence and combination of cognitive weaknesses within the PR-PM group is presented in Figure 14. Among PR-PM, weaknesses in the five cognitive skills considered were relatively prevalent, most frequently observed in transcoding (61%), visual-attention span (51%), and working memory (45%), but also in symbolic comparison (38%) and RAN (30%).

Regarding the combination of cognitive weaknesses, only 17% of PR-PM exhibited isolated weaknesses, mainly in transcoding (7%), symbolic comparison (4%), and visual-attention span (4%). The vast majority of PR-PM (72%) displayed multiple cognitive weaknesses, with 42% of them showing weaknesses in at least three cognitive skills. The most frequent combinations involved weaknesses in transcoding, visual-attention span, and working memory. Finally, 10% of PR-PM showed no weaknesses in the five cognitive skills considered.

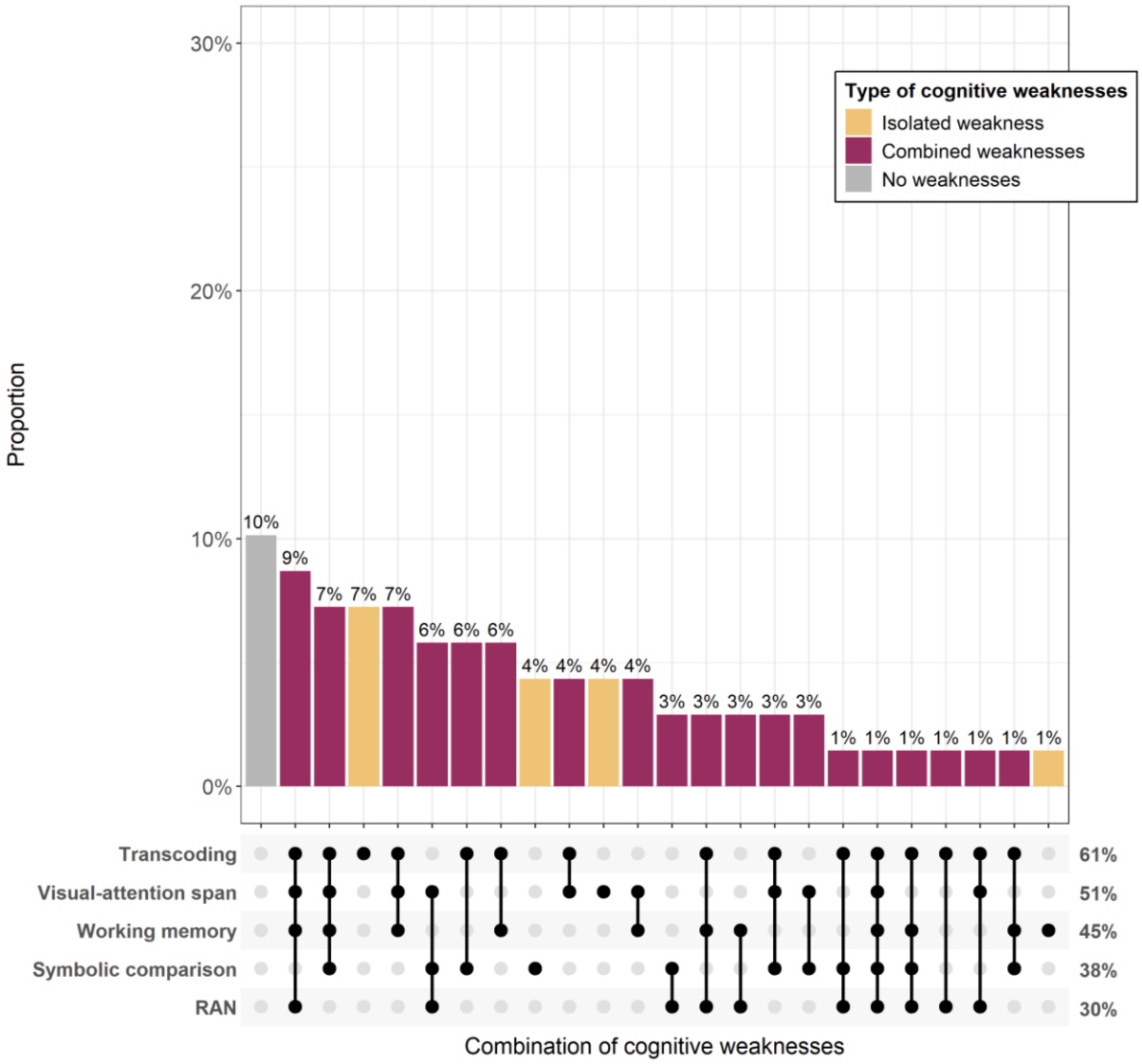

Figure 14. Prevalence and combination of cognitive weaknesses in the PR-PM group. Percentages above bars indicate the proportion of children exhibiting a given combination of cognitive weaknesses. Percentages at the right end of each row indicate the total proportion of children showing a weakness in that cognitive ability. A cognitive weakness was defined as a score at or below the 10th percentile of the average achievers group. Minor discrepancies between percentages reported in the text and those shown in the figure may occur due to rounding. RAN = rapid automatized naming; PR-PM = co-occurring poor readers and poor mathematics achievers.

5.4. Discussion

The present study aimed to: (i) examine the cognitive factors associated with isolated and co-occurring difficulties in reading and mathematics among third-grade children; and (ii) explore, for the first time, interindividual variability within each group of poor achievers (i.e., children with difficulties in reading only, mathematics only, or both academic domains). To this end, a multinomial logistic regression was conducted, including domain-general, reading-specific, and mathematics-specific cognitive factors to identify predictors of membership in each low-achieving group relative to a reference group of average achievers. This was followed by an analysis of the prevalence of cognitive weaknesses within each group to investigate intra-group heterogeneity.

The results indicated that, after controlling for sex, age, nonverbal IQ, and SES, membership in the poor readers only group was significantly predicted by RAN, visual-attention span, and transcoding, whereas membership in the poor mathematics achievers only group was predicted by working memory, symbolic comparison, and transcoding. Notably, membership in the group with co-occurring reading and mathematics difficulties was predicted by all the factors associated with the single-difficulty groups – namely, RAN, visual-attention span, working memory, symbolic comparison, and transcoding – reflecting an additive pattern of cognitive vulnerabilities in our sample of children with co-occurring difficulties. Furthermore, substantial heterogeneity in cognitive weaknesses was observed within each low-achieving group, with cumulative weaknesses across domain-general, reading-specific, and mathematics-specific abilities being particularly prevalent among children with co-occurring difficulties.

5.4.1. Cognitive factors associated with reading difficulties

With regard to reading difficulties, the results first revealed a unique contribution of RAN and visual-attention span to membership in the two groups of poor readers – those with isolated reading difficulties and those with co-occurring reading and mathematics difficulties. These findings are consistent with previous studies showing that both factors are independently associated with reading performance (Valdois et al., 2021; van den Boer et al., 2015; van den Boer & de Jong, 2018) and that deficits in RAN and visual-attention span are frequently observed in children with reading difficulties (Bosse et al., 2007; Dębska et al., 2022; Valdois et al., 2021; Ziegler et al., 2008). The present study extends this evidence by demonstrating that these predictive effects remain significant even after accounting for a broad range of other cognitive factors, and that they apply to poor readers both with and without co-occurring mathematics difficulties. Importantly, RAN and visual-attention span

were not predictive of membership in the group with isolated mathematics difficulties, highlighting a specific role in reading difficulties (Peterson et al., 2017).

Interestingly, transcoding also emerged as a significant predictor of group membership among children with poor reading, including not only those with co-occurring reading and mathematics difficulties, but also those with isolated reading difficulties. This finding aligns with previous evidence reporting transcoding deficits in children with reading difficulties (De Clercq-Quaegebeur et al., 2018; Moll et al., 2015; Raddatz et al., 2017; Teixeira & Moura, 2020). However, the present results extend these earlier findings by showing that transcoding remains a unique predictor of reading difficulties even after controlling for other cognitive skills – particularly phonological processes such as phonological awareness and RAN, on which transcoding is known to partly depend (Batista et al., 2023; Lopes-Silva et al., 2014). Moreover, the observed contribution of transcoding to reading difficulties may help explain why children with isolated reading difficulties, although performing within the average range in mathematics, nevertheless showed lower mathematical performance compared to average achievers.

Unlike prior research (Billard et al., 2010; Carroll et al., 2016; Grigorakis et al., 2022; S. Song et al., 2020), the present study did not find that phonological awareness uniquely contributed to reading difficulties. However, these previous studies included fewer cognitive predictors than the current study and focused predominantly on children with more severe reading difficulties. A possible explanation is that the predictive effect of phonological awareness on reading difficulties may be evident mainly in children with severe reading difficulties by third grade (Peterson & Pennington, 2015). An alternative explanation is that phonological awareness may share variance with other cognitive factors included in the present study, potentially obscuring its unique contribution to reading difficulties. Specifically, transcoding – identified here as a significant predictor – involves phonological processes such as phonological encoding and segmentation of verbal numerical inputs for conversion into written code (Batista et al., 2023; Lopes-Silva et al., 2014). Moreover, the predominant involvement of transcoding, rather than phonological awareness, in predicting reading difficulties in the present study suggests that additional aspects of transcoding unrelated to phonological awareness – such as the ability to associate auditory inputs (even non-linguistic ones) with visual symbols (Cirino et al., 2018) – may play a crucial role in reading (Altarelli et al., 2019; Pasqualotto et al., 2024).

5.4.2. Cognitive factors associated with mathematics difficulties

With regard to mathematics difficulties, the results first highlighted a significant contribution of working memory, both in children with isolated mathematics difficulties and in those with co-occurring mathematics and reading difficulties. These findings are consistent with prior evidence demonstrating the involvement of working memory in mathematics difficulties (David, 2012; Kroesbergen et al., 2023) and indicate that its effect is independent of other cognitive factors, including domain-specific mathematical skills (Mononen, Niemivirta, & Korhonen, 2022; Slot et al., 2016) – at least in the broader population of poor achievers. Notably, working memory did not emerge as a unique predictor of reading difficulties, suggesting a stronger influence on mathematics than on reading challenges (Morgan et al., 2017). Furthermore, other executive functions, such as inhibition and cognitive flexibility, were not significant predictors of mathematics difficulties, potentially reflecting a predominant role of working memory among executive functions in predicting mathematics performance (Bull & Lee, 2014; Spiegel et al., 2021). However, it cannot be ruled out that inhibition and cognitive flexibility may contribute to mathematics difficulties at other developmental stages, particularly in older children (Iglesias-Sarmiento et al., 2023).

In addition, symbolic comparison was found to contribute uniquely to mathematics difficulties, both in children with isolated mathematics difficulties and in those with co-occurring mathematics and reading difficulties. In contrast, non-symbolic magnitude processing did not emerge as a significant predictor in either group. These findings align with previous studies showing that symbolic skills are more predictive of mathematics performance than non-symbolic skills, at least after the onset of formal schooling (Fazio et al., 2014; Schneider et al., 2017). Furthermore, transcoding also uniquely predicted mathematics difficulties in both isolated and co-occurring groups, corroborating prior research reporting transcoding deficits in children with mathematics difficulties (Kivirähk-Koor & Kiive, 2025; Moura et al., 2013). Importantly, this effect was observed even when accounting for domain-general skills and phonological processes, such as phonological awareness and RAN (Vanbinst et al., 2020). Finally, such phonological processes did not predict isolated mathematics difficulties, thus providing no evidence for an association between phonological processing and mathematics performance, at least once domain-general and mathematics-specific skills are considered (Cirino et al., 2024; Durand et al., 2005; Fuchs et al., 2016; Peterson et al., 2017).

5.4.3. Cognitive patterns of co-occurring difficulties in reading and mathematics

For children with co-occurring difficulties in reading and mathematics, the results revealed a pattern reflecting the combination of the factors contributing to isolated reading difficulties and isolated mathematics difficulties. Specifically, RAN, visual-attention span, transcoding, symbolic comparison, and working memory emerged as unique predictors of co-occurring difficulties. These findings support the Additive model (Figure 3), which posits that co-occurring difficulties arise from the cumulative effect of cognitive factors independently associated with each domain (Ashkenazi et al., 2013; L. Peters & Ansari, 2019; Starling-Alves et al., 2025). Moreover, the results extend previous studies reporting such additive patterns (e.g., Landerl et al., 2009; Moll et al., 2015; Schwenck et al., 2015) by a simultaneous consideration of multiple domain-general, reading-specific, and mathematics-specific cognitive factors – an approach never before adopted so comprehensively in prior research.

Furthermore, although we found no evidence that language-related skills – particularly phonological processes – contribute to the co-occurrence of reading and mathematics difficulties, as would be predicted by the Increased Risk model (L. Peters & Ansari, 2019; Starling-Alves et al., 2025), the results indicate that transcoding might serve as a shared risk factor, predicting membership in all three groups of poor achievers. This suggests that transcoding may rely on cognitive mechanisms common to both reading and mathematics, such as the ability to associate phonological representations with visual symbols – which could explain its role across both domains (Cirino et al., 2018). However, it is also possible that the processes underlying transcoding weaknesses may differ between poor readers and poor mathematics achievers – for instance, reflecting impaired phonological processes in the former group and impaired numerical symbol processing in the latter one (Lopes-Silva et al., 2016; Moll et al., 2015). This hypothesis warrants further investigation and has important implications for better understanding the role of transcoding in reading and mathematics difficulties, and particularly in their co-occurrence.

5.4.4. Within-group cognitive heterogeneity

The results of this study also revealed significant cognitive heterogeneity within each group of poor achievers. While previous studies had identified distinct cognitive subtypes among poor readers (Valdois et al., 2021; Willems et al., 2016) and poor mathematics achievers (Bartelet et al., 2014; W. W. L. Chan & Wong, 2020; Ouyang et al., 2024), they typically did not assess performance in the other academic domain, leaving it unclear whether some of the observed variability could be attributed to children with co-occurring difficulties

versus those with difficulties confined to a single domain. The present study addresses this gap and demonstrates that cognitive heterogeneity exists even among poor readers only and poor mathematics achievers only. Specifically, among children with isolated reading difficulties, most exhibited isolated cognitive weaknesses, particularly in visual-attention span and RAN, whereas combined weaknesses across these two skills were less common (Valdois et al., 2021). Similarly, among children with poor mathematics performance, isolated weaknesses in transcoding and working memory were more frequent than cumulative weaknesses across both abilities. However, weaknesses in symbolic comparison were more often observed in combination with other cognitive weaknesses than in isolation, suggesting that symbolic comparison weaknesses may especially contribute to poor mathematical performance when occurring alongside other cognitive weaknesses (Toll et al., 2016).

Importantly, the results also showed, for the first time, that children with co-occurring difficulties in reading and mathematics constitute a heterogeneous population, exhibiting distinct patterns of cognitive weaknesses. Notably, the prevalence of isolated cognitive weaknesses in this group was much lower than that of multiple cognitive weaknesses, indicating that a combination of cognitive weaknesses observed in single-difficulty groups characterizes the majority of children with co-occurring difficulties. While this pattern aligns with the Additive model (Ashkenazi et al., 2013; L. Peters & Ansari, 2019; Starling-Alves et al., 2025), it nevertheless appears that not all children with co-occurring difficulties share the same combination of cognitive weaknesses, emphasizing the importance of considering this heterogeneity when designing targeted interventions.

Furthermore, it is worth noting that approximately 20% of children with poor reading only exhibited weaknesses in mathematics-specific skills – such as symbolic comparison – and around 20% of children with poor mathematics only showed weaknesses in reading-specific skills, such as RAN or visual-attention span. This suggests that cross-domain associations – for instance, between symbolic processing and reading (Moll et al., 2015; Träff et al., 2017) or between RAN and mathematics (Cui et al., 2017; Georgiou, Tziraki, et al., 2013) – may reflect shared processes that could contribute to difficulties in the other academic domain for a subset of children, without emerging as significant predictors at the group level. Alternatively, poor readers with mathematics-specific weaknesses and poor mathematics achievers with reading-specific weaknesses may also perform moderately below average in the other domain, without meeting the criteria for poor performance (as defined in this study by a score below the 30th percentile). Indeed, previous studies have shown that children with isolated reading or mathematics difficulties often perform below average achievers in the other domain as well

(Andersson, 2010; Cirino et al., 2015; Connors et al., 2025; Starling-Alves et al., 2025; Swanson, Jerman, et al., 2009; Willcutt et al., 2013). To further explore these cross-domain effects, future research adopting dimensional approaches rather than categorical cut-offs would complement the present study by allowing for an examination of how cognitive factors contribute to the overlap between reading and mathematics across the full ability spectrum (Cirino et al., 2024; Jöbstl et al., 2023; L. Peters & Ansari, 2019; Vanbinst et al., 2020).

Finally, in each group of poor achievers, approximately 10–25% of children exhibited no weaknesses in the cognitive skills examined, a pattern also reported in previous studies (Bartelet et al., 2014; W. W. L. Chan & Wong, 2020; Ouyang et al., 2024; Valdois et al., 2021; Willems et al., 2016). This suggests that the academic difficulties observed in these children may be attributable to factors not considered in the present study, such as other cognitive abilities (e.g., planning, spatial skills, counting) (Deng et al., 2022; Geary et al., 2020; Moll et al., 2015) or emotional factors (e.g., anxiety, motivation) (Hart et al., 2016; Parhiala et al., 2018). However, these results should be interpreted with caution, as they are based on frequency distributions from relatively small groups. Larger-scale studies are needed to confirm these patterns and to investigate a broader range of factors that may contribute to poor academic performance in children who do not show measurable weaknesses in the assessed skills.

5.4.5. Educational implications

Overall, the findings of this study suggest that children with isolated reading difficulties may benefit from interventions targeting RAN (e.g., Vander Stappen & Reybroeck, 2018) and visual-attention span (e.g., Valdois et al., 2025), whereas children with isolated mathematics difficulties may benefit more from support aimed at enhancing working memory and symbolic processing skills (e.g., DePascale et al., 2024). Furthermore, strengthening transcoding skills appears to be important for all these children, regardless of whether their difficulties occur in reading or mathematics. Importantly, children with co-occurring difficulties in both domains may require more comprehensive support targeting all of these cognitive skills simultaneously. Nevertheless, the substantial interindividual variability observed within each group underlines the need for individualized interventions tailored to each child's specific cognitive profile, rather than relying solely on the type of academic difficulties experienced (Astle et al., 2019; Moll et al., 2019; Starling-Alves et al., 2025). Moreover, effective evaluation and support should consider a broad range of cognitive factors, encompassing both domain-specific and domain-general skills, to optimize outcomes for each child.

5.4.6. Limitations and future directions

This study has several limitations that should be considered when interpreting the results. First, its correlational design, with all measurements collected at a single time point, does not permit causal inferences regarding whether the identified cognitive factors lead to difficulties in reading and/or mathematics. Longitudinal studies are needed to examine whether cognitive weaknesses at a given time point predict the subsequent emergence of isolated versus co-occurring difficulties in these domains. Furthermore, interventional studies could also help address this issue by testing whether training specific cognitive skills improves reading and/or mathematics performance in the different groups of low-achieving children. Nevertheless, the present study could serve as a foundation for identifying the most promising cognitive skills to target in future interventions. Such an interventional approach would further help clarify which factors are causally involved in poor reading, poor mathematics achievement, or both.

Furthermore, the sample consisted exclusively of third-grade children. While limiting age-related variability among participants, it does not preclude the possibility that other cognitive factors may contribute to isolated or co-occurring difficulties in reading and mathematics at different developmental stages. Additionally, although the sample sizes for each group of poor achievers were comparable to, or even larger than, those in previous studies (e.g., Cirino et al., 2015; De Weerdt et al., 2013; Landerl et al., 2009; Raddatz et al., 2017), they remain relatively small, particularly for robustly characterizing interindividual variability within each group. Future research with larger samples is needed to examine intra-group variability more thoroughly. This would also allow the application of data-driven approaches, such as latent profile analyses (LPA). These approaches have the advantage of enabling the identification of distinct cognitive subtypes within groups, emerging directly from the data rather than relying on arbitrary cut-offs for low ability (Astle et al., 2022; Starling-Alves et al., 2025).

Finally, although this study incorporated a broad range of cognitive factors – including domain-general, reading-specific, and mathematics-specific skills – it is possible that other dimensions not considered here may also contribute to isolated or co-occurring difficulties in reading and mathematics. This possibility is further suggested by the finding that 10 to 25% of low-achieving children did not exhibit any weaknesses in the cognitive skills examined. In particular, cognitive factors such as planning (Deng et al., 2022), spatial skills (Geary et al., 2020; L. Peters et al., 2020), or counting (Fuchs et al., 2025; Moll et al., 2015; Raddatz et al.,

2017), as well as emotional factors (Geary et al., 2020; Hart et al., 2016; Parhiala et al., 2018), may play an important role in these difficulties and warrant further investigation. Furthermore, extending this approach to investigate the correlates of more complex academic skills, such as reading comprehension and word problem-solving, could provide insight into whether the patterns underlying co-occurring difficulties differ depending on whether foundational or higher-order academic outcomes are considered (Compton et al., 2012), thereby informing the design of (even) more tailored interventions.

5.4.7. Conclusion

In conclusion, this study demonstrated that co-occurring difficulties in reading and mathematics are characterized by a combination of cognitive factors that independently contribute to difficulties in each domain, supporting an additive pattern. Specifically, working memory, RAN, visual-attention span, symbolic comparison, and transcoding emerged as unique predictors of co-occurring difficulties. Furthermore, the results of this study reveal substantial heterogeneity in the cognitive weaknesses exhibited by children within each low-achieving group, emphasizing the importance of individualized approaches to effectively address each child's specific cognitive needs.

Overall, the present study highlighted that some of the variability observed among poor readers and poor mathematics achievers may reflect whether they also experience difficulties in the other domain. A broader range of cognitive factors appeared to contribute to co-occurring difficulties compared to isolated difficulties, with the vast majority of children with co-occurring difficulties exhibiting multiple cognitive weaknesses. Importantly, however, interindividual variability cannot be fully explained by co-occurrence alone, as distinct patterns of cognitive weaknesses were also observed among children with isolated reading or mathematics difficulties, as well as in those with co-occurring difficulties. This underlines the need for future studies with larger samples to better characterize this variability and to tailor support to each child's specific profile regardless of the type of academic difficulties experienced. Altogether, by jointly considering domain-general, reading-specific, and mathematics-specific factors in relation to both reading and mathematics, this study advances our understanding of the specific and overlapping processes underlying these academic domains.

Part 3: General discussion

The overarching objective of this thesis was to advance our understanding of the multifaceted factors associated with poor academic performance in reading and mathematics among primary school children. To this end, a comprehensive framework was adopted, assessing both domain-specific and domain-general cognitive factors, emotional factors – such as math anxiety (MA) – and environmental factors including parental socioeconomic status (SES) in a socioeconomically diverse sample of third-grade children. More specifically, this thesis aimed to (i) examine the extent to which SES and MA are related to different academic outcomes and whether cognitive factors mediate these relationships, and (ii) investigate the predictors of poor performance in reading and/or mathematics, while assessing interindividual variability within these populations.

1. A multi-level approach to academic achievement: socioeconomic, cognitive, and emotional influences

Academic performance in reading and mathematics results from the interplay of multiple influences, including socioeconomic (J. Liu et al., 2022a; Selvitopu & Kaya, 2023; Sirin, 2005), cognitive (Geary, 2013; Hulme & Snowling, 2013; Ruiz et al., 2024; Spiegel et al., 2021; Valdois et al., 2004), and emotional factors (Brumariu et al., 2023; Caviola et al., 2022; Raccanello et al., 2019). However, research adopting an integrative framework that simultaneously considers these multiple levels of explanation remains relatively scarce. Within this context, the first objective of the present thesis was to examine how these different dimensions, and specific factors therein, contribute to academic performance in reading and mathematics. More precisely, we aimed at determining whether (and which) cognitive factors mediate the relationships between SES and academic outcomes, as well as between MA and mathematics performance, while controlling for SES.

1.1. Socioeconomic associations with academic achievement : the mediating role of cognitive factors

A large body of literature has shown that SES is significantly associated with academic performance in reading and mathematics during elementary school (J. Liu et al., 2022a; Selvitopu & Kaya, 2023; Sirin, 2005), placing low-SES students at greater risk of experiencing

difficulties in these learning domains (Fluss et al., 2009; N. C. Jordan & Levine, 2009; Morgan et al., 2016; Murat, 2024; Pace et al., 2017). Moreover, SES relates to the development of cognitive skills that are crucial for proficiency in these academic domains. Among these, executive and language-related functions have been most consistently associated with SES and academic achievement (Hackman & Farah, 2009; Hoff, 2013; Lawson et al., 2018; Merz et al., 2019; Taylor et al., 2023), and several studies have reported that these skills mediate the relationship between SES and academic performance (Albert et al., 2020; Dilworth-Bart, 2012; X. Ding et al., 2024; J. Li et al., 2023). However, these cognitive skills represent only a subset of the abilities involved in such academic learning, and only few studies have examined whether SES also affects other cognitive skills, particularly domain-specific ones. In particular, some evidence suggests that SES could be associated with RAN (Dolean et al., 2019; Espinoza et al., 2022; Su et al., 2017), although findings remain mixed (Asadi et al., 2023; Lima et al., 2020; C. Liu & Georgiou, 2017). Critically, despite its well-established role in reading performance (Bosse & Valdois, 2009; Valdois et al., 2019, 2025; van den Boer et al., 2015), a potential link between SES and visual-attention span has yet to be investigated. Regarding mathematics, some studies have reported associations between SES and both symbolic and non-symbolic processing, though this evidence is inconsistent and primarily concerns children in kindergarten (Bernabini et al., 2020; Bonifacci et al., 2021; Meloni et al., 2023; Sepúlveda et al., 2020).

In this context, Study 1 aimed to comprehensively examine the unique mediating role of domain-general and domain-specific skills in the links between SES and reading, and SES and mathematics, at an age when academic demands increase (Fuchs et al., 2006) and wherein SES-related performance gaps widen (Kieffer, 2012). For reading, the results first revealed a unique mediating role of language-related domain-specific abilities, specifically phonological awareness and oral language, confirming the importance of these skills in socioeconomic disparities in reading (J. Li et al., 2023). Additionally, our study is the first to identify a mediating role of visual-attention span in the link between SES and reading, suggesting that interventions aimed at improving visual-attention span (e.g., Valdois et al., 2025), together with interventions targeting language skills (e.g., Bianco et al., 2012), could contribute to reducing SES-related educational inequalities in reading. For mathematics, the results showed a unique mediating role of working memory as well as transcoding skills in the relationship between SES and mathematical performance, suggesting that interventions targeting those skills (DePascale et al., 2024; Van Der Ven et al., 2017) may help mitigate socioeconomic inequalities in mathematics. Nevertheless, interventional studies are needed to empirically test these

hypotheses and assess the causal pathways relating SES, cognition, and academic performance.

Understanding which cognitive skills to target to support children from low-SES backgrounds is essential for addressing the risk of poor academic performance within this population (e.g., Fluss et al., 2009; Morgan et al., 2016) and, by extension, socioeconomic disparities in academic learning. Furthermore, it would be important to understand the mechanisms through which SES is related to the development of these cognitive skills. One potential pathway is the home environment (Bonifacci et al., 2021; Rakesh et al., 2024; Ursache & Noble, 2016). Notably, the home literacy and numeracy environments – including, among other aspects, the frequency of parent-child literacy or numeracy activities – has been shown to contribute to the SES gap in certain domain-specific skills, such as oral language and phonological awareness (Y. Jiang et al., 2024; J. Li et al., 2023; D. Liu et al., 2023), as well as symbolic numerical skills (DeFlorio & Beliakoff, 2015; L. Elliott & Bachman, 2018; Lu et al., 2025). An enriched home learning environment also appears to mediate the relationship between SES and working memory (Hackman et al., 2015; Sarsour et al., 2011). Another potential pathway involves emotional factors such as stress (Rakesh et al., 2024; Ursache & Noble, 2016), as socioeconomic disadvantage is associated with higher stress levels that can negatively affect neurocognitive functioning (Farah, 2017; Ursache & Noble, 2016). For example, chronic stress during childhood has been found to mediate the relationship between SES and working memory in young adulthood (Evans & Fuller-Rowell, 2013; Evans & Schamberg, 2009). Overall, further research systematically assessing these pathways will be pivotal in clarifying the underlying mechanisms of SES-related disparities in cognitive development, thereby facilitating early interventions addressing them.

1.2. Emotional influences on academic achievement : the mediating role of cognitive factors

Emotional factors represent another important influence on academic performance (e.g., Brumariu et al., 2023; Caviola et al., 2022; Raccanello et al., 2019). In this context, most studies have focused on mathematics (Batchelor et al., 2019), identifying MA as a key factor, wherein higher levels of MA are associated with lower mathematics outcomes (see Barroso et al., 2021; Caviola et al., 2022; Namkung et al., 2019; J. Zhang et al., 2019, for meta-analyses). Moreover, MA may influence mathematics via cognitive processes, notably working memory (Caviola et al., 2022; Finell et al., 2022; Pelegrina et al., 2024; Skagerlund et al., 2019; Szczygieł, 2021) and cognitive flexibility (Živković et al., 2022). However, few studies have focused on younger

children and simultaneously considered domain-general and domain-specific cognitive factors related to MA (Dubinkina et al., 2023; Lindskog et al., 2017; Núñez-Peña & Suárez-Pellicioni, 2014). Furthermore, SES has been associated not only with cognitive skills (Lawson et al., 2018; Meloni et al., 2023; Sepúlveda et al., 2020) and mathematics performance (Selvitopu & Kaya, 2023; Sirin, 2005), but also with MA, with children from low-SES backgrounds reporting higher levels of MA (Adimora et al., 2015; Guzmán et al., 2021). Yet, no study examining the mediating effects of cognitive factors on the link between MA and mathematics has accounted for the potential confounding effect of SES.

In this context, Study 2 aimed to comprehensively examine the mediating role of key domain-general and domain-specific cognitive abilities in the relationship between MA and different mathematics outcomes, while controlling for SES and other important covariates – such as general anxiety. The results indicated that both domain-general (working memory) and domain-specific (transcoding, symbolic comparison, and number ordering) factors significantly mediated the relationship between MA and mathematics performance, with their contributions varying across different mathematical tasks. These findings extend those of Study 1 by suggesting that interventions targeting working memory and symbolic processing skills (e.g., DePascale et al., 2024; Van Der Ven et al., 2017) could help mitigate the negative impact of MA on mathematics performance, although this particular hypothesis requires empirical testing.

Furthermore, the cognitive factors investigated in Study 2 represent only a subset of the potential contributors to the relationship between MA and mathematics (see Figure 15 for a schematic overview). In particular, other emotional aspects, such as mathematical grit (Yu et al., 2021), motivation (Chang & Beilock, 2016), avoidance of math-related situations (Lau et al., 2024), or participation in after-school mathematics activities (S. Song et al., 2023), may also play a significant mediating role in this relationship. Future research should incorporate these factors to provide a more comprehensive understanding of how MA adversely affects mathematics achievement. Beyond examining the mediators of this link, it is equally important to identify the factors contributing to the emergence of MA. Notably, environmental aspects, such as the richness of a child's home numeracy environment, which itself can be shaped by parents' attitudes toward mathematics (Carkoglu et al., 2023; Del Río et al., 2025), may play a critical role. Moreover, bidirectional associations between MA and mathematics performance have been reported (Carey et al., 2016; Du et al., 2021; Szczygieł et al., 2024), suggesting that MA may also arise from low mathematical ability. Accordingly, future studies should adopt a comprehensive longitudinal perspective, investigating the factors influencing both the

MA-mathematics link and the mathematics-MA link, thereby helping clarify the mechanisms underlying such reciprocal associations.

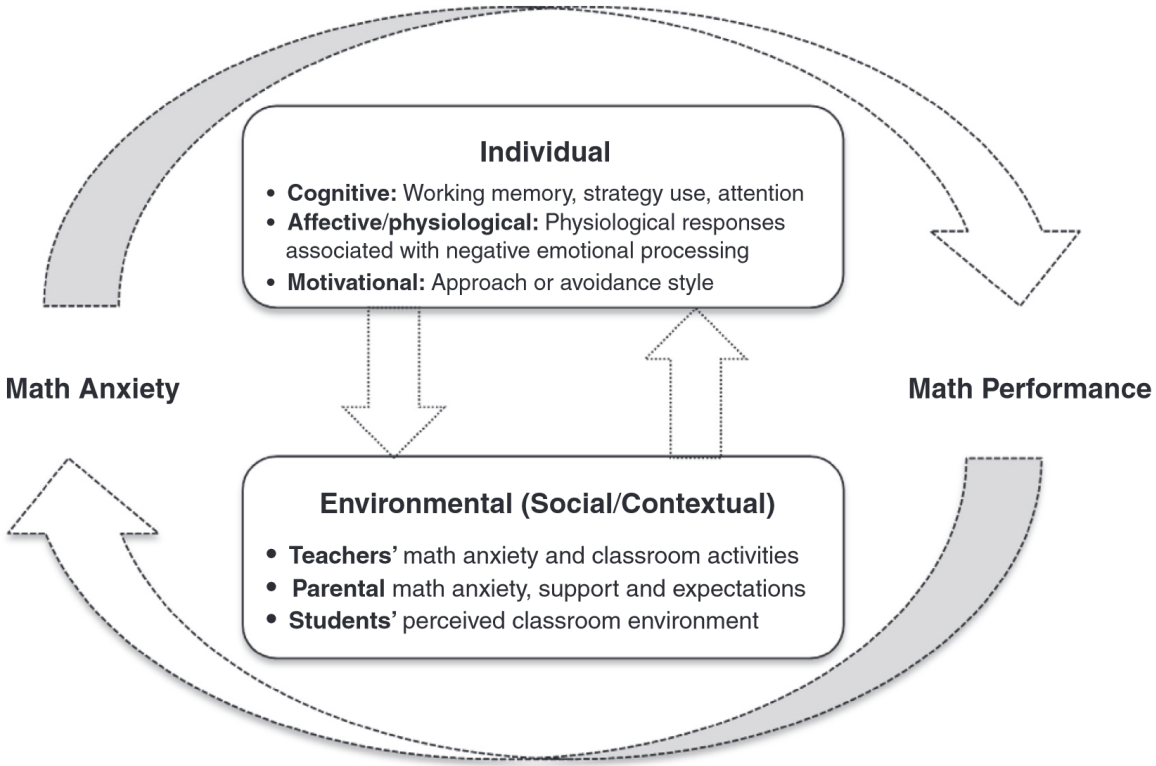

Figure 15. Overview of the multiple factors shaping the relationship between MA and mathematics. From Chang & Beilock (2016).

Furthermore, in this thesis, among emotional factors, only the role of MA was considered in relation to mathematics performance, given that it is the most extensively documented in the literature (see Barroso et al., 2021; Caviola et al., 2022; Namkung et al., 2019; J. Zhang et al., 2019, for meta-analyses). Nevertheless, independently of MA, mathematics performance has also been shown to be uniquely associated with positive emotional aspects, such as mathematics enjoyment (Raccanello et al., 2019; Villavicencio & Bernardo, 2016) and mathematics self-efficacy (Du et al., 2021; Živković et al., 2023). Accordingly, future research could extend the findings of Study 2 by jointly examining the effects of multiple emotional factors on mathematics performance, further assessing whether the mediating cognitive processes identified here for MA may also apply for other emotions.

Finally, an additional limitation of Study 2 is that emotional factors were considered only in relation to mathematics. This choice was motivated by the extensive literature on the

links between emotions and mathematics, in contrast to emotional factors associated with reading. Nevertheless, recent studies suggest that reading outcomes may also be influenced by emotional factors, such as reading anxiety, reading enjoyment, reading self-concept, or reading motivation (Chung et al., 2024; Pollack et al., 2021; Raccanello et al., 2019). Future research should therefore examine the impact of these emotional factors on reading performance and investigate whether cognitive factors may similarly mediate such relationship. This approach would provide a more comprehensive understanding of how emotional factors shape academic performance across domains, and clarify whether mathematics constitutes a special case in being more sensitive to emotional influences than other academic domains.

1.3. Toward an integrative perspective on the factors at play in academic achievement

Overall, the results of Studies 1 and 2 indicate that academic performance in reading and mathematics is shaped by a complex interplay of multiple factors, encompassing socioeconomic, cognitive, and emotional dimensions. Specifically, socioeconomic and emotional factors were found to be associated not only directly with academic outcomes but also indirectly through cognitive processes. These findings align with those of Dalmaijer et al. (2023), who, using a network analysis integrating socioeconomic, cognitive, and emotional variables, highlighted cognitive factors as a key intermediary linking socioeconomic and emotional factors to reading and mathematics performance – although their study included only a limited subset of cognitive abilities.

In this thesis, the relationships between socioeconomic, cognitive, and emotional factors were examined under the theoretical hypothesis that cognitive factors mediate these associations (e.g., Albert et al., 2020; J. Li et al., 2023; Živković et al., 2022). Nonetheless, this approach does not capture the full complexity of the interactions among these dimensions in their relation to academic performance. For instance, emotional factors may also mediate the link between SES and academic achievement (Chiu et al., 2012; Hofer et al., 2024; Hsin & Xie, 2017; Kriegbaum & Spinath, 2016; L. Ma et al., 2023; Michael & Kyriakides, 2023; Wiederkehr et al., 2015; Yeung et al., 2022). Additionally, some cognitive factors may act as moderators, such that the impact of SES on academic outcomes (Noble et al., 2006) or the influence of emotional factors on academic performance (Orbach et al., 2020; Orbach & Fritz, 2022b; Soltanlou et al., 2019) may vary depending on the level of cognitive competence.

Taken together, Studies 1 and 2 of this thesis sought to integrate different explanatory levels – namely, socioeconomic, cognitive, and emotional – in investigating the underpinnings of academic performance in reading and mathematics. Yet, it is important to note that socioeconomic, cognitive, and emotional dimensions represent only a subset of the factors contributing to individual differences in academic achievement (see Figure 16). Importantly, these dimensions interact dynamically with brain development (Farah, 2017; Noble & Mccandliss, 2005; Raizada, 2010; Rubinsten et al., 2018; Su et al., 2021; Szücs & Mammarella, 2024; Xu et al., 2025), as well as with genetic factors (Luttenberger et al., 2018; O'Connell, 2019; Rakesh et al., 2024; Rubinsten et al., 2018), highlighting the importance of multi-level approaches for a comprehensive understanding of the determinants of children's academic performance.

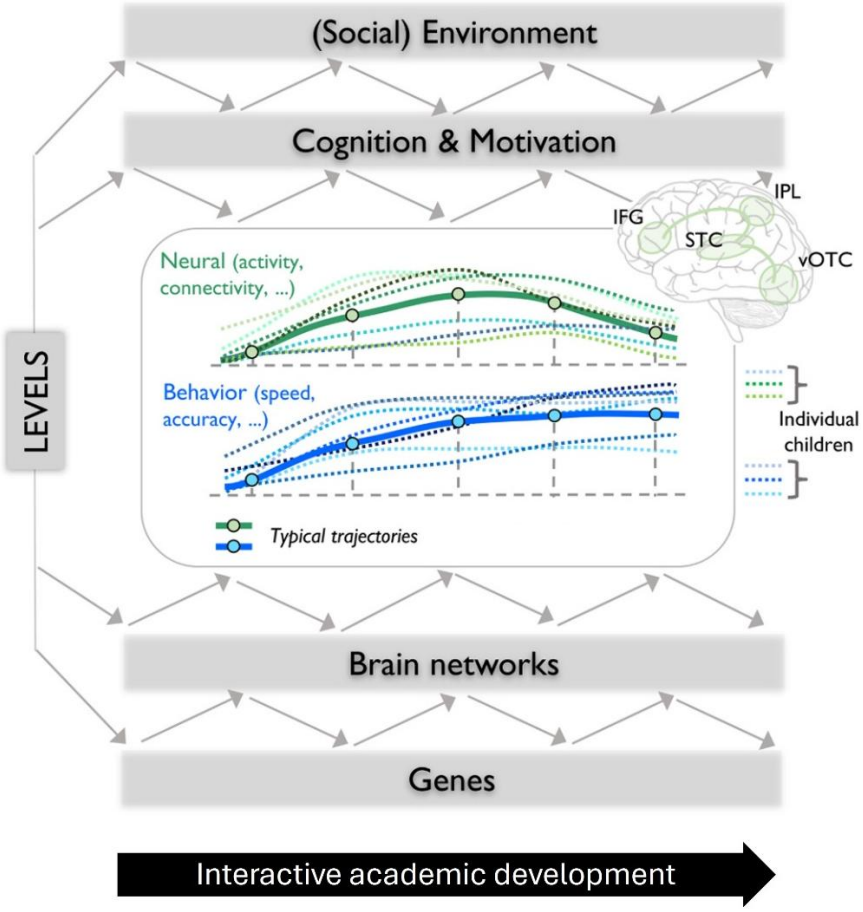

Figure 16. Schematic illustration of multiple interactive levels involved in children's academic development. Adapted from Bonte & Brem (2024).

Overall, the first two studies of this thesis indicated that low SES and high MA may constitute risk factors for poor academic performance, with several cognitive variables mediating these effects. Building on these findings, the subsequent studies focused specifically on children with poor reading and/or mathematics performance, with the aim of gaining a more precise understanding of their cognitive characteristics and shedding light on the heterogeneity within these groups.

2. Cognitive correlates of poor academic performance

Although various cognitive factors, including domain-specific and domain-general skills, have been shown to contribute to difficulties in reading (Kudo et al., 2015; Peng et al., 2022) and mathematics (Kroesbergen et al., 2023; Mishra & Khan, 2023), their combined contribution to poor academic performance has been elusive. In this context, Studies 3 and 4 of this thesis aimed to characterize the cognitive factors associated with poor reading and/or mathematics achievement, considering both group-level patterns as well as interindividual variability.

With regard to reading, Study 4 highlighted the unique contributions of domain-specific skills, namely RAN and visual-attention span, but also transcoding to reading difficulties. For mathematics, both domain-general and domain-specific factors – specifically working memory, symbolic comparison, and transcoding – contributed uniquely to mathematics difficulties. While these findings are consistent with previous research emphasizing the importance of these cognitive skills in reading (Moll et al., 2015; Valdois et al., 2021) and mathematics (Kivirähk-Koor & Kiive, 2025; Kroesbergen et al., 2023; Mononen, Niemivirta, & Korhonen, 2022), they also raise important questions regarding the generality of domain-general factors and the specificity of domain-specific factors.

2.1. The role of domain-general factors in academic difficulties

Study 4 revealed that working memory, a domain-general ability and core component of executive functions (Diamond, 2013; Friedman & Miyake, 2017), predicted poor performance exclusively in mathematics and not in reading – a pattern consistent with that observed in Study 1, across our total sample. This finding is somewhat surprising given the substantial evidence linking working memory to reading outcomes (see Ober et al., 2020; Peng, Wang, Li, et al., 2018; Spiegel et al., 2021, for meta-analyses), although prior research has occasionally

reported a stronger association between working memory and mathematics than with reading (Ernst et al., 2022; Mulder et al., 2017).

A first possible explanation is that most studies examining the effects of executive functions on academic performance have overlooked the role of domain-specific factors. Addressing this issue, Malone et al. (2022) investigated the predictive effect of executive functions on reading and mathematics in 5- to 6-year-old children, both with and without accounting for domain-specific factors. Executive functions significantly predicted academic performance when domain-specific factors were not included. However, this effect became nonsignificant once domain-specific predictors were incorporated, with unique effects observed only for domain-specific skills – namely, phonological awareness and RAN for reading, and transcoding and non-symbolic comparison for mathematics. In our study, working memory remained a significant predictor of mathematics even after accounting for domain-specific factors, which may be explained by task differences, as Malone et al. (2022) only included a single-digit math fluency task that likely relies less on working memory than more advanced calculation skills (Träff, 2013; Träff et al., 2023; see also Study 1). Nevertheless, for reading, these findings indicate that executive functions may not explain unique variance in performance beyond domain-specific factors and suggest that their influence may instead be indirect, operating through reading-specific skills (D. Liu et al., 2023; Morris & Lonigan, 2022).

Another explanation for the absence of a predictive effect of working memory on reading difficulties may lie in the age group examined in this thesis. Previous research suggests that working memory may play a particularly important role during the early stages of reading development, supporting the acquisition of grapheme-phoneme correspondences, with its influence decreasing once decoding becomes automatized (Blair & Razza, 2007; Gathercole et al., 2004; Geary, 2011). In contrast, the contribution of working memory may increase with age in the context of mathematics learning (Geary, 2011).

Finally, a further explanation may relate to task-specific features. Unlike other domain-general measures, the working memory task employed in this thesis involved numerical content (digit span), which might explain its association primarily with mathematics outcomes. Notably, Mingozzi et al. (2024) reported that although both children with reading difficulties and those with mathematics difficulties exhibited working memory deficits, the nature of these deficits varied depending on the stimuli. Specifically, children with reading difficulties performed poorly only on tasks using syllabic stimuli, whereas children with mathematics difficulties performed poorly only on tasks using numerical stimuli. Therefore,

the absence of a working memory measure involving alphabetical stimuli in the present thesis may have contributed to the lack of a working memory effect on reading performance observed in Studies 1 and 4. Such task characteristics may also help explain why certain executive functions, such as inhibition or cognitive flexibility, did not emerge as significant predictors of academic performance in either reading or mathematics. Indeed, some studies have found that associations between these abilities and academic outcomes are stronger, or only present, when domain-specific content is used (Starling-Alves et al., 2024; L.-C. Wang et al., 2012).

Beyond task format, these findings raise questions about the relevance of a strict dichotomy between domain-general and domain-specific processes. Notably, several authors have argued that a continuum between generality and specificity may better reflect how cognitive processes contribute to academic performance (Cartwright & Palian, 2024; Gilmore, 2023). This perspective may also help explain why many training programs targeting domain-general functions yield limited or no transfer effects on academic outcomes (Cartwright & Palian, 2024; Fyfe & Borriello, 2025; Melby-Lervåg & Hulme, 2013; Niebaum & Munakata, 2023; Sala & Gobet, 2020; Titz & Karbach, 2014). In contrast, interventions targeting reading-specific executive functions (i.e., incorporating reading-related content) have been shown to significantly enhance reading performance (Cartwright & Palian, 2024). Importantly, this view does not diminish the relevance of domain-general functions for academic achievement but rather underlines the need to understand the domain-specific pathways through which they exert their influence within each learning domain (Cartwright & Palian, 2024; Fyfe & Borriello, 2025). In this respect, promising approaches include embedding domain-specific content into executive function training (Niebaum & Munakata, 2023), targeting executive demands specific to each academic domain (Cartwright & Palian, 2024), fostering the activation of domain-general strategies within domain-specific training (Fyfe & Borriello, 2025), and teaching students how and why to apply domain-general strategies in specific learning contexts through metacognitive approaches (Buttelmann & Karbach, 2017; Fyfe & Borriello, 2025).

2.2. The role of domain-specific factors in academic difficulties

The results of Study 4 also raise important questions regarding the specificity of certain domain-specific factors. Notably, transcoding – typically considered a mathematics-specific skill due to its well-established role in mathematical performance (Banfi et al., 2022; Göbel et al., 2014; Habermann et al., 2020; Malone et al., 2020, 2021) – emerged as a significant

predictor not only of mathematics difficulties but also of reading difficulties. Although these findings are consistent with previous studies reporting weaknesses in verbal mathematical tasks, particularly transcoding, among children with reading difficulties (De Clercq-Quaegebeur et al., 2018; Moll et al., 2015; Raddatz et al., 2017), they nonetheless invite further reflection on the mechanisms that may underlie the relationship between transcoding and reading performance.

One possible explanation is that weak transcoding abilities may stem from reading difficulties. Indeed, a key component of the transcoding task involved number reading. It is therefore possible that poor readers experience difficulties decoding not only alphabetic but also numerical content. This assumption aligns with the view that transcoding, like reading, engages phonological and lexical access processes (Barrouillet et al., 2004; Batista et al., 2023; Lopes-Silva et al., 2014), which may be impaired in struggling readers (Melby-Lervåg et al., 2012; Norton & Wolf, 2012). Nevertheless, the fact that transcoding – rather than phonological awareness – emerged as a predictor of reading difficulties suggests that transcoding may tap into additional aspects of the reading process beyond phonological processing alone.

Notably, a second explanation is that weak transcoding skills in poor readers may reflect difficulties in forming associations between phonological representations and arbitrary visual symbols (Cirino et al., 2018). Indeed, just as transcoding involves converting numbers between oral and written codes, reading likewise requires mapping written graphemes or words onto their corresponding phonological forms (Blomert, 2011; Göbel et al., 2014). To test this hypothesis, future studies should examine whether performance on audio-visual associative learning tasks (e.g., Altarelli et al., 2019; Pasqualotto et al., 2024) predicts reading outcomes and mediates the relationship between transcoding and reading.

2.3. Co-occurring reading and mathematics difficulties: insights into the overlap between academic domains

The results of Study 4 further indicate that co-occurring difficulties in reading and mathematics are predicted by a combination of the cognitive factors associated with isolated difficulties in each domain, namely RAN, visual-attention span, working memory, symbolic comparison, and transcoding. This pattern of cognitive vulnerabilities supports the Additive model (see Figure 3 of the Theoretical Background section), which posits that co-occurring difficulties arise from the cumulative effects of cognitive factors that independently contribute

to each domain (Ashkenazi et al., 2013; L. Peters & Ansari, 2019; Starling-Alves et al., 2025). Nevertheless, the finding that transcoding predicts both reading and mathematics difficulties – whether isolated or co-occurring – suggests a potential involvement of shared underlying mechanisms between reading and mathematics that may be reflected in this task.

In particular, Pham et al. (2025) reported, based on an exploratory factor analysis in kindergarten children, that scores on a transcoding task did not load onto the same factor as other mathematics-specific skills, such as symbolic and non-symbolic comparison. Instead, transcoding loaded on a factor related to code-based skills, including knowledge of letter names and sounds, as well as phonological awareness. These findings suggest that transcoding may share more in common with processes involving the conversion between different code modalities across domains, rather than reflecting a skill specific to mathematics. This interpretation is further supported by studies showing that transcoding, alongside phonological awareness and RAN, significantly predicts the covariance between reading and mathematics (Cirino et al., 2018; Jöbstl et al., 2023), highlighting the interplay between visual, verbal, and semantic processes in these two domains (see Figure 17) (Banfi et al., 2024; Jöbstl et al., 2023).

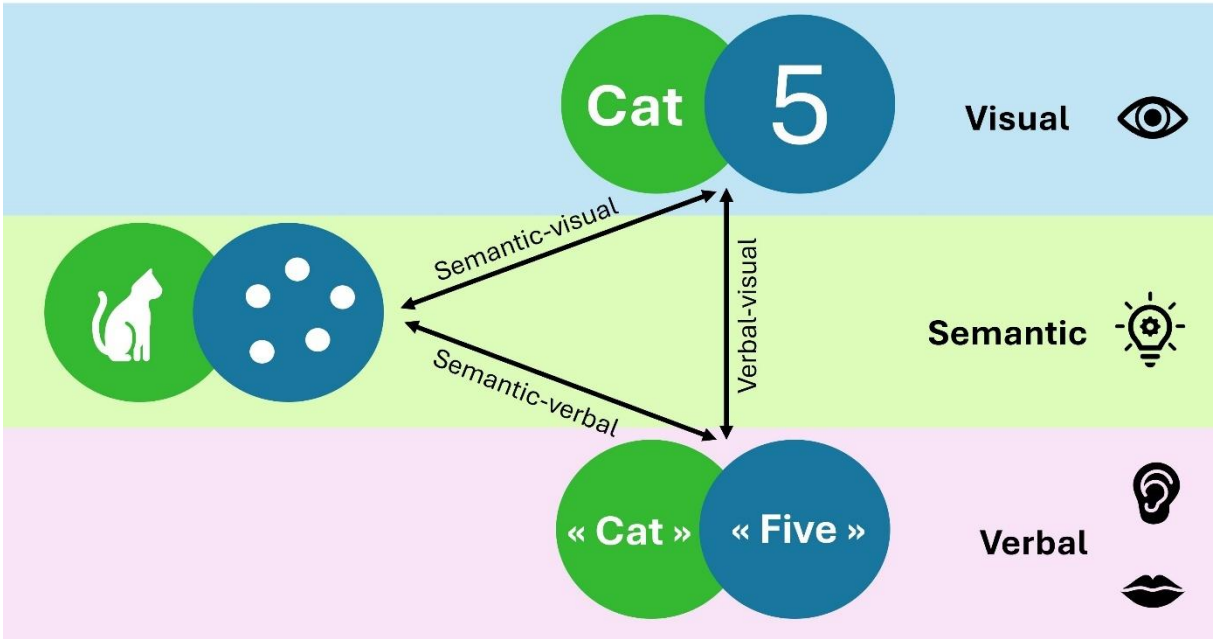

Figure 17. Illustration of shared processes between reading and mathematics. Adapted from Jöbstl et al. (2023). Green and blue circles represent processes associated with the reading and mathematics domains, respectively.

Future research should aim to clarify the interrelationships among these cognitive processes across academic domains, to determine whether transcoding reflects a shared mechanism (e.g., audio-visual mapping) or exerts distinct influences on reading (e.g., via phonological processes) and mathematics (e.g., via symbolic number processing). In this regard, assessing performance across different conditions of a visual-verbal mapping task – encompassing alphabetic, numerical, and neutral stimuli (e.g., Altarelli et al., 2019; Lyons et al., 2014) – and analyzing their interrelations and contributions to reading and mathematics performance could provide deeper insight into the specificity or generality of symbolic mapping and its potential role in the links between reading and mathematics.

Overall, evidence indicates that transcoding weaknesses are observed in both reading and mathematics difficulties (Moll et al., 2015; Raddatz et al., 2017; see also Study 4), and that transcoding contributes to the covariance between reading and mathematics across unselected samples of children with varying academic performance (Cirino et al., 2018; Jöbstl et al., 2023). These findings suggest that investigating the factors underlying co-occurring difficulties in reading and mathematics may, in fact, represent only a specific instance of examining the mechanisms contributing to the overlap between the two domains. Alternative approaches may thus involve shifting from categorical to dimensional frameworks to characterize the determinants of low academic performance in both domains (L. Peters & Ansari, 2019; Starling-Alves et al., 2025).

3. The nature and diversity of poor academic achievement

3.1. Dimensional and categorical perspectives on poor academic achievement

Traditionally, studies investigating the determinants of reading and mathematics difficulties have employed a categorical framework, comparing a group of children classified as having difficulties – typically based on performance below a designated cut-off – with a control group of children not meeting the criterion (Dowker, 2024; Peng et al., 2022; X. Zhang et al., 2020). While this approach has yielded important insights into the cognitive challenges faced by children with academic difficulties, it raises the question of what additional understanding it provides beyond that of a dimensional approach, examining continuously the association between cognitive abilities and academic performance across an unselected sample of children with varying levels of achievement (L. Peters & Ansari, 2019).

Thus, a growing body of literature has advocated for a shift from categorical to dimensional approaches. Categorical approaches have been criticized for relying on arbitrary selection criteria, which can vary substantially across studies (Murphy et al., 2007; Peng et al., 2022; L. Peters & Ansari, 2019). They also imply that children on either side of a cut-off are qualitatively distinct, thereby underestimating the complex interplay between reading and mathematics across different performance levels (Branum-Martin et al., 2013; L. Peters & Ansari, 2019; Starling-Alves et al., 2025). In contrast, increasing evidence suggests that reading and mathematics are better represented as dimensional continua, with individuals above or below a given threshold differing primarily in the severity of their difficulties (Branum-Martin et al., 2013; L. Peters & Ansari, 2019). Notably, this dimensional perspective can better account for the observation that children with isolated difficulties in one domain often perform relatively poorly in the other domain as well, without meeting criteria for co-occurring difficulties (Starling-Alves et al., 2025) – a pattern also observed in Study 4 of this thesis for children with isolated reading difficulties (see Figure 18 for a schematic representation).

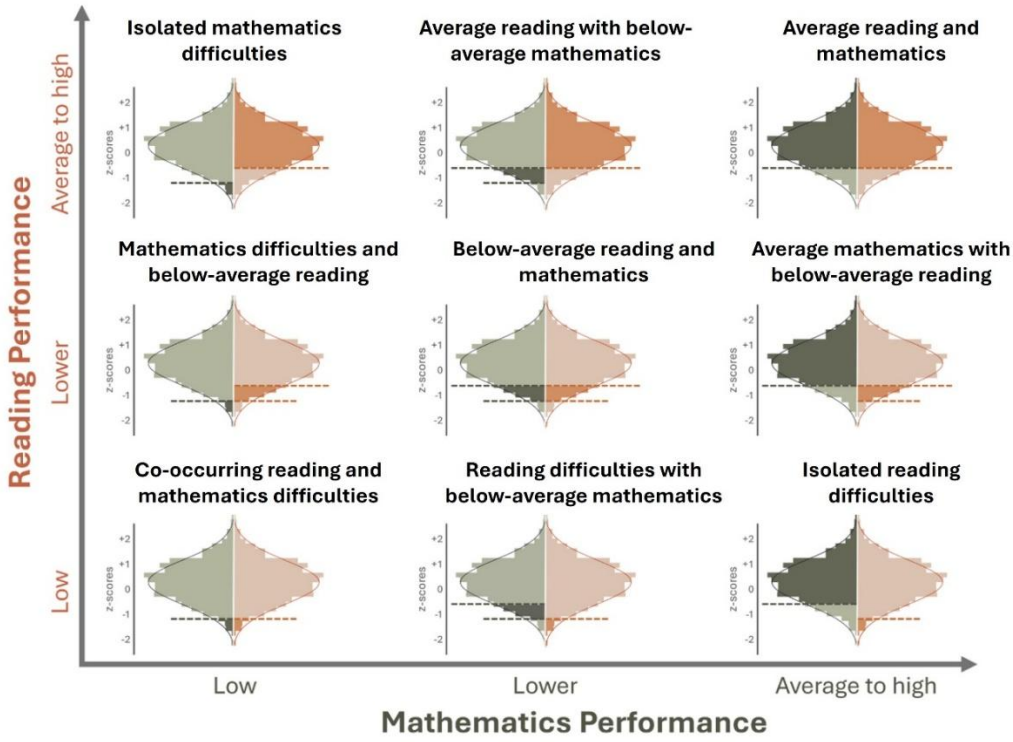

Figure 18. Reading and mathematics as overlapping continuous dimensions. Adapted from Starling-Alves et al. (2025). Reading performance (orange) and mathematics performance (green) are conceptualized as continuous dimensions, allowing for a wide range of performance patterns across the two domains.

Nevertheless, a dimensional approach implicitly assumes that predictors of academic performance exert uniform effects across all performance levels. Yet, research indicates that some cognitive factors may only emerge as significant predictors at specific levels of performance (Banfi et al., 2024; McIlraith, 2018). Consequently, relying solely on a dimensional approach could obscure factors particularly relevant to low performance. For this reason, the present thesis employed both a dimensional perspective (Studies 1 and 2) and a categorical approach focused on children with poor academic performance (Studies 3 and 4). A valuable extension of Study 4 would be to investigate whether the same cognitive factors predict not only academic difficulties but also the distinctiveness and the overlap between reading and mathematics across the full performance spectrum.

Furthermore, the question of whether children with the most severe manifestations of academic difficulties constitute a qualitatively distinct population from those with more moderate difficulties remains debated, with some divergence between the reading and mathematics domains. In reading, the view that dyslexia represents a continuum rather than a discrete category is now widely accepted (Carroll et al., 2025; Snowling & Hulme, 2024). In contrast, such a perspective remains controversial in mathematics (Kaufmann et al., 2013), with many studies comparing the cognitive profiles of children with dyscalculia to those with less severe difficulties (i.e., children with low numeracy). Findings from these studies are mixed, with some reporting differences in cognitive characteristics between these groups (W. W. L. Chan et al., 2013; Geary et al., 2007; Mononen, Niemivirta, & Korhonen, 2022), whereas others do not (X. Zhang et al., 2020). Furthermore, M. A. Barnes et al. (2020) highlighted that conclusions regarding the cognitive profile of children with mathematics difficulties vary depending on the threshold used to define poor performance. For example, ANS deficits were observed only with a stricter 16th percentile criterion, but not with the 25th percentile, suggesting that such deficits may be predominantly characteristic of children with the most severe mathematical difficulties (see also W. W. L. Chan et al., 2013).

In line with this inconclusive literature, supporting both the conceptualization of dyscalculia as a distinct qualitative disorder and as the extreme end of a continuum (Kaufmann et al., 2013), the results of Studies 3 and 4 may have been partly influenced by the inclusion of children with varying degrees of academic difficulties. Indeed, a relatively liberal threshold for defining poor academic performance (i.e., the 30th percentile) was used, in line with the objective of focusing on the broad population of low-performing children. However, this approach may have introduced heterogeneity in difficulty severity, potentially affecting both the factors emerging as significant predictors of group membership and the interindividual

variability in cognitive profiles. Accordingly, future studies should systematically investigate how the cognitive profiles of poor readers and poor mathematics achievers vary as a function of difficulty severity, a question likely requiring larger sample sizes than those available in the present thesis to be examined reliably.

3.2. Interindividual variability in poor academic achievement

A major limitation of both group-based categorical approaches and whole-sample dimensional approaches is that they primarily focus on average effects. However, patterns observed on average at the group level or across an entire sample may not apply consistently to all individuals. Consequently, relying exclusively on these approaches to study the cognitive characteristics associated with poor academic performance risks overlooking important interindividual variability (Astle et al., 2024; Starling-Alves et al., 2025), which is crucial to consider for designing interventions tailored to the specific needs of individual children rather than to the group average.

In this context, Studies 3 and 4 of this thesis specifically examined the heterogeneity of cognitive profiles among children with poor reading and/or mathematics performance. Study 3 first revealed, using a data-driven approach, the existence of distinct cognitive profiles within both poor readers and poor mathematics achievers, characterized by either broad and pronounced or selective and moderate cognitive weaknesses. These findings align with previous evidence showing that children with difficulties in these academic domains do not constitute homogeneous groups (e.g., Bartelet et al., 2014; W. W. L. Chan & Wong, 2020; Ouyang et al., 2024; Valdois et al., 2021; Willems et al., 2016). Moreover, children with co-occurring difficulties in reading and mathematics were overrepresented in profiles exhibiting broad and pronounced cognitive weaknesses, suggesting that part of the interindividual variability observed may be attributable to whether difficulties are isolated or co-occurring across domains (Brandenburg et al., 2021).

To further explore this possibility, Study 4 examined the prevalence and combinations of different cognitive weaknesses in children with isolated reading difficulties, isolated mathematics difficulties, and co-occurring difficulties. The results revealed substantial heterogeneity in cognitive profiles within each group, emphasizing that support strategies should be tailored to each child's cognitive profile rather than solely based on the type of academic difficulty (Astle et al., 2019; Moll et al., 2019; Starling-Alves et al., 2025). These findings echo research adopting a transdiagnostic approach to neurodevelopmental disorders,

demonstrating that similar cognitive profiles can manifest across different academic difficulties, independent of diagnostic classification (Astle et al., 2019, 2022). Likewise, Study 4 provided evidence that identical patterns of cognitive weaknesses may be observed in children with difficulties in reading only, mathematics only, or both domains, highlighting the value of an interindividual perspective when developing educational interventions.

Nevertheless, the approaches used in this thesis to characterize interindividual variability among low-performing children are not without limitations. First, although latent profile analysis (LPA) is a particularly useful method for identifying subgroups of individuals sharing similar characteristics, profiles are inherently defined by the average features of their members, potentially obscuring substantial within-profile variability (Astle et al., 2022; Huijsmans et al., 2020). Moreover, examining the prevalence and combinations of different cognitive weaknesses also presents methodological constraints. Specifically, it requires defining a threshold to classify weak cognitive ability, which is necessarily arbitrary and dichotomizes a continuous distribution of performance. Additionally, for reasons of clarity and interpretability, only a limited set of cognitive skills was considered in this analysis, leaving open the possibility that unexamined dimensions – even if not significant predictors in the multinomial logistic regression model of Study 4 – may still represent relevant cognitive challenges for some children. Finally, the sample sizes of poor achiever groups in Studies 3 and 4 were relatively modest, emphasizing the need to replicate these analyses in larger samples to assess the robustness of the observed patterns. Overall, the results of Studies 3 and 4 should be viewed as an initial step in characterizing interindividual variability in poor readers and/or poor mathematics achievers and as a call to incorporate person-centered approaches alongside group-centered ones in future research.

4. Theoretical and educational implications

The findings of this thesis have important theoretical and educational implications. From a theoretical standpoint, the results highlight that reading and mathematics outcomes are influenced by a complex interplay of multiple factors, including cognitive, socioeconomic, and emotional dimensions, thereby supporting the relevance of multi-level approaches to the study of low academic performance (Bonte & Brem, 2024). Moreover, the findings advocate for moving beyond a strict partitioning of domain-general and domain-specific processes (Cartwright & Palian, 2024; Gilmore, 2023) and a separate consideration of reading and mathematics domains, instead emphasizing the need for a more nuanced examination of both

distinct and shared mechanisms underlying academic performance across these two domains (Cirino et al., 2024; Koponen et al., 2018). Finally, the results underline the importance of considering interindividual variability among low-performing children and suggest that, although categorical, dimensional, and person-centered approaches each have limitations, their complementary use (e.g., Q. Song & Thomas, 2025) may provide the most comprehensive insights into characterizing poor academic performance.

From an educational perspective, this research provides a foundation for developing and evaluating targeted interventions aimed at supporting and preventing academic difficulties. First, the findings suggest that focused cognitive training on particular skills may help reduce SES-related educational inequalities in reading and mathematics and mitigate the detrimental effects of MA on mathematics performance, although these hypotheses require empirical validation. Second, the results highlight the importance of considering the interrelations between reading and mathematics in both assessment and intervention, as a substantial proportion of children experiencing difficulties in one domain also face challenges – of varying severity – in the other (Koponen et al., 2018; see also Study 4). Finally, the findings underline that a one-size-fits-all approach is unlikely to meet the diverse needs of children with poor academic performance, calling instead for individualized support tailored to each child's unique profile (Carroll et al., 2016; Ouyang et al., 2024). In this regard, digital intervention programs hold particular promise, as they enable support to be adapted dynamically to each child's specific needs and progress over time (Butterworth & Kovas, 2013; Butterworth & Laurillard, 2010; Farhah et al., 2025; Pasqualotto et al., 2022).

5. Limitations and future directions

5.1. Limitations related to the research design

The research conducted in this thesis has several limitations that should be acknowledged. The primary limitation concerns the correlational design of the project, in which all measurements were collected at a single time point. Although the integration of a large set of cognitive, emotional, and socioeconomic factors and the joint consideration of reading and mathematics represent an important and novel contribution, the results reported in this thesis do not allow any causal inferences to be drawn. This work should therefore be viewed as an initial step that opens promising avenues for future longitudinal and interventional research. In particular, longitudinal designs would enable a more reliable identification of low-performing children based on the persistence of their difficulties over

time (Carroll et al., 2016; Morgan et al., 2016; T. T.-Y. Wong et al., 2014), help determine whether the predictors of academic performance differ from those underlying academic development (Träff et al., 2025), and shed light on the developmental stability of cognitive profiles as well as academic trajectories of low-performing children with distinct cognitive profiles (Bonte & Brem, 2024; Caviola et al., 2024; W. W. L. Chan & Wong, 2020). In this regard, a research project is currently being developed in collaboration with the DEPP, aiming to examine interindividual differences in developmental trajectories among the children recruited for this thesis, using their subsequent yearly national assessments results in French and mathematics.

Furthermore, interventional studies are essential to determine whether the cognitive factors identified as mediating variables in Studies 1 and 2 can effectively help reduce the effect of SES and MA on academic performance. It will also be crucial to empirically test whether intervention approaches tailored to each child's cognitive profile are indeed more effective than non-personalized ones in improving the academic outcomes of low-achieving children. In this regard, a key challenge will be to identify how such individualized approaches can be implemented most efficiently, with digital educational tools likely representing a promising avenue (Butterworth & Kovas, 2013; Butterworth & Laurillard, 2010; Farhah et al., 2025; Pasqualotto et al., 2022). Finally, extending these investigations to other age groups will be important to achieve a more comprehensive understanding of the complex interplay among cognitive, socioeconomic, and emotional factors across development, and to determine the most effective strategies to both (i) support children experiencing academic difficulties at different developmental stages and (ii) prevent their emergence at earlier stages (Billard & Barbe, 2016; Fuchs et al., 2005).

5.2. Methodological limitations

The work conducted in this thesis also presents some methodological limitations. In particular, the lack of standardization for some measures or existing norms that were deemed outdated and based on too small validation samples led us to identify low-achieving children relative to the total sample recruited. However, this approach raises the issue that the total sample may not have represented a population comparable to the general population. Specifically, the children recruited for this project were enrolled in REP and REP+ schools, environments in which academic difficulties have been shown to be more prevalent than in other educational settings (Fluss et al., 2009). Consequently, using this sample as a reference for identifying poor academic achievers may have underestimated the actual prevalence of

academic difficulties compared with what would have been observed using a sample more representative of the general population, while raising the possibility that some children in the control group may also exhibit moderate academic challenges. This observation further underlines the need to develop new standardized assessment tools based on large samples or, at least, to regularly update the norms of existing instruments.

Furthermore, certain limitations pertain to the measures employed in this thesis. In particular, for many constructs, only a single indicator was available, preventing the construction of latent variables or composite scores that could have provided a more reliable assessment of the targeted constructs (Nachtigall et al., 2003; Ullman, 2006). Additionally, for the various academic and cognitive tasks, only performance data were collected, whereas examining the strategies that children used to complete some tasks could have provided valuable complementary and more mechanistic insights. For example, in the visual search task assessing selective attention, analyzing the visual search strategies implemented by the children may have offered important information (Guilbert & Guiraud-Vinatea, 2022; Guilbert & Rochette, 2023) and might explain the lack of associations with academic performance observed in this thesis. Finally, due to the sensitive nature of the information, the parental SES score was based solely on parents' education and occupation, omitting income, which nonetheless constitutes an integral component of SES (Antonoplis, 2023; C. D. Cowan et al., 2012; Duncan & Magnuson, 2012; Ursache & Noble, 2016). Including this dimension could potentially yield associations with academic and cognitive outcomes different from those reported in this thesis (Claes et al., 2024; L. Ren et al., 2021; Walhovd et al., 2022).

5.3. Future perspectives

Finally, although this thesis represents a first step toward a more integrative understanding of poor academic performance in reading and mathematics and its interindividual variability, it remains far from exhaustive in terms of the factors considered and the approaches used. In particular, other cognitive skills known to influence reading and mathematics performance – such as letter knowledge (Hulme & Snowling, 2013; Norton & Wolf, 2012) and morphological awareness (Casalis et al., 2004; Metsala et al., 2021) for reading, as well as spatial skills (Hawes, Moss, et al., 2019) and counting skills (Koponen et al., 2019) for mathematics – were not examined. Moreover, cognitive factors in this thesis were studied independently to assess their unique predictive contributions, an approach that may have overlooked important interrelationships among them. For example, several studies have shown that domain-general cognitive skills can influence academic performance indirectly via

domain-specific skills (J. Y.-C. Chan & Scalise, 2022; Cragg et al., 2017; D. Liu et al., 2023; Morris & Lonigan, 2022; Spencer et al., 2020; X. Zhang et al., 2017), whereas others have highlighted mediating effects of domain-general abilities on the relationship between domain-specific processes and academic outcomes (Gimbert et al., 2019; Hassinger-Das et al., 2014; Krajewski & Schneider, 2009). Future longitudinal research is therefore needed to clarify the interplay among these cognitive factors in shaping academic performance over time and to shed light on the causal role of these variables.

Additionally, future research should explore further dimensions of interindividual variability. In particular, diversity in emotional profiles is likely to contribute to distinct patterns of academic performance (Cueli et al., 2024; Orbach & Fritz, 2022a; Parhiala et al., 2018). Moreover, Study 1 focused on cognitive factors associated with SES-related inequalities in reading and mathematics overall, without examining whether children of comparable SES may exhibit heterogeneous cognitive profiles (Scalise et al., 2021). Notably, children from low-SES backgrounds also display substantial heterogeneity in academic performance, with a significant proportion achieving high academic outcomes (Holzer et al., 2025; OECD, 2023). Thus, a complementary research perspective may involve identifying the factors underlying academic resilience among low-SES children (Masten et al., 1999; Thorsen et al., 2021; Y. Yan & Gai, 2022), thereby offering valuable insights into adaptation and maladaptation in socioeconomically disadvantaged contexts (Baysarowich et al., 2025; Ellis et al., 2017, 2022). Taken together, integrating cognitive, emotional, and socioeconomic factors in the study of interindividual variability in academic performance (Hart et al., 2016; Holzer et al., 2025) could yield a more nuanced understanding of children's heterogeneous profiles across multiple levels.

6. Conclusion

Throughout this thesis, we investigated the role of cognitive, socioeconomic, and emotional factors in poor academic performance in reading and mathematics in primary school children.

Adopting a dimensional approach across the entire sample, we first showed that SES was significantly associated with various reading and mathematics outcomes and that cognitive factors played a mediating role in these relationships. Furthermore, we found that mathematics performance was influenced by math anxiety (MA) beyond the effect of SES, with particular cognitive factors mediating this relationship.

Using a categorical approach focused on low-achieving children, combined with an interindividual perspective, we then highlighted the existence of distinct cognitive profiles among poor readers and poor mathematics achievers. Moreover, we showed that co-occurring difficulties in reading and mathematics were characterized by a combination of the cognitive factors contributing to isolated difficulties in each domain. Importantly, our results further revealed substantial cognitive heterogeneity within groups of children with difficulties in reading only, mathematics only, as well as both domains.

Overall, the findings of this thesis suggest that targeted cognitive interventions could help mitigate the effects of SES and MA on academic performance. They also underline the importance of adopting a differential perspective when studying the factors underlying poor academic achievement, highlighting the need to tailor support to each child's specific cognitive profile. Nevertheless, given the correlational design employed in this thesis, future longitudinal and interventional studies are required to determine the causality and directionality of the relationships identified in this thesis.

In conclusion, this thesis represents a first step toward an integrative understanding of individual differences in reading and mathematics achievement, bringing together levels of explanation and academic domains that are rarely examined jointly. It lays the groundwork for more comprehensive – yet also more detailed – approaches capable of accounting for the complex, multi-level interplay between factors underlying poor academic performance and its interindividual variability.

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Appendices

Appendix 1. Parental questionnaire assessing demographic and SES information

QUESTIONNAIRE PARENTS

Madame, Monsieur,

Nous vous remercions d'avoir accepté de participer à l'étude que nous avons effectuée dans la classe de votre enfant. Dans ce cadre, nous aurions besoin de vos réponses au questionnaire suivant. Les renseignements que vous fournirez seront extrêmement précieux pour nous aider à mieux comprendre les processus d'apprentissage chez l'enfant.

Nous attirons votre attention sur le fait qu'il n'y a pas de « bonnes » ou de « mauvaises » réponses aux questions et nous vous garantissons que vos réponses à ce questionnaire resteront strictement confidentielles et ne comporteront pas votre nom (utilisation d'un code pour chaque enfant).

Si vous ne parvenez pas à remplir ce questionnaire ou pour toute question de compréhension, n'hésitez pas à nous contacter afin de répondre aux questions à l'oral par téléphone.

En restant à votre disposition, nous vous remercions pour votre collaboration !

Code du participant : _____

INFORMATIONS GENERALES

1. **Vous êtes :**

   □ Mère (ou tutrice légale) □ Père (ou tuteur légal)

   □ Autre : _____

2. **L'autre parent impliqué dans l'éducation de l'enfant est :**
(Si pas d'autre éducateur, ne rien écrire)

□ Mère (ou tutrice légale) □ Père (ou tuteur légal)

□ Autre : _____

3. **Votre enfant présente-t-il des troubles de la vue ou de l'audition ?**

□ Non □ Oui et ils sont corrigés (lunettes, appareil auditif, …)

□ Oui et ils ne sont pas corrigés (précisez) :_____

4. **Votre enfant présente-t-il une maladie particulière ou des difficultés d'apprentissage ?**

□ Non □ Oui (précisez) :_____

_____

5. **Quelle est la (ou quelles sont les) première(s) langue(s) qu'a parlée(s) votre enfant ?**

□ Le français □ Autre(s) langue(s) : _____

Si le français n'est pas la première langue de votre enfant, à quel âge a-t-il commencé à apprendre le français ?

□ Moins de 3 ans □ 3 - 5 ans □ 6 - 7 ans □ 8 ans et plus

INFORMATIONS SOCIO-DEMOGRAPHIQUES

6. **Quel est votre diplôme le plus élevé ?**

Si votre diplôme le plus élevé a été obtenu à l'étranger, indiquez le diplôme qui paraît le plus proche de celui que vous avez obtenu.

S'il s'agit d'un Diplôme Universitaire (DU), indiquez le diplôme le plus élevé précédent.

	Vous	L'autre parent
Pas de scolarité ou scolarité en **école maternelle**	□	□
Scolarité jusqu'à la fin de l'**école primaire**	□	□
Diplôme du **Brevet des collèges**	□	□
CAP, BEP ou équivalent (aide-soignant, auxiliaire de vie, titre AFPA, …)	□	□
Diplôme du **Baccalauréat** (général, technologique, professionnel) ou équivalent (DAEU, capacité en droit, …)	□	□
Diplôme de niveau **Bac+2** (BTS, DUT, DEUG, DEUST, …)	□	□
Diplôme de niveau **Bac+3** (Licence, Licence professionnelle, Classe préparatoire, …)	□	□
Diplôme de niveau **Bac+4** (Maîtrise)	□	□
Diplôme de niveau **Bac+5** (Master, DEA, DESS, diplôme de grande école, …)	□	□
Diplôme de niveau **Bac+8** (Doctorat)	□	□
Autre diplôme (précisez)	□ _____ _____ _____	□ _____ _____ _____

7. Quelle est votre situation professionnelle ?

*Soyez le plus précis possible, en indiquant **un métier ou une profession** (par exemple : coiffeur, secrétaire, conducteur de train, ingénieur en aéronautique) et non un statut professionnel (par exemple : ne pas indiquer que vous êtes employé, cadre, fonctionnaire, intérimaire, agent RATP)*

	Vous	L'autre parent
En activité professionnelle **Quel est votre métier actuel ?**	□ _____ _____ _____	□ _____ _____ _____
A la retraite **Quel était votre dernier métier ?**	□ _____ _____ _____	□ _____ _____ _____
Au chômage **Quel était votre dernier métier ?**	□ _____ _____ _____	□ _____ _____ _____
Femme ou homme au foyer	□	□
Étudiant·e	□	□
Autre (précisez)	□ _____ _____ _____	□ _____ _____ _____

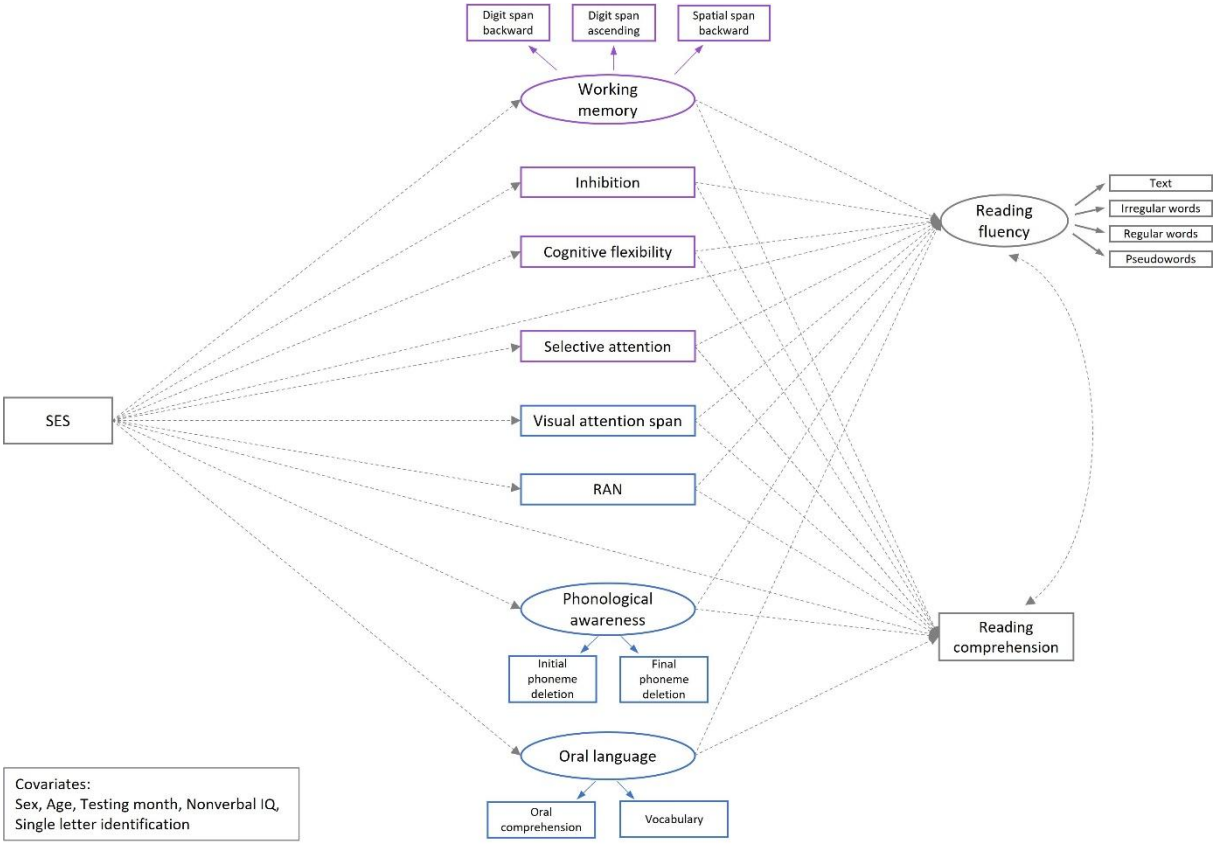
Merci beaucoup pour votre participation !

Appendix 2. SEMA questionnaire translated in French

Instructions: « Je vais te lire quelques questions de mathématiques. Pour chaque question, je veux que tu t'imagines en train d'y répondre. Ensuite, montre-moi comment tu te sens à l'idée de répondre à cette question. Par exemple, tu peux te sentir *(montrer en même temps)* : Pas du tout nerveux, Un peu nerveux, Moyennement nerveux, Très nerveux ou Très très neveux. Attention, tu ne dois pas réellement répondre à la question, tu dois juste t'imaginer en train de répondre et me montrer comment tu te sens. Voici un exemple. »	
Exemple 1.	Qui est le président de la France ?
Item 1.	Thomas a acheté 2 pizzas de 6 parts chacune. Combien de parts au total Thomas a-t-il dû partager avec ses amis ?
Item 2.	L'opération suivante est-elle juste : 9 + 7 = 18 ?
Item 3.	Combien d'argent a Anne si elle possède 2 pièces de 1 euro et 4 pièces de 1 centime ?
Item 4.	Comment écris-tu le nombre *quatre cent quatre-vingt-deux* ?
Item 5.	Dessine-moi les aiguilles d'une horloge pour qu'on puisse lire 15h15.
Item 6.	Dessine-moi un carré et un triangle au tableau.
Item 7.	Compte de 5 en 5 à partir de 10 jusqu'à 55.
Item 8.	Quelle heure sera-t-il dans 20 minutes ?
Item 9.	L'opération suivante est-elle juste : 15 – 7 = 8 ?
Item 10.	Léa a plus d'argent que Marie. Marie a plus d'argent que Julie. Qui a le plus d'argent entre Léa et Julie ?
Instructions : « Maintenant, je vais te montrer des phrases sur des situations qui impliquent les maths. Pour chaque phrase, imagine-toi que la situation est en train d'arriver et montre-moi comment tu te sens, comme on vient de faire. Voici un exemple. »	
Exemple 2.	Tu es sur le point de faire un tour de montagnes russes.
Item 11.	Tu es en classe en train de faire des maths et ton professeur est sur le point d'enseigner quelque chose de nouveau.
Item 12.	Tu dois t'asseoir pour commencer tes devoirs de maths.
Item 13.	Tu comptes tout l'argent que tu as dans ta tirelire.
Item 14.	Quelqu'un te demande de couper une tarte aux pommes en quatre parts égales.

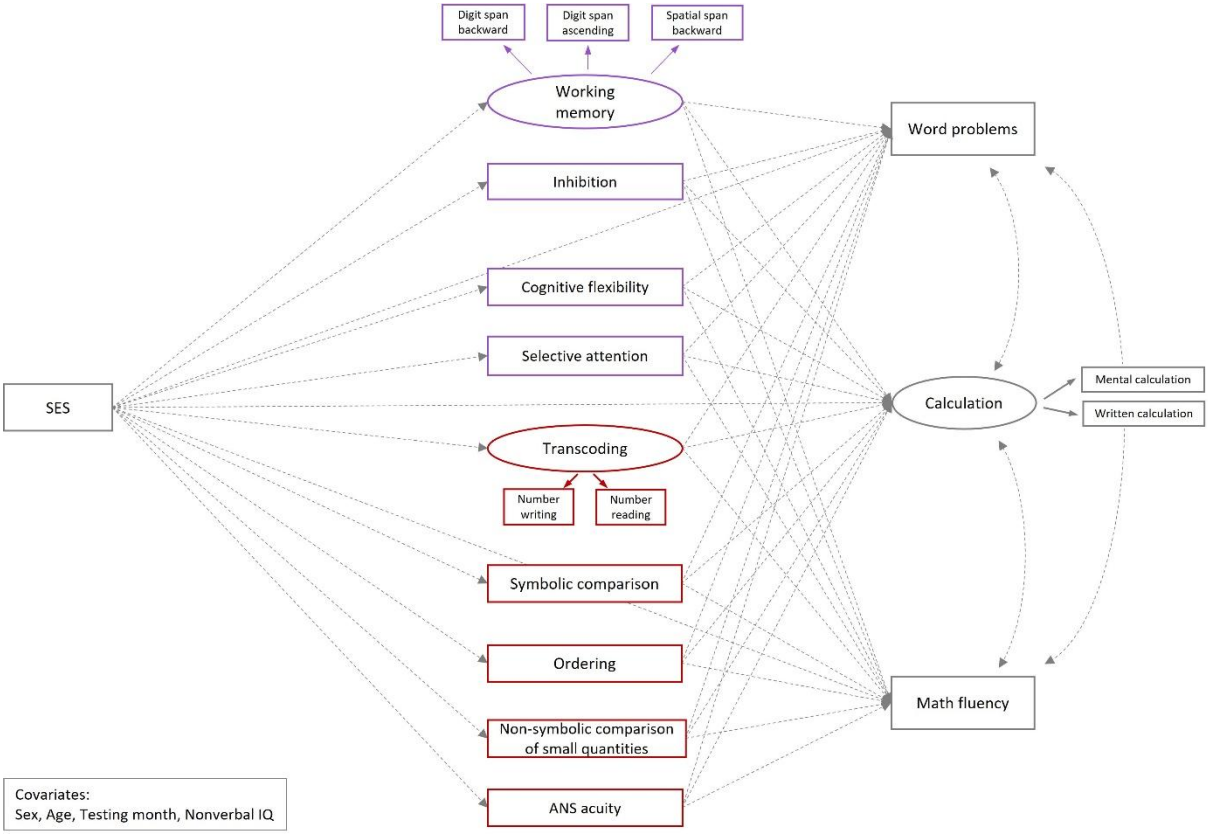
Item 15.	Tu es sur le point de faire une évaluation de maths.
Item 16.	Tu ne comprends pas quelque chose en maths. Tu demandes à ton professeur de t'aider.
Item 17.	Ton professeur te donne un tas de problèmes d'addition à résoudre.
Item 18.	Ton professeur te donne un tas de problèmes de soustraction à résoudre.
Item 19.	Tu es en classe en train de résoudre un problème de maths au tableau.
Item 20.	Tu es en train d'écouter ton professeur qui t'explique comment résoudre un problème de maths.

Appendix 3. SEM mediation model examining cognitive mediators of the SES-reading relationship (Study 1)



Note. Latent variables are depicted by ovals, whereas observed variables are represented by squares. Domain-general factors are shown in purple (upper half) and domain-specific factors in blue (lower half). Covariates were regressed onto each mediator and dependent variable (except for single-letter identification, which was regressed onto visual-attention span only). Covariances between all mediators were specified in the model but are not shown in the figure for clarity. SES = socioeconomic status; RAN = rapid automatized naming.

Appendix 4. SEM mediation model examining cognitive mediators of the SES-mathematics relationship (Study 1)



Note. Latent variables are depicted by ovals, whereas observed variables are represented by squares. Domain-general factors are shown in purple (upper half) and domain-specific factors in red (lower half). Covariates were regressed onto each mediator and dependent variable. Covariances between all mediators were specified in the model but are not shown in the figure for clarity. SES = socioeconomic status; ANS = approximate number system.

Appendix 5. Bivariate correlations among observed variables included in the reading model (Study 1)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1. Text fluency	_																								
2. Irregular words fluency	.80*	_																							
3. Regular words fluency	.85*	.81*	_																						
4. Pseudowords fluency	.80*	.66*	.81*	_																					
5. Written comprehension	.46*	.39*	.42*	.42*	_																				
6. Digit span backward	.27*	.22*	.23*	.25*	.30*	_																			
7. Digit span ascending	.30*	.28*	.26*	.23*	.28*	.34*	_																		
8. Spatial span backward	.17*	.20*	.19*	.15*	.24*	.36*	.30*	_																	
9. Inhibition	–.19*	–.16*	–.16*	–.18*	–.20*	–.21*	–.19*	–.27*	_																
10. Flexibility	–.18*	–.16*	–.19*	–.20*	–.20*	–.25*	–.23*	–.20*	.35*	_															
11. Selective attention	.22*	.23*	.21*	.19*	.12*	.18*	.15*	.19*	–.20*	–.25*	_														
12. Oral comprehension	.30*	.34*	.28*	.20*	.43*	.26*	.33*	.33*	–.27*	–.24*	.16*	_													
13. Vocabulary	.30*	.30*	.23*	.15*	.31*	.18*	.24*	.20*	–.18*	–.16*	.18*	.43*	_												
14. Initial phoneme deletion	.28*	.22*	.26*	.27*	.27*	.21*	.29*	.17*	–.15*	–.22*	.03	.22*	.12*	_											
15. Final phoneme deletion	.13*	.12*	.15*	.11*	.28*	.15*	.22*	.14*	–.11*	–.13*	.09	.22*	.08	.43*	_										
16. RAN	–.34*	–.24*	–.26*	–.29*	–.21*	–.18*	–.27*	–.20*	.21*	.21*	–.23*	–.21*	–.18*	–.18*	–.08	_									
17. Visual-attention span	.52*	.48*	.55*	.53*	.36*	.23*	.33*	.28*	–.24*	–.21*	.13*	.27*	.19*	.22*	.16*	–.31*	_								
18. Parental education	.30*	.28*	.28*	.17*	.27*	.24*	.26*	.22*	–.25*	–.14*	.14*	.48*	.38*	.14*	.12*	–.07	.16*	_							
19. Parental occupation	.29*	.29*	.24*	.14*	.25*	.23*	.22*	.29*	–.23*	–.12*	.09	.42*	.40*	.20*	.12*	–.08	.12*	.68*	_						
20. SES composite	.32*	.31*	.28*	.17*	.28*	.26*	.26*	.28*	–.26*	–.15*	.13*	.48*	.43*	.19*	.14*	–.08	.15*	.92*	.92*	_					
21. Sex	.08	–.02	–.03	–.01	.00	–.05	–.11*	–.07	.04	.18*	.03	–.02	.06	–.01	–.02	–.01	–.11*	.00	–.01	–.01	_				
22. Age	.21*	.24*	.16*	.15*	.12*	.08	.07	.06	–.04	–.09	.21*	.13*	.15*	–.03	–.02	–.09	.12*	.00	–.03	–.02	.00	_			
23. Testing month	.21*	.25*	.17*	.11*	.10*	.07	.06	.00	.03	–.05	.16*	.14*	.18*	–.03	–.02	–.12	.13*	.00	–.01	–.01	.07	.68*	_		
24. Nonverbal IQ	.31*	.32*	.25*	.23*	.29*	.21*	.18*	.23*	–.18*	–.21*	.24*	.32*	.24*	.13*	.09	–.07	.18*	.31*	.26*	.31*	.14*	.17*	.14*	_	
25. Single letter identification	.25*	.20*	.20*	.22*	.16*	.08*	.18*	.08*	–.15*	–.11*	.11*	.12*	.05	.10*	.07	–.19*	.35*	–.04	–.06	–.04	–.03	.09*	.08	.07	_

Note. Zero-order correlations are provided. Sex was dummy coded with boys = –0.5 and girls = 0.5. RAN = rapid automatized naming; SES = socioeconomic status. *$p < .05$.

Appendix 6. Bivariate correlations among observed variables included in the math model (Study 1)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1. Word problems	_																						
2. Mental calculation	.62*	_																					
3. Written calculation	.55*	.67*	_																				
4. Math fluency	.51*	.60*	.67*	_																			
5. Digit span backward	.37*	.34*	.37*	.32*	_																		
6. Digit span ascending	.49*	.41*	.38*	.37*	.34*	_																	
7. Spatial span backward	.40*	.41*	.35*	.27*	.36*	.30*	_																
8. Inhibition	–.24*	–.25*	–.28*	–.23*	–.21*	–.19*	–.27*	_															
9. Flexibility	–.32*	–.37*	–.31*	–.34*	–.25*	–.23*	–.20*	.35*	_														
10. Selective attention	.20*	.19*	.22*	.32*	.18*	.15*	.19*	–.20*	–.25*	_													
11. Number writing	.45*	.50*	.42*	.44*	.25*	.35*	.27*	–.23*	–.29*	.11*	_												
12. Number reading	.41*	.47*	.39*	.37*	.22*	.30*	.25*	–.27*	–.30*	.12*	.55*	_											
13. Symbolic comparison	.34*	.37*	.38*	.54*	.22*	.28*	.21*	–.26*	–.32*	.40*	.28*	.16*	_										
14. Ordering	.44*	.42*	.42*	.59*	.32*	.35*	.33*	–.31*	–.39*	.35*	.26*	.24*	.56*	_									
15. Non-symbolic comparison of small quantities	.23*	.26*	.26*	.36*	.12*	.16*	.15*	–.20*	–.24*	.35*	.15*	.05	.76*	.43*	_								
16. ANS acuity	–.16*	–.16*	–.23*	–.15*	–.15*	–.15*	–.12*	.13*	.14*	–.11*	–.13*	–.14*	–.15*	–.17*	–.10*	_							
17. Parental education	.36*	.33*	.29*	.15*	.24*	.26*	.22*	–.25*	–.14*	.14*	.28*	.25*	.15*	.12*	.08	–.07	_						
18. Parental occupation	.36*	.31*	.23*	.11*	.23*	.22*	.29*	–.23*	–.12*	.09	.19*	.21*	.07	.10	.03	–.06	.68*	_					
19. SES composite	.38*	.35*	.28*	.14*	.26*	.26*	.28*	–.26*	–.15*	.13*	.24*	.24*	.13*	.12*	.06	–.07	.92*	.92*	_				
20. Sex	–.13*	–.16*	–.10*	–.18*	–.05	–.11*	–.07	.04	.18*	.03	–.10*	–.12*	–.04	–.02	.01	–.13*	.00	–.01	–.01	_			
21. Age	.15*	.17*	.25*	.21*	.08	.07	.06	–.04	–.09	.21*	.06	.10*	.22*	.24*	.24*	–.06	.00	–.03	–.02	.00	_		
22. Testing month	.15*	.12*	.25*	.22*	.07	.06	.00	.03	–.05	.16*	.07	.08	.16*	.22*	.15*	–.13*	.00	–.01	–.01	.07	.68*	_	
23. Nonverbal IQ	.32*	.29*	.29*	.17*	.21*	.18*	.23*	–.18*	–.21*	.24*	.21*	.19*	.14*	.19*	.14*	–.17*	.31*	.26*	.31*	.14*	.17*	.14*	_

Note. Zero-order correlations are provided. Sex was dummy coded with boys = –0.5 and girls = 0.5. ANS = approximate number system; SES = socioeconomic status. *$p < .05$.

Appendix 7. Complete reading SEM model with all parameter estimates (Study 1)

7A. Paths from SES and covariates to cognitive variables

Paths	β	b	SE	*p*
SES → Working memory	.38	0.45	0.08	< .001
SES → Inhibition	–.24	–0.24	0.05	< .001
SES → Flexibility	–.11	–0.11	0.05	.025
SES → Selective attention	.10	0.10	0.05	.056
SES → Oral language	.62	0.94	0.13	< .001
SES → Phonological awareness	.21	0.22	0.07	.001
SES → RAN	–.08	–0.08	0.05	.138
SES → Visual-attention span	.13	0.13	0.05	.011
Sex → Working memory	–.16	–0.37	0.14	.006
Sex → Inhibition	.04	0.08	0.09	.365
Sex → Flexibility	.21	0.41	0.09	< .001
Sex → Selective attention	.01	0.02	0.09	.832
Sex → Oral language	–.01	–0.04	0.15	.803
Sex → Phonological awareness	–.03	–0.05	0.12	.668
Sex → RAN	.00	0.01	0.09	.938
Sex → Visual-attention span	–.13	–0.25	0.08	.003
Age → Working memory	.08	0.10	0.09	.279
Age → Inhibition	–.09	–0.09	0.06	.108
Age → Flexibility	–.05	–0.05	0.06	.371
Age → Selective attention	.18	0.18	0.06	.001
Age → Oral language	.06	0.10	0.10	.324
Age → Phonological awareness	–.04	–0.04	0.08	.601
Age → RAN	–.02	–0.02	0.06	.734
Age → Visual-attention span	.02	0.02	0.06	.786
Testing month → Working memory	–.00	–0.00	0.09	.987

Testing month → Inhibition	.10	0.10	0.06	.109
Testing month → Flexibility	–.01	–0.01	0.07	.933
Testing month → Selective attention	.01	0.01	0.06	.887
Testing month → Oral language	.17	0.25	0.11	.026
Testing month → Phonological awareness	–.03	–0.03	0.08	.698
Testing month → RAN	–.10	–0.10	0.07	.167
Testing month → Visual-attention span	.09	0.09	0.06	.143
Nonverbal IQ → Working memory	.25	0.30	0.07	< .001
Nonverbal IQ → Inhibition	–.11	–0.11	0.05	.013
Nonverbal IQ → Flexibility	–.19	–0.19	0.04	< .001
Nonverbal IQ → Selective attention	.18	0.18	0.05	< .001
Nonverbal IQ → Oral language	.21	0.32	0.10	.001
Nonverbal IQ → Phonological awareness	.12	0.13	0.07	.051
Nonverbal IQ → RAN	–.03	–0.03	0.05	.462
Nonverbal IQ → Visual-attention span	.13	0.13	0.05	.006
Single letter identification → Visual-attention span	.26	0.25	0.04	< .001

7B. Paths from cognitive variables and covariates to reading outcomes

Paths	Reading fluency				Reading comprehension			
	β	b	SE	*p*	β	b	SE	*p*
SES → Reading (total effect c)	.25	0.35	0.07	< .001	.22	0.22	0.05	< .001
SES → Reading (direct effect c')	.15	0.20	0.09	.035	–.19	–0.19	0.10	.058
Working memory → Reading	–.05	–0.06	0.13	.642	–.00	–0.00	0.13	.986
Inhibition → Reading	.04	0.06	0.05	.270	.03	0.03	0.05	.478
Flexibility → Reading	.00	0.01	0.05	.910	.02	0.02	0.05	.726
Selective attention → Reading	.08	0.11	0.06	.079	–.03	–0.03	0.05	.560
Oral language → Reading	.05	0.04	0.12	.723	.61	0.40	0.10	< .001
Phonological awareness → Reading	.16	0.21	0.08	.006	.16	0.16	0.08	.057
RAN → Reading	–.11	–0.15	0.06	.009	.01	0.01	0.05	.806
Visual-attention span → Reading	.45	0.63	0.07	< .001	.15	0.16	0.06	.012
Sex → Reading	.04	0.11	0.11	.335	.00	0.01	0.10	.960

Age → Reading	.08	0.12	0.07	.096	.04	0.04	0.06	.499
Testing month → Reading	.05	0.07	0.07	.337	–.09	–0.09	0.07	.195
Nonverbal IQ → Reading	.11	0.16	0.06	.009	.05	0.05	0.05	.328

7C. Variances

Variances	β	b	SE	*p*
SES	1.00	0.99	0.06	< .001
Working memory	.71	1.00	_	_
Inhibition	.91	0.91	0.09	< .001
Flexibility	.90	0.90	0.15	< .001
Selective attention	.90	0.90	0.06	< .001
Oral language	.44	1.00	_	_
Phonological awareness	.92	1.00	_	_
RAN	.98	0.98	0.12	< .001
Visual-attention span	.86	0.82	0.05	< .001
Reading fluency	.54	1.00	_	_
Reading comprehension	.60	0.60	0.06	< .001
Sex	1.00	0.25	0.001	< .001
Age	1.00	1.00	0.05	< .001
Testing month	1.00	1.00	0.03	< .001
Nonverbal IQ	1.00	1.00	0.06	< .001

7D. Covariances

Covariances	β	b	SE	*p*
Working memory ↔ Inhibition	–.29	–0.27	0.06	< .001
Working memory ↔ Flexibility	–.31	–0.29	0.06	< .001
Working memory ↔ Selective attention	.21	0.20	0.07	.002
Working memory ↔ Oral language	.57	0.57	0.10	< .001
Working memory ↔ Phonological awareness	.46	0.46	0.09	< .001
Working memory ↔ RAN	–.39	–0.39	0.07	< .001
Working memory ↔ Visual-attention span	.41	0.37	0.06	< .001

Inhibition ↔ Flexibility	.31	0.28	0.06	< .001
Inhibition ↔ Selective attention	–.15	–0.13	0.04	.002
Inhibition ↔ Oral language	–.23	–0.22	0.08	.004
Inhibition ↔ Phonological awareness	–.12	–0.12	0.06	.042
Inhibition ↔ RAN	.20	0.18	0.06	.002
Inhibition ↔ Visual-attention span	–.16	–0.14	0.04	.001
Flexibility ↔ Selective attention	–.21	–0.19	0.05	< .001
Flexibility ↔ Oral language	–.23	–0.22	0.07	.004
Flexibility ↔ Phonological awareness	–.23	–0.22	0.06	< .001
Flexibility ↔ RAN	.19	0.18	0.05	< .001
Flexibility ↔ Visual-attention span	–.12	–0.10	0.05	.046
Selective attention ↔ Oral language	.11	0.11	0.07	.115
Selective attention ↔ Phonological awareness	.03	0.03	0.06	.637
Selective attention ↔ RAN	–.20	–0.19	0.04	< .001
Selective attention ↔ Visual-attention span	.05	0.05	0.04	.282
Oral language ↔ Phonological awareness	.31	0.31	0.10	.003
Oral language ↔ RAN	–.30	–0.30	0.09	.001
Oral language ↔ Visual-attention span	.26	0.24	0.07	< .001
Phonological awareness ↔ RAN	–.20	–0.20	0.06	< .001
Phonological awareness ↔ Visual-attention span	.23	0.21	0.06	< .001
RAN ↔ Visual-attention span	–.26	–0.23	0.05	< .001
Reading fluency ↔ Reading comprehension	.24	0.18	0.05	< .001

Note. Both standardized (β) and unstandardized (*b*) estimates are reported. SE = standard error; SES = socioeconomic status; RAN = rapid automatized naming.

Appendix 8. Complete mathematics SEM model with all parameter estimates (Study 1)

8A. Paths from SES and covariates to cognitive variables

Paths	β	b	SE	*p*
SES → Working memory	.38	0.45	0.08	< .001
SES → Inhibition	–.23	–0.23	0.05	< .001
SES → Flexibility	–.10	–0.10	0.05	.040
SES → Selective attention	.09	0.09	0.05	.086
SES → Transcoding	.27	0.30	0.06	< .001
SES → Symbolic comparison	.11	0.11	0.05	.032
SES → Ordering	.09	0.09	0.05	.100
SES → Non-symbolic comparison of small quantities	.04	0.04	0.05	.451
SES → ANS acuity	–.03	–0.03	0.05	.563
Sex → Working memory	–.16	–0.38	0.14	.005
Sex → Inhibition	.04	0.08	0.09	.351
Sex → Flexibility	.21	0.42	0.09	< .001
Sex → Selective attention	.01	0.02	0.09	.845
Sex → Transcoding	–.18	–0.39	0.11	< .001
Sex → Symbolic comparison	–.05	–0.10	0.09	.273
Sex → Ordering	–.06	–0.13	0.10	.188
Sex → Non-symbolic comparison of small quantities	.00	0.00	0.09	.999
Sex → ANS acuity	–.09	–0.19	0.08	.025
Age → Working memory	.09	0.11	0.09	.244
Age → Inhibition	–.10	–0.10	0.06	.099
Age → Flexibility	–.05	–0.05	0.06	.361
Age → Selective attention	.18	0.18	0.06	.001
Age → Transcoding	.02	0.03	0.07	.704
Age → Symbolic comparison	.19	0.19	0.06	.002
Age → Ordering	.14	0.14	0.07	.036
Age → Non-symbolic comparison of small quantities	.25	0.25	0.06	< .001

Age → ANS acuity	.08	0.08	0.08	.373
Testing month → Working memory	–.01	–0.01	0.09	.923
Testing month → Inhibition	.10	0.10	0.06	.099
Testing month → Flexibility	–.01	–0.01	0.07	.944
Testing month → Selective attention	.01	0.01	0.06	.911
Testing month → Transcoding	.07	0.08	0.08	.291
Testing month → Symbolic comparison	.04	0.04	0.06	.575
Testing month → Ordering	.13	0.13	0.07	.040
Testing month → Non-symbolic comparison of small quantities	–.03	–0.03	0.06	.651
Testing month → ANS acuity	–.16	–0.16	0.09	.067
Nonverbal IQ → Working memory	.25	0.29	0.07	< .001
Nonverbal IQ → Inhibition	–.11	–0.11	0.05	.013
Nonverbal IQ → Flexibility	–.19	–0.19	0.04	< .001
Nonverbal IQ → Selective attention	.18	0.18	0.05	< .001
Nonverbal IQ → Transcoding	.20	0.22	0.07	.001
Nonverbal IQ → Symbolic comparison	.08	0.08	0.05	.076
Nonverbal IQ → Ordering	.13	0.13	0.05	.013
Nonverbal IQ → Non-symbolic comparison of small quantities	.10	0.10	0.05	.037
Nonverbal IQ → ANS acuity	–.14	–0.14	0.06	.016

8B. Paths from cognitive variables and covariates to mathematics outcomes

Paths	Word problems				Calculation				Math fluency			
	β	b	SE	*p*	β	b	SE	*p*	β	b	SE	*p*
SES → Math (total effect c)	.31	0.31	0.04	< .001	.31	0.64	0.12	< .001	.10	0.10	0.05	.056
SES → Math (direct effect c')	.06	0.06	0.05	.238	.04	0.08	0.12	.513	_	_	_	_
Working memory → Math	.60	0.51	0.11	< .001	.47	0.83	0.25	.001	.15	0.13	0.08	.102
Inhibition → Math	.08	0.08	0.04	.062	.04	0.09	0.09	.335	.05	0.05	0.04	.212
Flexibility → Math	–.01	–0.01	0.05	.909	–.03	–0.06	0.10	.508	.03	0.03	0.04	.466
Selective attention → Math	–.05	–0.05	0.04	.237	–.05	–0.10	0.10	.343	.06	0.06	0.04	.139
Transcoding → Math	.16	0.15	0.08	.052	.34	0.64	0.18	< .001	.31	0.28	0.06	< .001
Symbolic comparison → Math	–.02	–0.02	0.06	.793	.05	0.10	0.16	.522	.26	0.26	0.06	< .001

Ordering → Math	.02	0.02	0.08	.785	.04	0.08	0.16	.608	.28	0.28	0.07	< .001
Non-symbolic comparison of small quantities → Math	.08	0.08	0.06	.154	.08	0.17	0.13	.181	–.03	–0.03	0.05	.565
ANS acuity → Math	.03	0.03	0.04	.478	–.03	–0.05	0.10	.599	.01	0.01	0.03	.661
Sex → Math	–.03	–0.06	0.08	.443	–.06	–0.23	0.18	.205	–.10	–0.21	0.07	.005
Age → Math	–.00	–0.00	0.05	.949	.08	0.18	0.12	.127	–.04	–0.04	0.05	.409
Testing month → Math	.08	0.08	0.06	.156	.07	0.15	0.12	.230	.10	0.10	0.05	.029
Nonverbal IQ → Math	.05	0.05	0.05	.256	.05	0.11	0.10	.284	–.02	–0.02	0.04	.662

8C. Variances

Variances	β	b	SE	*p*
SES	1.00	1.00	0.06	< .001
Working memory	.71	1.00	_	_
Inhibition	.91	0.91	0.09	< .001
Flexibility	.90	0.90	0.15	< .001
Selective attention	.90	0.90	0.06	< .001
Transcoding	.82	1.00	_	_
Symbolic comparison	.92	0.93	0.06	< .001
Ordering	.90	0.90	0.07	< .001
Non-symbolic comparison of small quantities	.93	0.93	0.07	< .001
ANS acuity	.95	0.95	0.32	.003
Word problems	.42	0.42	0.05	< .001
Calculation	.23	1.00	_	_
Math fluency	.44	0.44	0.04	< .001
Sex	1.00	0.25	0.00	< .001
Age	1.00	1.00	0.05	< .001
Testing month	1.00	1.00	0.03	< .001
Nonverbal IQ	1.00	1.00	0.06	< .001

8D. Covariances

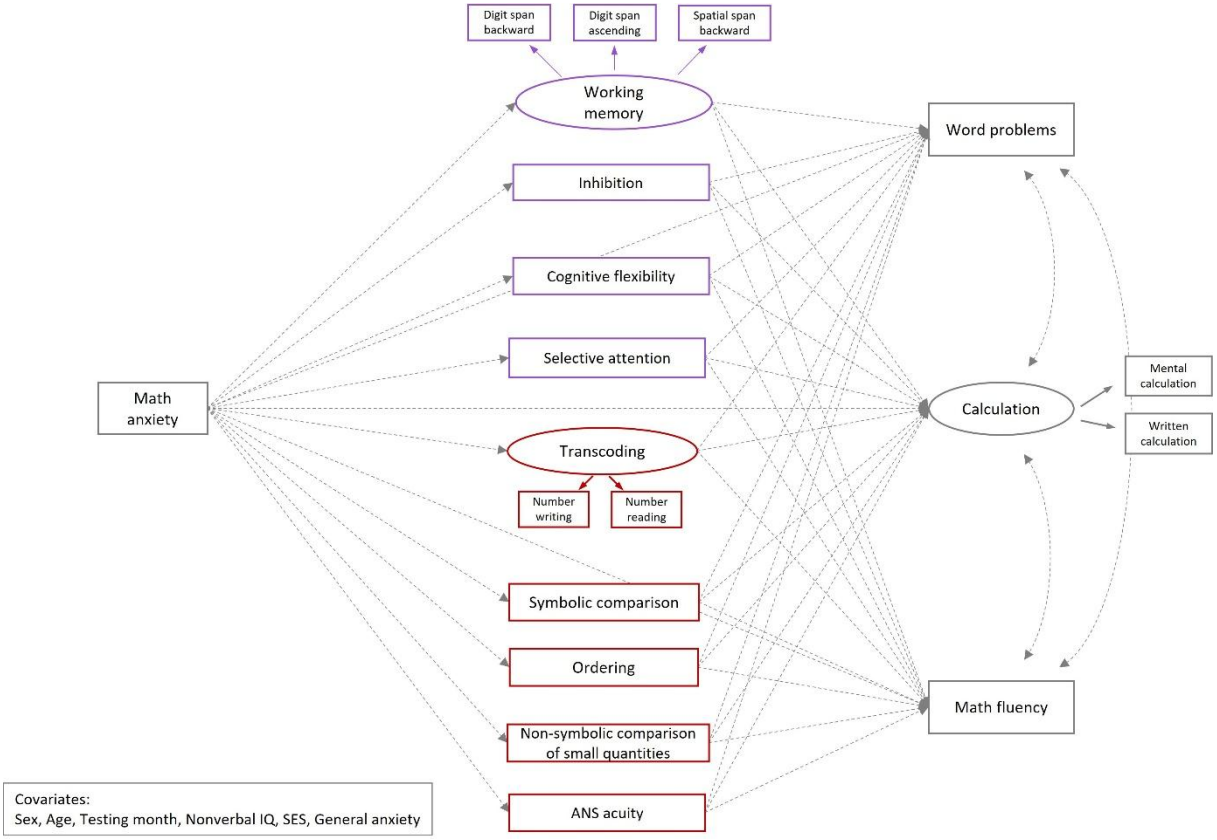
Covariances	β	b	SE	*p*
Working memory ↔ Inhibition	–.29	–0.28	0.06	< .001

Working memory ↔ Flexibility	–.31	–0.29	0.06	< .001
Working memory ↔ Selective attention	.22	0.21	0.07	.001
Working memory ↔ Transcoding	.55	0.55	0.06	< .001
Working memory ↔ Symbolic comparison	.36	0.35	0.06	< .001
Working memory ↔ Ordering	.57	0.54	0.07	< .001
Working memory ↔ Non-symbolic comparison of small quantities	.20	0.19	0.06	.002
Working memory ↔ ANS acuity	–.24	–0.23	0.05	< .001
Inhibition ↔ Flexibility	.31	0.28	0.06	< .001
Inhibition ↔ Selective attention	–.15	–0.14	0.04	.002
Inhibition ↔ Transcoding	–.25	–0.24	0.06	< .001
Inhibition ↔ Symbolic comparison	–.22	–0.20	0.05	< .001
Inhibition ↔ Ordering	–.29	–0.26	0.05	< .001
Inhibition ↔ Non-symbolic comparison of small quantities	–.17	–0.16	0.05	< .001
Inhibition ↔ ANS acuity	.12	0.11	0.03	.001
Flexibility ↔ Selective attention	–.21	–0.19	0.05	< .001
Flexibility ↔ Transcoding	–.32	–0.30	0.07	< .001
Flexibility ↔ Symbolic comparison	–.28	–0.26	0.05	< .001
Flexibility ↔ Ordering	–.36	–0.32	0.05	< .001
Flexibility ↔ Non-symbolic comparison of small quantities	–.22	–0.20	0.06	< .001
Flexibility ↔ ANS acuity	.15	0.14	0.04	< .001
Selective attention ↔ Transcoding	.08	0.07	0.05	.165
Selective attention ↔ Symbolic comparison	.36	0.33	0.05	< .001
Selective attention ↔ Ordering	.29	0.26	0.05	< .001
Selective attention ↔ Non-symbolic comparison of small quantities	.30	0.28	0.05	< .001
Selective attention ↔ ANS acuity	–.08	–0.07	0.04	.054
Transcoding ↔ Symbolic comparison	.25	0.24	0.06	< .001
Transcoding ↔ Ordering	.27	0.25	0.07	< .001
Transcoding ↔ Non-symbolic comparison of small quantities	.09	0.09	0.06	.132
Transcoding ↔ ANS acuity	–.17	–0.16	0.06	.006
Symbolic comparison ↔ Ordering	.51	0.47	0.05	< .001
Symbolic comparison ↔ Non-symbolic comparison of small quantities	.75	0.69	0.06	< .001
Symbolic comparison ↔ ANS acuity	–.14	–0.13	0.03	< .001

Ordering ↔ Non-symbolic comparison of small quantities	.38	0.35	0.05	< .001
Ordering ↔ ANS acuity	–.16	–0.15	0.04	.001
Non-symbolic comparison of small quantities ↔ ANS acuity	–.09	–0.08	0.04	.023
Word problems ↔ Calculation	.22	0.14	0.07	.032
Word problems ↔ Math fluency	.11	0.05	0.03	.080
Calculation ↔ Math fluency	.64	0.42	0.05	< .001

Note. Both standardized (β) and unstandardized (*b*) estimates are reported. SE = standard error; SES = socioeconomic status; ANS = approximate number system.

Appendix 9. SEM mediation model examining cognitive mediators of the MA-mathematics relationship (Study 2)



Note. Latent variables are represented by ovals and observed variables by squares. Domain-general factors are shown in purple (upper half) and domain-specific factors in red (lower half). Covariates were regressed onto each mediator and dependent variable. Covariances between all mediators were specified in the model, but are omitted from the present figure for clarity. ANS = approximate number system; SES = socioeconomic status.

Appendix 10. Bivariate correlations among observed variables included in the SEM model (Study 2)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1. Math anxiety	_																						
2. Word problems	–.30*	_																					
3. Mental calculation	–.35*	.62*	_																				
4. Written calculation	–.30*	.55*	.67*	_																			
5. Math fluency	–.30*	.51*	.60*	.67*	_																		
6. Digit span backward	–.17*	.37*	.34*	.37*	.32*	_																	
7. Digit span ascending	–.22*	.49*	.41*	.38*	.37*	.34*	_																
8. Spatial span backward	–.22*	.40*	.41*	.35*	.27*	.36*	.30*	_															
9. Inhibition	.05	–.24*	–.25*	–.28*	–.23*	–.21*	–.19*	–.27*	_														
10. Flexibility	.21*	–.32*	–.37*	–.31*	–.34*	–.25*	–.23*	–.20*	.35*	_													
11. Selective attention	–.09	.20*	.19*	.22*	.32*	.18*	.15*	.19*	–.20*	–.25*	_												
12. Number dictation	–.31*	.45*	.50*	.42*	.44*	.25*	.35*	.27*	–.23*	–.29*	.11*	_											
13. Number reading	–.26*	.41*	.47*	.39*	.37*	.22*	.30*	.25*	–.27*	–.30*	.12*	.55*	_										
14. Symbolic comparison	–.19*	.34*	.37*	.38*	.54*	.22*	.28*	.21*	–.26*	–.32*	.40*	.28*	.16*	_									
15. Ordering	–.27*	.44*	.42*	.42*	.59*	.32*	.35*	.33*	–.31*	–.39*	.35*	.26*	.24*	.56*	_								
16. Non-symbolic comparison of small quantities	–.07	.23*	.26*	.26*	.36*	.12*	.16*	.15*	–.20*	–.24*	.35*	.15*	.05	.76*	.43*	_							
17. ANS acuity	.09	–.16*	–.16*	–.23*	–.15*	–.15*	–.15*	–.12*	.13*	.14*	–.11*	–.13*	–.14*	–.15*	–.17*	–.10*	_						
18. Sex	.12*	–.13*	–.16*	–.10*	–.18*	–.05	–.11*	–.07	.04	.18*	.03	–.10*	–.12*	–.04	–.02	.01	–.13*	_					
19. Age	–.07	.15*	.17*	.25*	.21*	.08	.07	.06	–.04	–.09	.21*	.06	.10*	.22*	.24*	.24*	–.06	.00	_				
20. Testing month	–.01	.15*	.12*	.25*	.22*	.07	.06	.00	.03	–.05	.16*	.07	.08	.16*	.22*	.15*	–.13*	.07	.68*	_			
21. Nonverbal IQ	–.21*	.32*	.29*	.29*	.17*	.21*	.18*	.23*	–.18*	–.21*	.24*	.21*	.19*	.14*	.19*	.14*	–.17*	.14*	.17*	.14*	_		
22. SES composite	–.18*	.38*	.35*	.28*	.14*	.26*	.26*	.28*	–.26*	–.15*	.13*	.24*	.24*	.13*	.12*	.06	–.07	–.01	–.02	–.01	.31*	_	
23. General anxiety	.41*	–.15*	–.13*	–.11*	–.10*	–.16*	–.17*	–.11*	.01	.15*	–.04	–.16*	–.13*	–.11*	–.13*	–.06	–.04	.21*	–.04	.08	–.11*	–.14*	_

Note. Zero-order correlations are provided. Sex was dummy coded with boys = –0.5 and girls = 0.5. ANS = approximate number system; SES = socioeconomic status. *$p < .05$.

Appendix 11. Complete SEM model with all parameter estimates (Study 2)

11A. Paths from MA and covariates to cognitive variables

Paths	β	b	SE	*p*
MA → Working memory	–0.18	–0.22	0.08	.005
MA → Inhibition	–0.01	–0.01	0.05	.853
MA → Flexibility	0.12	0.12	0.06	.030
MA → Selective attention	–0.03	–0.03	0.05	.576
MA → Transcoding	–0.29	–0.33	0.08	< .001
MA → Symbolic comparison	–0.14	–0.14	0.05	.007
MA → Ordering	–0.22	–0.22	0.05	< .001
MA → Non-symbolic comparison of small quantities	–0.02	–0.02	0.05	.711
MA → ANS acuity	0.10	0.11	0.06	.062
Sex → Working memory	–0.11	–0.28	0.14	.047
Sex → Inhibition	0.05	0.11	0.09	.225
Sex → Flexibility	0.18	0.37	0.09	< .001
Sex → Selective attention	0.01	0.02	0.09	.796
Sex → Transcoding	–0.13	–0.31	0.12	.008
Sex → Symbolic comparison	–0.02	–0.05	0.09	.602
Sex → Ordering	–0.03	–0.06	0.10	.557
Sex → Non-symbolic comparison of small quantities	0.01	0.02	0.09	.828
Sex → ANS acuity	–0.09	–0.19	0.08	.024
Age → Working memory	0.06	0.07	0.10	.434
Age → Inhibition	–0.11	–0.11	0.06	.072
Age → Flexibility	–0.04	–0.04	0.06	.512
Age → Selective attention	0.18	0.18	0.06	.001
Age → Transcoding	–0.00	–0.00	0.07	.956
Age → Symbolic comparison	0.18	0.18	0.06	.005
Age → Ordering	0.11	0.11	0.07	.080

Age → Non-symbolic comparison of small quantities	0.25	0.25	0.06	< .001
Age → ANS acuity	0.07	0.07	0.08	.376
Testing month → Working memory	0.02	0.03	0.09	.791
Testing month → Inhibition	0.11	0.11	0.06	.070
Testing month → Flexibility	–0.02	–0.02	0.06	.790
Testing month → Selective attention	0.01	0.01	0.06	.904
Testing month → Transcoding	0.09	0.11	0.08	.184
Testing month → Symbolic comparison	0.05	0.05	0.06	.438
Testing month → Ordering	0.15	0.15	0.07	.020
Testing month → Non-symbolic comparison of small quantities	–0.02	–0.02	0.06	.741
Testing month → ANS acuity	–0.15	–0.15	0.09	.074
Nonverbal IQ → Working memory	0.20	0.25	0.07	.001
Nonverbal IQ → Inhibition	–0.12	–0.12	0.05	.007
Nonverbal IQ → Flexibility	–0.17	–0.17	0.04	< .001
Nonverbal IQ → Selective attention	0.17	0.17	0.05	< .001
Nonverbal IQ → Transcoding	0.15	0.17	0.07	.012
Nonverbal IQ → Symbolic comparison	0.05	0.05	0.05	.249
Nonverbal IQ → Ordering	0.09	0.09	0.05	.089
Nonverbal IQ → Non-symbolic comparison of small quantities	0.09	0.09	0.05	.059
Nonverbal IQ → ANS acuity	–0.13	–0.13	0.06	.039
SES → Working memory	0.34	0.42	0.09	< .001
SES → Inhibition	–0.24	–0.24	0.05	< .001
SES → Flexibility	–0.08	–0.08	0.05	.090
SES → Selective attention	0.09	0.09	0.05	.094
SES → Transcoding	0.23	0.26	0.06	< .001
SES → Symbolic comparison	0.09	0.09	0.05	.085
SES → Ordering	0.06	0.06	0.05	.269
SES → Non-symbolic comparison of small quantities	0.03	0.03	0.05	.511
SES → ANS acuity	–0.02	–0.02	0.05	.666
General anxiety → Working memory	–0.09	–0.11	0.08	.161
General anxiety → Inhibition	–0.05	–0.05	0.05	.278
General anxiety → Flexibility	0.04	0.04	0.06	.556

General anxiety → Selective attention	0.01	0.01	0.05	.925
General anxiety → Transcoding	–0.02	–0.02	0.07	.797
General anxiety → Symbolic comparison	–0.03	–0.03	0.05	.562
General anxiety → Ordering	–0.02	–0.02	0.05	.749
General anxiety → Non-symbolic comparison of small quantities	–0.03	–0.03	0.05	.484
General anxiety → ANS acuity	–0.07	–0.07	0.05	.164

11B. Paths from cognitive variables and covariates to mathematics outcomes

Paths	Word problems				Calculation				Math fluency			
	β	b	SE	*p*	β	b	SE	*p*	β	b	SE	*p*
MA → Math (total effect c)	–0.19	–0.19	0.05	< .001	–0.30	–0.65	0.13	< .001	–0.26	–0.26	0.05	< .001
MA → Math (direct effect c′)	–0.03	–0.03	0.04	.442	–0.10	–0.22	0.10	.022	–0.06	–0.06	0.04	.139
Working memory → Math	0.62	0.50	0.10	< .001	0.49	0.87	0.26	.001	0.17	0.14	0.08	.073
Inhibition → Math	0.09	0.09	0.04	.051	0.04	0.09	0.10	.337	0.05	0.05	0.04	.208
Flexibility → Math	–0.01	–0.01	0.06	.869	–0.04	–0.07	0.10	.449	0.03	0.03	0.04	.504
Selective attention → Math	–0.05	–0.05	0.04	.222	–0.05	–0.10	0.11	.326	0.06	0.06	0.04	.148
Transcoding → Math	0.16	0.14	0.07	.064	0.32	0.59	0.18	.001	0.29	0.25	0.06	< .001
Symbolic comparison → Math	–0.02	–0.02	0.06	.770	0.04	0.09	0.16	.591	0.25	0.25	0.06	< .001
Ordering → Math	0.02	0.02	0.08	.822	0.03	0.06	0.17	.735	0.27	0.27	0.07	< .001
Non-symbolic comparison of small quantities → Math	0.08	0.08	0.06	.137	0.10	0.20	0.13	.128	–0.02	–0.02	0.05	.659
ANS acuity → Math	0.03	0.03	0.04	.404	–0.01	–0.03	0.10	.751	0.02	0.02	0.03	.493
Sex → Math	–0.04	–0.09	0.08	.313	–0.07	–0.29	0.19	.117	–0.11	–0.23	0.07	.002
Age → Math	0.01	0.01	0.05	.931	0.09	0.20	0.12	.097	–0.03	–0.03	0.05	.508
Testing month → Math	0.07	0.07	0.06	.226	0.06	0.13	0.12	.317	0.10	0.10	0.05	.047
Nonverbal IQ → Math	0.05	0.05	0.05	.233	0.05	0.10	0.10	.304	–0.02	–0.02	0.04	.652
SES → Math	0.06	0.06	0.05	.230	0.04	0.08	0.12	.515	–0.09	–0.09	0.05	.054
General anxiety → Math	0.08	0.08	0.04	.051	0.13	0.27	0.10	.008	0.09	0.09	0.04	.017

11C. Variances

Variances	β	b	SE	*p*

MA	1.00	1.00	0.07	< .001
Working memory	0.66	1.00	_	_
Inhibition	0.91	0.91	0.09	< .001
Flexibility	0.89	0.88	0.15	< .001
Selective attention	0.90	0.90	0.06	< .001
Transcoding	0.74	1.00	_	_
Symbolic comparison	0.90	0.91	0.06	< .001
Ordering	0.85	0.85	0.07	< .001
Non-symbolic comparison of small quantities	0.92	0.93	0.07	< .001
ANS acuity	0.94	0.94	0.32	.003
Word problems	0.41	0.41	0.05	< .001
Calculation	0.22	1.00	_	_
Math fluency	0.43	0.43	0.04	< .001
Sex	1.00	0.25	0.00	< .001
Age	1.00	1.00	0.05	< .001
Testing month	1.00	1.00	0.03	< .001
Nonverbal IQ	1.00	1.00	0.06	< .001
SES	1.00	1.00	0.06	< .001
General anxiety	1.00	1.00	0.06	< .001

11D. Covariances

Covariances	β	b	SE	*p*
Working memory ↔ Inhibition	–0.31	–0.30	0.06	< .001
Working memory ↔ Flexibility	–0.28	–0.27	0.06	< .001
Working memory ↔ Selective attention	0.22	0.21	0.07	.002
Working memory ↔ Transcoding	0.52	0.52	0.07	< .001
Working memory ↔ Symbolic comparison	0.34	0.32	0.06	< .001
Working memory ↔ Ordering	0.55	0.51	0.07	< .001
Working memory ↔ Non-symbolic comparison of small quantities	0.19	0.19	0.06	.003
Working memory ↔ ANS acuity	–0.23	–0.23	0.05	< .001
Inhibition ↔ Flexibility	0.32	0.28	0.06	< .001
Inhibition ↔ Selective attention	–0.15	–0.14	0.04	.001

Inhibition ↔ Transcoding	–0.27	–0.26	0.06	< .001
Inhibition ↔ Symbolic comparison	–0.23	–0.21	0.05	< .001
Inhibition ↔ Ordering	–0.30	–0.26	0.05	< .001
Inhibition ↔ Non-symbolic comparison of small quantities	–0.18	–0.16	0.04	< .001
Inhibition ↔ ANS acuity	0.12	0.11	0.03	.001
Flexibility ↔ Selective attention	–0.21	–0.19	0.05	< .001
Flexibility ↔ Transcoding	–0.29	–0.28	0.07	< .001
Flexibility ↔ Symbolic comparison	–0.27	–0.24	0.05	< .001
Flexibility ↔ Ordering	–0.34	–0.30	0.05	< .001
Flexibility ↔ Non-symbolic comparison of small quantities	–0.22	–0.20	0.05	< .001
Flexibility ↔ ANS acuity	0.14	0.13	0.04	< .001
Selective attention ↔ Transcoding	0.07	0.07	0.05	.198
Selective attention ↔ Symbolic comparison	0.36	0.32	0.05	< .001
Selective attention ↔ Ordering	0.30	0.26	0.05	< .001
Selective attention ↔ Non-symbolic comparison of small quantities	0.30	0.28	0.05	< .001
Selective attention ↔ ANS acuity	–0.07	–0.07	0.04	.059
Transcoding ↔ Symbolic comparison	0.22	0.20	0.06	< .001
Transcoding ↔ Ordering	0.21	0.20	0.07	.003
Transcoding ↔ Non-symbolic comparison of small quantities	0.09	0.09	0.06	.149
Transcoding ↔ ANS acuity	–0.15	–0.15	0.05	.006
Symbolic comparison ↔ Ordering	0.50	0.44	0.05	< .001
Symbolic comparison ↔ Non-symbolic comparison of small quantities	0.75	0.69	0.06	< .001
Symbolic comparison ↔ ANS acuity	–0.13	–0.12	0.03	< .001
Ordering ↔ Non-symbolic comparison of small quantities	0.38	0.34	0.05	< .001
Ordering ↔ ANS acuity	–0.15	–0.13	0.04	.001
Non-symbolic comparison of small quantities ↔ ANS acuity	–0.09	–0.08	0.04	.020
Word problems ↔ Calculation	0.20	0.13	0.07	.058
Word problems ↔ Math fluency	0.10	0.04	0.03	.125
Calculation ↔ Math fluency	0.63	0.41	0.06	< .001

Note. Both standardized (β) and unstandardized (*b*) estimates are reported. SE = standard error; MA = math anxiety; ANS = approximate number system; SES = socioeconomic status.

Appendix 12. Composite scores derived via PCA (Studies 3 and 4)

Composite score	Indicators	Factor loadings	Eigenvalue	Proportion of variance explained
Reading fluency	Text reading	.94	3.37	.84
	Irregular word reading	.89		
	Regular word reading	.95		
	Pseudoword reading	.89		
Calculation	Mental calculation	.86	2.27	.76
	Written calculation	.89		
	Math fluency	.86		
Working memory	Digit span backward	.77	1.65	.55
	Digit span ascending	.73		
	Spatial span backward	.73		
Phonological awareness	Initial phoneme deletion	.84	1.43	.71
	Final phoneme deletion	.84		
Transcoding	Number dictation	.88	1.55	.78
	Number reading	.88		
SES	Parental education	.92	1.70	.85
	Parental occupation	.92		

Appendix 13. Descriptive statistics of the total sample (Studies 3 and 4)

Variable	N	Mean	SD	Min	Max
Demographics, SES, and nonverbal IQ					
Sex (% of girls)	461	52.28%	_	_	_
Age	461	102.53	4.67	92	113
Testing month	461	6.17	3.20	1	11
Parental education	379	13.56	3.81	0	20
Parental occupation	407	45.58	23.21	14.21	88.70
SES composite	414	0	1	–2.69	1.98
Nonverbal IQ	461	13.95	3.14	7	24
Academic variables					
Text fluency	461	83.16	29.73	2	184
Irregular words fluency	461	22.04	17.98	0	109.09
Regular words fluency	461	39.21	19.53	0	103.64
Pseudowords fluency	461	28.04	13.31	0	70.59
Reading composite	461	0	1	–2.54	3.23
Mental calculation	461	29.58	9.04	0	44
Written calculation	461	12.56	3.01	1	21
Math fluency	461	38.72	13.11	6	86
Math composite	461	0	1	–3.37	2.52
Domain-general cognitive variables					
Digit span backward	461	6.66	1.73	3	12
Digit span ascending	461	6.02	2.02	1	11
Spatial span backward	461	5.40	1.96	0	11
Working memory composite	461	0	1	–2.53	3.62
Inhibition	461	33.37	19.46	–17.80	123.80
Cognitive flexibility	461	102.44	40.67	5.20	403.10
Reading-specific cognitive variables					

Initial phoneme deletion	461	7.04	2.72	0	10
Final phoneme deletion	461	7.41	2.63	0	10
Phonological awareness composite	461	0	1	–3.00	1.27
RAN	461	23.33	6.65	13	64
Visual-attention span	461	80.33	11.60	43	100
Single-letter identification (control)	461	98.65	27.43	13	150
Math-specific cognitive variables					
Number dictation	461	13.78	2.64	4	16
Number reading	461	14.83	1.84	4	16
Transcoding composite	461	0	1	–5.56	1.02
Symbolic comparison	461	39.41	8.08	16	56
ANS acuity (*w*)	461	0.31	0.25	0.02	3.37

Note. For the cognitive measures, lower scores on the Weber fraction (*w*), RAN, inhibition, and flexibility tasks indicate better performance. In the inhibition task, scores are adjusted for processing speed using a baseline condition without interference; negative scores indicate that a participant performed better in the inhibition than in the baseline condition (observed in 3 participants). Composite scores are PCA-derived *z* scores computed from variables residualized on age and testing month. RAN = rapid automatized naming; ANS = approximate number system; SES = socioeconomic status.

Appendix 14. Bivariate correlations among variables (Studies 3 and 4)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Reading (composite score)	_													
2. Mathematics (composite score)	.42*	_												
3. Working memory (composite score)	.33*	.56*	_											
4. Inhibition	–.20*	–.30*	–.30*	_										
5. Flexibility	–.19*	–.38*	–.30*	.35*	_									
6. Phonological awareness (composite score)	.27*	.31*	.31*	–.14*	–.22*	_								
7. RAN	–.29*	–.25*	–.28*	.21*	.20*	–.16*	_							
8. Visual-attention span	.51*	.35*	.35*	–.20*	–.18*	.21*	–.25*	_						
9. Transcoding (composite score)	.36*	.55*	.41*	–.28*	–.33*	.35*	–.19*	.32*	_					
10. Symbolic comparison	.26*	.46*	.30*	–.26*	–.31*	.06	–.24*	.18*	.24*	_				
11. ANS acuity	–.17*	–.19*	–.19*	.13*	.14*	–.13*	.11*	–.11*	–.15*	–.14*	_			
12. SES (composite score)	.31*	.31*	.36*	–.26*	–.15*	.19*	–.08	.18*	.28*	.14*	–.07	_		
13. Sex	.00	–.18*	–.11*	.03	.18*	–.01	.00	–.11*	–.13*	–.04	–.12*	–.01	_	
14. Nonverbal IQ	.28*	.25*	.26*	–.17*	–.18*	.14*	–.05	.15*	.21*	.10*	–.16*	.32*	.15*	_

Note. Zero-order correlations are provided. Academic and cognitive variables were residualized for age and testing month. Sex was dummy coded with boys = –0.5 and girls = 0.5. RAN = rapid automatized naming; ANS = approximate number system; SES = socioeconomic status. *$p < .05$.

Appendix 15. Fit indices for LPA models with different variance-covariance specifications in poor readers (Study 3)

Model specification	Number of profiles	AIC	BIC	Entropy	Minimum probability	Smallest n (%)	BLRT (*p*)
Equal variances and covariances fixed to 0	1	2449.15	2484.36	1.00	1.00	1.00	_
	2	2390.46	2446.22	0.70	0.85	0.29	0.010
	3	2389.13	2465.42	0.76	0.72	0.16	0.198
	4	2364.66	2461.49	0.77	0.73	0.09	0.010
	5	2347.64	2465.02	0.81	0.80	0.07	0.010
	6	2349.37	2487.29	0.76	0.79	0.07	0.376
Varying variances and covariances fixed to 0	1	2449.15	2484.36	1.00	1.00	1.00	_
	2	**2323.22**	**2396.58**	**0.75**	**0.93**	**0.45**	**0.010**
	3	2333.35	2444.86	0.88	0.91	0.09	0.861
	4	2325.22	2474.87	0.74	0.83	0.09	0.069
	5	2298.85	2486.66	0.77	0.70	0.12	0.010
	6	2306.67	2532.63	0.78	0.72	0.09	0.604
Equal variances and equal covariances	1	2396.19	2475.42	1.00	1.00	1.00	_
	2	2387.42	2487.19	0.79	0.92	0.39	0.059
	3	2387.00	2507.32	0.76	0.88	0.22	0.149
	4	2359.42	2500.27	0.78	0.87	0.12	0.010
	5	2344.27	2505.66	0.82	0.86	0.05	0.010
	6	2339.43	2521.37	0.83	0.85	0.05	0.149
Varying variances and varying covariances	1	2396.19	2475.42	1.00	1.00	1.00	_
	2	2326.52	2487.91	0.87	0.95	0.31	0.010
	3	2315.36	2558.92	0.95	0.98	0.13	0.208
	4	2311.82	2637.55	0.91	0.92	0.14	0.465
	5	2308.90	2716.79	0.87	0.88	0.14	0.257
	6	2323.28	2813.34	0.91	0.88	0.12	0.743

Note. AIC = Akaike information criterion; BIC = Bayesian information criterion; BLRT = bootstrapped likelihood ratio test. The selected profile solution is bolded.

Appendix 16. Fit indices for LPA models with different variance-covariance specifications in poor mathematics achievers (Study 3)

Model specification	Number of profiles	AIC	BIC	Entropy	Minimum probability	Smallest n (%)	BLRT (*p*)
Equal variances and covariances fixed to 0	1	2458.72	2493.93	1.00	1.00	1.00	_
	2	2389.82	2445.57	0.86	0.93	0.22	0.010
	3	2393.52	2469.81	0.57	0.69	0.17	0.475
	4	2396.05	2492.89	0.67	0.74	0.01	0.277
	5	2338.59	2455.97	0.76	0.69	0.04	0.010
	6	2307.60	2445.52	0.83	0.74	0.01	0.010
Varying variances and covariances fixed to 0	1	2458.72	2493.93	1.00	1.00	1.00	_
	2	**2314.76**	**2388.13**	**0.74**	**0.88**	**0.43**	**0.010**
	3	2319.40	2430.91	0.75	0.78	0.17	0.475
	4	2282.14	2431.80	0.73	0.79	0.10	0.010
	5	2263.77	2451.58	0.79	0.83	0.09	0.030
	6	2261.17	2487.13	0.81	0.75	0.06	0.050
Equal variances and equal covariances	1	2407.84	2487.08	1.00	1.00	1.00	_
	2	2381.92	2481.69	0.90	0.89	0.17	0.010
	3	2392.01	2512.32	0.65	0.72	0.19	0.960
	4	2412.99	2553.85	0.73	0.73	0.09	0.901
	5	2348.64	2510.03	0.84	0.84	0.03	0.010
	6	2351.75	2533.69	0.86	0.83	0.03	0.436
Varying variances and varying covariances	1	2407.84	2487.08	1.00	1.00	1.00	_
	2	2312.69	2474.09	0.76	0.91	0.43	0.010
	3	2309.71	2553.28	0.85	0.93	0.27	0.287
	4	2312.51	2638.24	0.90	0.92	0.06	0.792
	5	2290.99	2698.88	0.89	0.85	0.08	0.079
	6	2324.36	2814.42	0.92	0.85	0.09	0.475

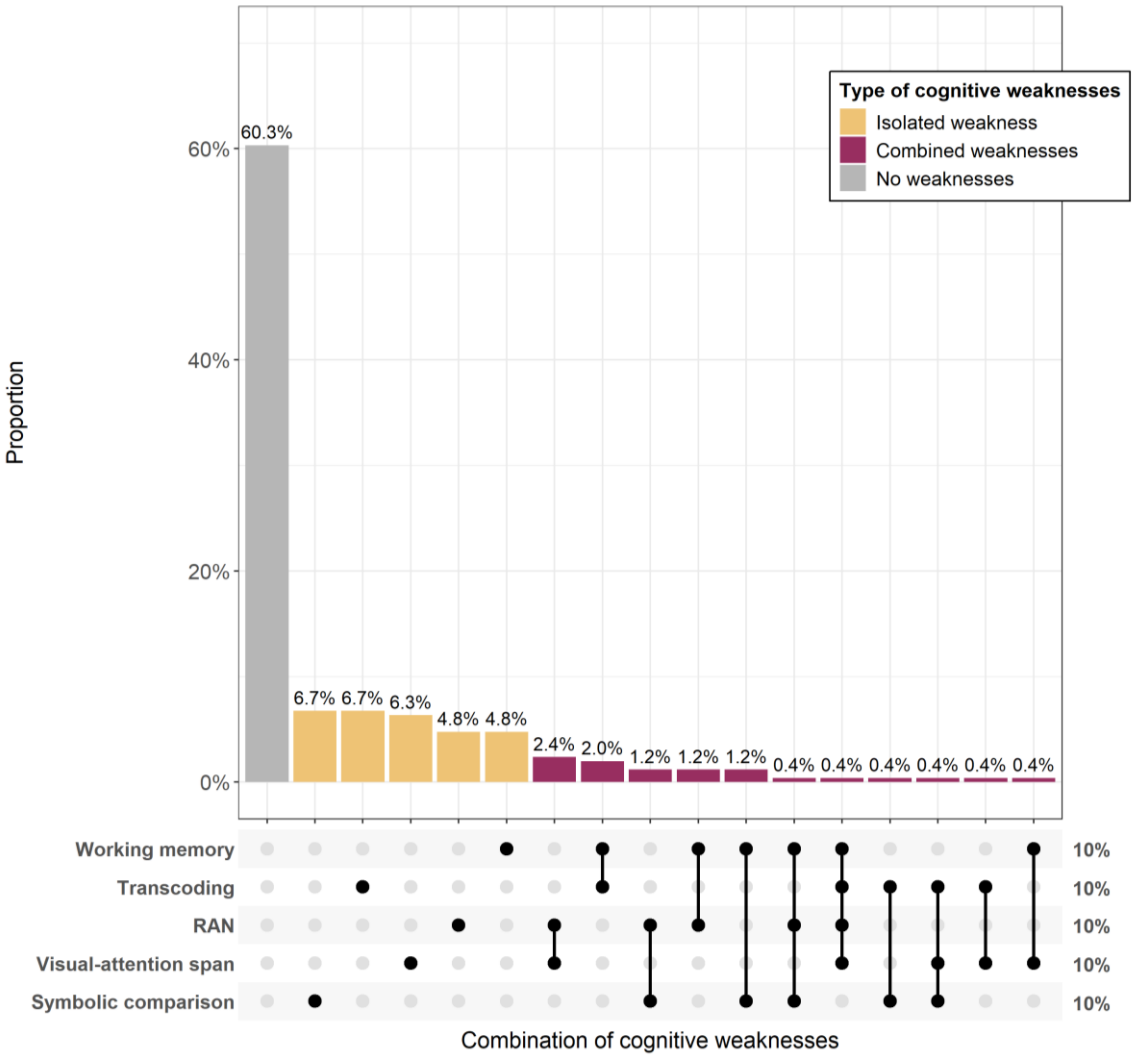
Note. AIC = Akaike information criterion; BIC = Bayesian information criterion; BLRT = bootstrapped likelihood ratio test. The selected profile solution is bolded.

Appendix 17. Prevalence of cognitive weaknesses across all cognitive factors by group (Study 4)

Variable	PR (*n* = 70)	PM (*n* = 70)	PR-PM (*n* = 69)	Average achievers (*n* = 252)
Domain-general cognitive variables				
Working memory	12.86%	31.43%	44.93%	10.32%
Inhibition	24.29%	22.86%	24.64%	10.32%
Cognitive flexibility	17.14%	24.29%	40.58%	10.32%
Reading-specific cognitive variables				
Phonological awareness	4.29%	15.71%	33.33%	10.32%
RAN	25.71%	22.86%	30.43%	10.32%
Visual-attention span	47.14%	21.43%	50.72%	10.32%
Mathematics-specific cognitive variables				
Transcoding	22.86%	45.71%	60.87%	10.32%
Symbolic comparison	22.86%	28.57%	37.68%	10.32%
ANS acuity	24.29%	27.14%	36.23%	10.32%

Note. Percentages represent the proportion of children within each group exhibiting a cognitive weakness, defined as a score at or below the 10th percentile of the average achievers group. By definition, the proportion of cognitive weaknesses in average achievers was 10% for each variable. PR = poor readers only; PM = poor mathematics achievers only; PR-PM = co-occurring poor readers and poor mathematics achievers; RAN = rapid automatized naming; ANS = approximate number system.

Appendix 18. Prevalence and combination of cognitive weaknesses in the average achievers group (Study 4)



Note. Percentages above the bars indicate the proportion of children exhibiting a given combination of cognitive weaknesses. Percentages at the right end of each line indicate the total proportion of children showing a weakness in the corresponding cognitive ability. A cognitive weakness was defined as a score at or below the 10th percentile of the average achievers group. By definition, the proportion of cognitive weaknesses in average achievers was 10% for each variable. RAN = rapid automatized naming.

Publications

Accepted

Taieb, E., Borst, G., Le Stanc, L., Houdé, O., Altarelli, I.*, & Iuculano, T.* (accepted). Domain-general and domain-specific cognitive factors mediating the relationship between math anxiety and mathematical performance in primary school children. *Scientific Reports*.

Under review

Taieb, E., Le Stanc, L., Borst, G., Houdé, O., Altarelli, I.*, & Iuculano, T.* (under review). Cognitive factors mediating socioeconomic influences on reading and mathematics achievement among primary school children.

In preparation

Taieb, E., Borst, G., Le Stanc, L., Houdé, O., Iuculano, T.*, & Altarelli, I.* (in prep.). Cognitive correlates of isolated and co-occurring difficulties in reading and mathematics among primary school children.

Résumé substantiel de la thèse

Contexte

L'apprentissage de la lecture et des mathématiques à l'école primaire constitue une étape cruciale du développement académique, prédictive de la réussite scolaire et professionnelle ultérieure. Cependant, une proportion importante d'enfants éprouve des difficultés à acquérir des compétences adéquates dans ces domaines. Les dernières évaluations internationales PIRLS et TIMSS indiquent en effet qu'entre 25% et 30% des élèves de CM1 n'atteignent pas les niveaux de compétences attendus pour leur âge en lecture et en mathématiques (Mullis et al., 2023; Von Davier et al., 2024). Si les formes les plus sévères de ces difficultés, telles que la dyslexie et la dyscalculie, ont fait l'objet d'un vaste corpus de recherches, peu d'études se sont intéressées à la population plus large des enfants présentant de faibles performances en lecture ou en mathématiques. Cette lacune est d'autant plus préoccupante que, contrairement aux enfants avec troubles spécifiques des apprentissages, ceux qui présentent des difficultés plus modérées disposent rarement d'un accompagnement adapté qui pourrait pourtant leur être bénéfique. Compte tenu des conséquences négatives à long-terme des difficultés en lecture et en mathématiques à l'école primaire – tant sur la réussite académique future (Duncan et al., 2007), le niveau socio-économique atteint à l'âge adulte (Ritchie & Bates, 2013), que sur bien-être psychologique (Parsons & Bynner, 2005) – il apparaît essentiel de mieux comprendre les multiples facteurs susceptibles d'influencer les différences individuelles dans ces domaines académiques. Parmi ces facteurs, la littérature a notamment mis en évidence le rôle de variables cognitives, socio-économiques et émotionnelles.

Un grand nombre de processus cognitifs sont impliqués dans les apprentissages de la lecture et des mathématiques. Parmi eux, on distingue les facteurs cognitifs domaine-spécifiques, qui soutiennent spécifiquement la lecture ou les mathématiques, des facteurs domaine-généraux, impliqués de manière transversale dans différents types d'apprentissage et contribuant ainsi à la fois à la lecture et aux mathématiques.

Parmi les facteurs domaine-spécifiques de la lecture, la recherche souligne l'importance des compétences liées au langage, telles que la conscience phonologique (capacité à identifier et manipuler les unités phonologiques du langage), la dénomination rapide automatisée (RAN) (capacité à accéder rapidement à des représentations lexicales) et

le langage oral, incluant notamment le vocabulaire et la compréhension orale (Hulme & Snowling, 2013). De plus, des processus visuo-attentionnels, tels que l'empan visuo-attentionnel – défini comme le nombre d'éléments visuels distincts qu'un individu est capable de traiter en une seule fixation (Valdois, 2022; Valdois et al., 2004) – jouent également un rôle. Concernant les facteurs domaine-spécifiques des mathématiques, ceux-ci englobent des processus non-symboliques, tels que la capacité innée à traiter approximativement les quantités (Feigenson et al., 2004; Odic & Starr, 2018), ainsi que des processus symboliques (Banfi et al., 2022; Lyons et al., 2014), incluant la comparaison symbolique (capacité à comparer des nombres représentés sous forme de chiffres arabes), le transcodage (capacité à passer du code oral (e.g., « cinq ») au code écrit (e.g., 5) et vice versa), et la capacité à traiter l'ordre des nombres. En ce qui concerne les facteurs domaine-généraux, on retrouve notamment les fonctions exécutives (Diamond, 2013; Spiegel et al., 2021) – comprenant la mémoire de travail (capacité à maintenir et manipuler des informations en mémoire), l'inhibition (capacité à supprimer des stimuli ou réponses non pertinentes) et la flexibilité cognitive (capacité à alterner efficacement entre différentes tâches ou processus mentaux) – ainsi que l'attention sélective (capacité à se concentrer sur une tâche en ignorant les stimuli distracteurs) (Stevens & Bavelier, 2012).

Il est important de souligner que ces différents facteurs cognitifs ont été démontrés comme prédictifs de la réussite scolaire en lecture et/ou en mathématiques, et sont également affectés chez les enfants présentant des difficultés dans ces domaines. Néanmoins, la majorité des recherches sur la réussite et les difficultés en lecture et en mathématiques a généralement considéré un nombre limité de facteurs simultanément, laissant incertaine la question de leurs effets indépendants sur les performances académiques. De plus, il convient de noter que le développement de ces compétences cognitives ne se déroule pas indépendamment du contexte environnemental dans lequel les enfants grandissent.

Le statut socio-économique (SES) parental a été identifié comme un facteur influençant de manière significative les performances académiques en lecture et en mathématiques (J. Liu et al., 2022a; Selvitopu & Kaya, 2023; Sirin, 2005), ainsi que diverses compétences cognitives des enfants. Parmi celles-ci, la littérature a largement documenté un effet du SES sur les fonctions exécutives et les compétences langagières (Hackman & Farah, 2009; Merz et al., 2019). Par ailleurs, il a été démontré que ces processus cognitifs jouent un rôle médiateur dans la relation entre SES et performances académiques (X. Ding et al., 2024; J. Li et al., 2023). Cependant, il reste largement inconnu si d'autres processus cognitifs impliqués dans la lecture ou les mathématiques peuvent également être affectés par le SES et constituer des médiateurs

de ces relations. De plus, très peu d'études ont examiné le rôle médiateur simultané de différentes compétences cognitives – à la fois domaine-générales et domaine-spécifiques – dans les relations entre SES et performances académiques en lecture et en mathématiques, ce qui laisse incertaine la contribution unique de chacune de ces compétences dans les écarts de performances scolaires associés au SES.

Par ailleurs, en plus de facteurs cognitifs et socio-économiques, des facteurs émotionnels ont également été identifiés comme influençant la réussite académique, en particulier dans le domaine des mathématiques. Plus spécifiquement, l'anxiété mathématique (MA) – définie comme des sentiments de tension, d'appréhension ou de peur face à des situations impliquant les mathématiques – a été montrée comme ayant un impact négatif sur les performances en mathématiques, et ce dès le début de l'école primaire (Namkung et al., 2019; Ramirez et al., 2018; Wu et al., 2012). Plusieurs mécanismes ont été proposés pour expliquer ce lien. Il a notamment été suggéré que la MA pourrait réduire les performances en consommant les ressources limitées de la mémoire de travail par des pensées anxieuses ou en diminuant la capacité à inhiber des stimuli internes ou externes non pertinents pour la tâche mathématique (Suárez-Pellicioni et al., 2016). Par ailleurs, certaines études indiquent que la MA n'affecterait pas uniquement de tels processus de haut niveau, mais pourrait également être associée à des déficits dans des compétences de traitement numériques basiques chez les individus présentant une forte MA (Maloney et al., 2010; Suárez-Pellicioni et al., 2016). Ainsi, bien qu'il ait été montré que la MA peut impacter différentes compétences cognitives, tant domaine-générales que domaine-spécifiques, impliquées dans les mathématiques, très peu d'études ont examiné si ces compétences jouent un rôle médiateur dans la relation entre MA et performances en mathématiques. Parmi les recherches existantes, le rôle médiateur de la mémoire de travail semble se confirmer de manière consistante, tandis que les résultats concernant les compétences domaine-spécifiques restent controversés (Skagerlund et al., 2019; Szczygieł, 2021). Ces observations soulignent la nécessité d'approches intégratives examinant le rôle médiateur conjoint de différentes compétences domaine-générales et domaine-spécifiques dans la relation entre MA et performances mathématiques.

De surcroît, certaines études indiquent que la MA peut être influencée par le SES, avec des niveaux plus élevés de MA observés chez les enfants issus de milieux socio-économiques défavorisés (Adimora et al., 2015; Guzmán et al., 2021). Il apparaît donc essentiel de contrôler pour le potentiel effet confondant du SES dans l'étude des facteurs cognitifs contribuant au lien entre MA et performances mathématiques, ce qui n'a, à ce jour, été réalisé par aucune étude.

De manière générale, il ressort que les performances académiques sont influencées par de multiples facteurs, incluant des dimensions cognitives, socio-économiques et émotionnelles. Toutefois, tous les enfants présentant de faibles performances académiques ne présentent pas nécessairement les mêmes caractéristiques. Notamment, chez les enfants faibles lecteurs, différents profils cognitifs ont été observés, avec certains enfants présentant des faiblesses uniquement en conscience phonologique, d'autres uniquement en RAN, ou encore d'autres uniquement en empan visuo-attentionnel (Valdois et al., 2021). De manière similaire, des profils cognitifs distincts ont été identifiés chez les enfants présentant de faibles performances en mathématiques, caractérisés par des difficultés dans le traitement non-symbolique, le traitement symbolique, ou encore la mémoire de travail (Bartelet et al., 2014; W. W. L. Chan & Wong, 2020). Ainsi, ces observations suggèrent que les enfants faibles lecteurs et faibles en mathématiques ne présentent pas tous les mêmes caractéristiques cognitives. Néanmoins, peu d'études adoptant une approche interindividuelle ont intégré à la fois des facteurs cognitifs domaine-spécifiques et domaine-généraux pour caractériser l'hétérogénéité des faiblesses cognitives chez les enfants faibles performeurs, fournissant ainsi un aperçu partiel des profils cognitifs existants chez ces populations. Cela souligne l'importance de considérer cette variabilité interindividuelle en incluant un large éventail de facteurs cognitifs, afin de proposer des interventions adaptées aux besoins spécifiques de chaque enfant rencontrant des difficultés dans ces domaines académiques.

Par ailleurs, une autre source de variabilité parmi les enfants présentant de faibles performances académiques réside dans le fait que les difficultés peuvent concerner exclusivement le domaine des mathématiques ou de la lecture, ou bien se manifester simultanément dans les deux domaines. Il a ainsi été rapporté que jusqu'à 50% des enfants présentant des difficultés dans un domaine en présentent également dans l'autre (Grigorenko et al., 2020; Koponen et al., 2018). Néanmoins, malgré leur prévalence importante, les difficultés co-occurrentes en lecture et en mathématiques ont reçu peu d'attention, laissant les processus cognitifs les sous-tendant encore largement méconnus.

Plusieurs modèles ont été proposés pour expliquer l'émergence de difficultés touchant les deux domaines simultanément (Ashkenazi et al., 2013; Starling-Alves et al., 2025). Le modèle additif postule que la co-occurrence des difficultés résulte de l'effet cumulatif de déficits cognitifs indépendamment associés à chaque domaine d'apprentissage. Le modèle des trois troubles indépendants suggère, quant à lui, que les enfants présentant des difficultés co-occurrentes possèdent un profil cognitif distinct, caractérisé par des altérations cognitives différentes et/ou plus sévères que celles observées chez les enfants avec des difficultés isolées

dans un seul domaine. Enfin, le modèle du risque accru propose que des difficultés en lecture et dans des compétences cognitives verbales, telles qu'en conscience phonologique, augmenteraient le risque de développer également des difficultés en mathématiques, dans la mesure où certains processus mathématiques — comme la résolution de problèmes verbaux ou la récupération de faits arithmétiques en mémoire — mobilisent de telles compétences linguistiques (De Smedt et al., 2013; Starling-Alves et al., 2025).

Les données empiriques restent toutefois controversées et aucun modèle ne s'est imposé comme prédominant, bien que les trois hypothèses ne soient pas nécessairement mutuellement exclusives (Starling-Alves et al., 2025). Une limite majeure des recherches antérieures est qu'elles ont rarement pris en compte une gamme étendue de compétences cognitives, incluant à la fois des processus domaine-généraux, lecture-spécifiques et mathématiques-spécifiques, dans l'étude des facteurs contribuant aux difficultés isolées et co-occurrentes (L. Peters et al., 2020). Ces observations soulignent la nécessité d'études intégratives, prenant en compte l'ensemble de ces facteurs, afin de caractériser plus finement les besoins des enfants présentant des difficultés isolées ou co-occurrentes en lecture et en mathématiques.

Objectifs de la thèse

Dans ce contexte, la présente thèse a pour objectif de contribuer à la compréhension des déterminants multifactoriels des faibles performances en lecture et en mathématiques à l'école primaire, en intégrant des facteurs cognitifs, socio-économiques et émotionnels. Elle vise également à caractériser la variabilité interindividuelle parmi les enfants présentant de faibles performances dans l'un ou l'autre de ces domaines, ou dans les deux simultanément. De manière générale, cette thèse pourra offrir des perspectives pertinentes pour le développement futur d'interventions ciblées, visant à fournir un soutien personnalisé aux enfants rencontrant de telles difficultés académiques.

Plus spécifiquement, le premier objectif consiste à examiner l'effet du SES sur les performances en lecture et en mathématiques, ainsi qu'à déterminer si des facteurs cognitifs domaine-généraux et/ou domaine-spécifiques jouent un rôle médiateur dans ces relations (Étude 1). Le deuxième objectif vise à évaluer l'impact de la MA sur les performances en mathématiques, en contrôlant pour le SES, et à identifier d'éventuels facteurs cognitifs médiateurs de cette relation (Étude 2). Le troisième objectif porte sur la caractérisation de la diversité des profils cognitifs pouvant exister chez les enfants faibles performeurs en lecture

et en mathématiques (Étude 3). Enfin, le quatrième objectif consiste à investiguer les caractéristiques cognitives associées aux difficultés en lecture seulement, en mathématiques seulement, et dans les deux domaines, ainsi qu'à examiner la variabilité interindividuelle pouvant être présente au sein de chaque groupe (Étude 4).

Méthode

Pour répondre aux différents objectifs de cette thèse, un large échantillon d'enfants de CE2 a été recruté. Ce groupe d'âge a été spécifiquement choisi car il correspond à un stade développemental caractérisé par des exigences académiques croissantes (Fuchs et al., 2006), une période critique dans l'augmentation des écarts de performance liés au SES (Kieffer, 2012) et dans le développement de la MA (Wu et al., 2012), et une stabilité des difficultés académiques, réduisant ainsi la probabilité qu'elles ne constituent que de simples retards dans l'acquisition de la lecture et des mathématiques (Koponen et al., 2018). Par ailleurs, les enfants recrutés étaient scolarisés dans des écoles élémentaires REP et REP+ de Paris et de sa proche banlieue. Ce choix a permis d'inclure des enfants issus d'une grande diversité de milieux socio-économiques tout en conservant un contexte pédagogique relativement homogène.

Un total de 597 enfants a été initialement recruté. Toutefois, seuls les participants présentant une vision normale ou corrigée, sans trouble neurologique ou du neurodéveloppement, n'ayant pas redoublé ni sauté de classe, ayant acquis le français avant l'âge de trois ans, et présentant un QI non-verbal supérieur à deux écarts-types en dessous de la norme pour l'âge ont été inclus dans les analyses. L'échantillon final comprenait 472 participants (245 filles, 227 garçons ; âge moyen = 102,6 ± 4,7 mois).

Pour ce projet de thèse, la collecte des données s'est déroulée entre mai 2022 et décembre 2023 dans 19 écoles. Chaque enfant a été évalué individuellement dans une salle calme par des assistants de recherche ou des stagiaires formés en psychologie ou en orthophonie. L'évaluation comprenait quatre sessions d'environ 30 minutes, espacées en moyenne d'une semaine. La première session portait sur les performances académiques en lecture et en mathématiques ainsi que sur le QI non-verbal ; la deuxième, sur les fonctions cognitives domaine-générales ; la troisième, sur les fonctions cognitives spécifiques à la lecture ; et enfin, la quatrième, sur les compétences cognitives spécifiques aux mathématiques, ainsi que sur les facteurs émotionnels. Les informations démographiques et socio-économiques ont été recueillies via un questionnaire parental (voir Annexe 1). Le protocole expérimental a été approuvé par le Comité d'éthique de l'Université Paris Cité (N° IRB : 00012023-42).

Les mesures collectées couvraient différents aspects, incluant :

- les **performances académiques**, évaluées par la fluence et la compréhension de lecture (BALE; Jacquier-Roux et al., 2010), ainsi que la résolution de problèmes verbaux, le calcul mental et écrit, et la fluence mathématique (ZAREKI-R; von Aster & Dellatolas, 2006; WJ-III; Woodcock et al., 2001).
- les **compétences cognitives domaine-générales**, comprenant la mémoire de travail verbale (WISC-V; Wechsler, 2014) et visuelle (WNV; Wechsler & Naglieri, 2006), l'inhibition et la flexibilité cognitive (NEPSY-II; Korkman et al., 2007), ainsi que l'attention sélective (recherche visuelle) (WISC-V; Wechsler, 2014).
- les **compétences cognitives domaine-spécifiques de la lecture**, mesurées par la conscience phonologique (BALE; Jacquier-Roux et al., 2010), la RAN (BALE; Jacquier-Roux et al., 2010), le langage oral (BALE; Jacquier-Roux et al., 2010; ELO; Khomsi, 2001) et l'empan visuo-attentionnel (Bosse et al., 2007).
- les **compétences cognitives domaine-spécifiques des mathématiques**, évaluées par le transcodage (ZAREKI-R; von Aster & Dellatolas, 2006), la comparaison symbolique (Numeracy Screener; Lafay et al., 2018; Nosworthy et al., 2013), le traitement de l'ordre numérique (Numeracy Screener; Hutchison et al., 2022; Nosworthy et al., 2013), ainsi que la comparaison non-symbolique de petites quantités (Numeracy Screener; Lafay et al., 2018; Nosworthy et al., 2013) et de grandes quantités (Panamath; Halberda et al., 2008).
- les **facteurs émotionnels**, comprenant la MA (SEMA; Wu et al., 2012) et l'anxiété générale (R-CMAS; Castro, 1999; Reynolds & Richmond, 1978).
- le **SES parental**, calculé à partir d'un score composite intégrant le plus haut niveau d'études et le plus haut score de profession (Ganzeboom, 2010) de l'un ou l'autre parent (OECD, 2023).

Etude 1

La première étude visait à examiner les relations entre le SES et les performances académiques en lecture et en mathématiques, tout en évaluant le rôle médiateur éventuel de facteurs cognitifs, tant domaine-généraux que domaine-spécifiques.

De nombreuses recherches ont montré que le SES est significativement associé à la réussite scolaire (J. Liu et al., 2022a; Selvitopu & Kaya, 2023; Sirin, 2005), les enfants issus de milieux défavorisés présentant en moyenne des performances plus faibles en lecture et en

mathématiques que leurs pairs de haut SES. Par ailleurs, plusieurs études ont suggéré que le SES pourrait également affecter le développement de compétences cognitives impliquées dans ces apprentissages (Noble, Norman, et al., 2005; Ursache & Noble, 2016). En particulier, des travaux ont mis en évidence un effet du SES sur les compétences domaine-générales et montré qu'elles pouvaient médier la relation entre SES et performances académiques (X. Ding et al., 2024). Concernant les facteurs domaine-spécifiques à la lecture, la conscience phonologique et le langage oral ont été identifiés comme médiateurs significatifs du lien entre SES et lecture (J. Li et al., 2023). Cependant, l'impact du SES sur d'autres compétences domaine-spécifiques reste peu documenté, avec des résultats controversés pour la RAN et aucune donnée concernant l'empan visuo-attentionnel. Pour ce qui est des facteurs domaine-spécifiques des mathématiques, certaines données suggèrent un effet du SES sur le transcodage ainsi que sur la comparaison symbolique et non-symbolique chez des enfants de maternelle (Bachman et al., 2022; Fischer & Thierry, 2021; Meloni et al., 2023), mais aucune étude n'a encore examiné si ces processus cognitifs pourraient médier la relation entre SES et performances mathématiques. Enfin, la majorité de ces travaux n'ont pas considéré simultanément les fonctions domaine-générales et domaine-spécifiques, laissant peu claires leurs contributions respectives aux liens entre SES et lecture, et SES et mathématiques.

Cette étude visait donc à combler ces lacunes en examinant, chez des enfants de CE2, le rôle médiateur de facteurs cognitifs domaine-généraux et domaine-spécifiques dans les relations entre le SES et les performances en lecture — spécifiquement la fluence et la compréhension de lecture — ainsi qu'entre le SES et les performances en mathématiques — spécifiquement la résolution de problèmes verbaux, le calcul et la fluence mathématique. Pour ce faire, des modèles par équations structurelles (SEM) ont été construits afin d'investiguer les médiateurs cognitifs de ces relations, tant pour la lecture que pour les mathématiques.

Les résultats ont montré que la relation entre le SES et les performances en lecture était médiée exclusivement par des facteurs cognitifs domaine-spécifiques, tandis que celle entre le SES et les performances en mathématiques était médiée à la fois par des compétences domaine-spécifiques et domaine-générales. Plus précisément, pour la lecture, la conscience phonologique et l'empan visuo-attentionnel ont émergé comme médiateurs du lien entre le SES et la fluence de lecture, tandis que le langage oral et, dans une moindre mesure, l'empan visuo-attentionnel médiaient la relation entre le SES et la compréhension de lecture. En ce qui concerne les mathématiques, la relation entre le SES et la résolution de problèmes verbaux était médiée par la mémoire de travail, tandis que celle entre le SES et les compétences de calcul l'était par la mémoire de travail et les compétences de transcodage. Enfin, la relation

entre le SES et la fluence mathématique n'est pas apparue comme statistiquement significative.

Concernant le lien entre le SES et la lecture, les résultats confirment le rôle médiateur de compétences linguistiques, telles que la conscience phonologique et le langage oral, des effets déjà documentés dans la littérature (J. Li et al., 2023). De manière importante, les résultats montrent que de tels effets persistent même lorsque des facteurs domaine-généraux sont pris en compte simultanément. De manière originale, les résultats indiquent également que l'empan visuo-attentionnel joue un rôle médiateur dans cette relation, soulignant qu'au-delà de facteurs linguistiques, le SES est aussi associé à certains processus visuo-attentionnels. Pour ce qui est du lien entre le SES et les mathématiques, les résultats confirment un rôle médiateur des fonctions domaine-générales, en particulier de la mémoire de travail (Morgan et al., 2024; Waters et al., 2021), et révèlent de manière nouvelle que les compétences de transcodage constituent également un médiateur, indiquant que le SES est également lié à des compétences domaine-spécifiques, à l'école primaire.

De manière générale, ces résultats mettent en évidence le rôle des facteurs cognitifs dans les relations entre le SES et les performances académiques en lecture et en mathématiques, révélant des patterns différenciés selon le domaine académique considéré. Ainsi, si des facteurs domaine-spécifiques ont émergé comme médiateurs dans les deux domaines, le rôle médiateur de fonctions domaine-générales n'a été observé que pour les mathématiques. Ce constat contraste avec des études antérieures ayant mis en évidence un effet médiateur des fonctions domaine-générales tant en lecture qu'en mathématiques (Albert et al., 2020; Nesbitt et al., 2013). Une explication possible est que ces études n'avaient pas pris en compte de facteurs domaine-spécifiques. En effet, des recherches ont montré que lorsque des compétences domaine-spécifiques, en particulier linguistiques, sont considérées simultanément, l'effet médiateur des fonctions exécutives dans la relation entre SES et lecture disparaît (Dilworth-Bart, 2012; Fitzpatrick et al., 2014).

Sur le plan éducatif, ces résultats suggèrent que des interventions ciblant les compétences langagières et l'empan visuo-attentionnel (Bianco et al., 2012; Valdois et al., 2025), ainsi que la mémoire de travail et le transcodage (DePascale et al., 2024; Van Der Ven et al., 2017), pourraient contribuer à réduire les inégalités éducatives liées au SES en lecture et en mathématiques, respectivement. Toutefois, cette hypothèse devra être testée de manière expérimentale, le design corrélationnel de la présente étude ne permettant pas d'inférer de liens causaux. Par ailleurs, de futures recherches devraient adopter une

perspective développementale et inclure d'autres groupes d'âge afin de déterminer quels facteurs cognitifs sont les plus pertinents à cibler pour réduire les inégalités sociales dans les apprentissages scolaires à différents stades du développement.

Etude 2

La deuxième étude de cette thèse avait pour objectif d'examiner la relation entre la MA et les performances en mathématiques chez des enfants de CE2, tout en contrôlant pour l'effet du SES. Elle visait également à déterminer si des compétences cognitives, domaine-générales et/ou domaine-spécifiques, pouvaient jouer un rôle médiateur dans cette relation.

De nombreuses études ont montré que la MA exerce des effets délétères sur les performances en mathématiques dès le début de l'école primaire (Ramirez et al., 2018; Wu et al., 2012), et ce pour différents types de tâches, incluant la résolution de problèmes verbaux, le calcul et la fluence mathématique (Sorvo et al., 2017; Wu et al., 2012). Par ailleurs, il a été suggéré que la MA pourrait influencer les performances en mathématiques de manière indirecte, via son impact sur des compétences cognitives impliquées dans ces apprentissages. Dans ce contexte, la majorité des recherches portant sur le rôle des facteurs cognitifs dans le lien entre MA et mathématiques a mis en évidence un effet médiateur de la mémoire de travail (Caviola et al., 2022; Finell et al., 2022; Pelegrina et al., 2024). Il a également été proposé que d'autres fonctions exécutives, telles que la flexibilité cognitive, pourraient jouer un rôle médiateur similaire (Živković et al., 2022). Cependant, très peu d'études ont examiné simultanément le rôle médiateur de différentes fonctions domaine-générales, et aucune n'a porté sur des enfants à l'école primaire. De plus, peu de travaux ont exploré si des facteurs domaine-spécifiques, tels que les processus symboliques et non-symboliques, pouvaient être affectés par la MA et agir comme médiateurs dans cette relation. Parmi ces travaux, les résultats restent par ailleurs controversés, certaines études chez l'adulte montrant un rôle médiateur des processus symboliques (Skagerlund et al., 2019), tandis que d'autres études chez l'enfant ne l'observent pas (Szczygieł, 2021). De manière importante, aucune recherche n'a encore examiné si d'autres fonctions domaine-spécifiques, telles que le transcodage ou la capacité à ordonner des nombres, pouvaient médier le lien entre MA et performances mathématiques. Enfin, bien que les enfants de faible SES soient plus à risque de présenter une MA élevée (Guzmán et al., 2021) ainsi que de faibles performances en mathématiques (N. C. Jordan & Levine, 2009; Morgan et al., 2016), aucune étude antérieure n'a contrôlé pour l'effet potentiellement confondant du SES dans cette relation.

Dans ce contexte, l'étude 2 de cette thèse visait à examiner l'impact de la MA sur différentes compétences mathématiques — incluant la résolution de problèmes verbaux, le calcul et la fluence mathématique — en tenant compte du SES ainsi que d'autres covariables importantes telles que le sexe, l'âge, le QI non-verbal et l'anxiété générale. Par ailleurs, cette étude avait pour objectif de déterminer si des compétences cognitives domaine-générales et/ou domaine-spécifiques jouaient un rôle médiateur dans ces relations.

Les résultats ont montré que la MA prédisait négativement l'ensemble des compétences mathématiques considérées, indépendamment du SES. Par ailleurs, les analyses de médiation ont révélé que des compétences domaine-générales et domaine-spécifiques jouaient un rôle médiateur dans la relation entre MA et performances mathématiques, avec des variations selon le type de tâche. Plus précisément, la mémoire de travail a émergé comme médiateur du lien entre MA et résolution de problèmes, ainsi qu'entre MA et compétences de calcul. Les compétences de transcodage médiaient la relation entre MA et compétences de calcul, ainsi qu'entre MA et fluence mathématique. Enfin, les capacités de comparaison symbolique et de traitement de l'ordre numérique médiaient uniquement l'association entre MA et fluence mathématique.

Concernant le rôle des facteurs domaine-généraux dans le lien entre MA et performances mathématiques, les résultats confirment un effet médiateur de la mémoire de travail (Caviola et al., 2022; Finell et al., 2022; Szczygieł, 2021), et montrent que cet effet persiste même lorsque différents facteurs domaine-spécifiques sont pris en compte. En revanche, aucune autre fonction domaine-générale n'a joué de rôle médiateur dans cette relation, ce qui pourrait refléter l'importance particulière de la mémoire de travail, comparativement aux autres fonctions domaine-générales, dans les performances en mathématiques (Spiegel et al., 2021; Van der Ven et al., 2012).

De manière intéressante, notre étude est la première à montrer chez l'enfant que différents facteurs domaine-spécifiques jouent un rôle médiateur dans la relation entre MA et performances en mathématiques. De manière intéressante, cet effet a été observé uniquement pour les compétences domaine-spécifiques symboliques — incluant le transcodage, la comparaison symbolique et la capacité à ordonner des nombres — et non pour les compétences non-symboliques. Ces résultats s'alignent avec des recherches antérieures ayant montré un impact spécifique de la MA sur les processus de traitement symbolique (Dietrich et al., 2015; Zaleznik et al., 2023) et suggèrent que la MA pourrait susciter une anxiété

ou une aversion envers les symboles numériques, impactant de ce fait les performances seulement dans les tâches comportant du contenu symbolique.

Sur le plan éducatif, cette étude montre que l'impact de la MA sur les performances en mathématiques, ainsi que sur les compétences cognitives qui les sous-tendent, est déjà observable en CE2. Les résultats suggèrent que des interventions cognitives ciblant la mémoire de travail et les processus de traitement symbolique (DePascale et al., 2024) pourraient contribuer à atténuer l'effet néfaste de la MA sur les performances mathématiques. Néanmoins, le design corrélationnel de cette étude ne permet pas d'inférer de liens causaux, soulignant la nécessité de futures recherches interventionnelles pour explorer cette possibilité. Par ailleurs, des études longitudinales seraient utiles pour clarifier la directionnalité des relations entre MA et performances mathématiques, car il est également possible que de faibles compétences cognitives entraînent des performances mathématiques réduites, générant en conséquence des niveaux élevés de MA.

De manière générale, les deux premières études de cette thèse ont montré qu'un faible SES et une MA élevée étaient associés à des performances académiques plus faibles, et que des facteurs cognitifs pouvaient jouer un rôle médiateur dans ces relations. S'appuyant sur ces résultats, les deux études suivantes de cette thèse se sont concentrées spécifiquement sur les enfants présentant de faibles performances en lecture et/ou en mathématiques, en visant à caractériser leurs profils cognitifs tout en tenant compte de la variabilité interindividuelle pouvant exister au sein de ces populations.

Etude 3

La troisième étude de cette thèse avait pour objectif de caractériser l'hétérogénéité des profils cognitifs chez les enfants faibles lecteurs et faibles en mathématiques.

De nombreuses études ont montré que diverses compétences cognitives pouvaient être affectées chez les enfants présentant des difficultés en lecture ou en mathématiques. En particulier, il a été mis en évidence que des altérations cognitives tant domaine-spécifiques (Geary, 2013; Hulme & Snowling, 2013) que domaine-générales (Peng et al., 2022; Peng, Wang, & Namkung, 2018) pouvaient être présentes chez ces enfants. Cependant, si cela peut être vrai pour la moyenne des enfants faibles lecteurs ou faibles en mathématiques, cela ne signifie pas que tous présentent le même profil de faiblesses cognitives. Par exemple, plusieurs

études ont montré l'existence de divers profils chez les enfants faibles lecteurs, certains présentant principalement des altérations phonologiques, tandis que d'autres semblaient davantage affectés au niveau de processus visuo-attentionnels (J.-R. Cho & Ji, 2011; Valdois et al., 2021). De manière similaire, des recherches sur les enfants faibles en mathématiques ont identifié des sous-groupes distincts, certains présentant des faiblesses en traitement non-symbolique, d'autres en traitement symbolique, ou encore d'autres en mémoire de travail (Bartelet et al., 2014; W. W. L. Chan & Wong, 2020). Ces données soulignent l'existence d'une importante variabilité interindividuelle dans les profils cognitifs d'enfants présentant des difficultés académiques en lecture ou en mathématiques. Toutefois, la majorité des études antérieures se sont concentrées sur un nombre restreint de processus cognitifs, considérant rarement simultanément des facteurs domaine-spécifiques et domaine-généraux, ce qui limite la compréhension des combinaisons de faiblesses cognitives susceptibles d'être associées aux faibles performances scolaires en lecture et en mathématiques.

Dans ce contexte, cette étude visait à examiner l'hétérogénéité des profils cognitifs d'enfants de CE2 présentant de faibles performances en lecture ou en mathématiques. L'objectif était de déterminer, à l'aide d'une analyse de profils latents (LPA), si des sous-groupes distincts pouvaient être identifiés à partir de différentes combinaisons de faiblesses cognitives domaine-générales et domaine-spécifiques, tant chez les enfants en difficulté de lecture que chez ceux en difficulté de mathématiques.

Sur la base des performances sur une mesure composite de fluence de lecture et de compétences en calcul, deux sous-groupes d'enfants ont été constitués. Le premier comprenait des enfants faibles lecteurs, définis comme présentant un score inférieur ou égal au 30ème percentile sur la mesure de fluence de lecture. De manière analogue, les enfants faibles en mathématiques étaient définis comme ceux obtenant un score inférieur ou égal au 30ème percentile sur la mesure de calcul. Selon ces critères, chacun des groupes d'enfants en difficulté – faibles lecteurs et faibles en mathématiques – comptait 139 participants. Il est important de noter que 69 enfants remplissaient les critères de faibles performances à la fois en lecture et en mathématiques et ont été inclus dans les deux analyses.

Chez les faibles lecteurs, la LPA a révélé l'existence de deux profils distincts : un premier, caractérisé en moyenne par d'importantes faiblesses dans l'ensemble des compétences cognitives — tant domaine-spécifiques que domaine-générales — et un second, présentant des faiblesses modérées limitées à l'empan visuo-attentionnel. De manière similaire, la LPA a identifié deux profils cognitifs distincts chez les enfants faibles en mathématiques. Le premier

profil se distinguait par des faiblesses marquées dans l'ensemble des compétences cognitives, tandis que le second présentait des déficits modérés uniquement en mémoire de travail et en comparaison symbolique. De manière notable, dans les deux cas, les enfants présentant des difficultés co-occurrentes en lecture et en mathématiques étaient surreprésentés dans les profils affichant des faiblesses cognitives globales et prononcées.

Ainsi, ces résultats s'alignent avec des études antérieures ayant mis en évidence une diversité de profils cognitifs tant chez les enfants faibles lecteurs que chez ceux faibles en mathématiques (Bartelet et al., 2014; W. W. L. Chan & Wong, 2020; Valdois et al., 2021; Willems et al., 2016) et soulignent l'importance d'intégrer également des facteurs cognitifs domaine-généraux dans une telle approche. Par ailleurs, ils montrent que les enfants cumulant des difficultés dans les deux domaines semblent présenter des faiblesses cognitives plus larges et prononcées (Brandenburg et al., 2021).

De manière générale, cette étude souligne l'importance de prendre en compte la variabilité interindividuelle lors de l'investigation des facteurs cognitifs impliqués dans les difficultés en lecture et en mathématiques. En effet, l'existence de profils cognitifs distincts au sein de ces populations implique qu'une même intervention ne sera probablement pas efficace pour tous, soulignant la nécessité de développer des interventions individualisées, adaptées au profil cognitif spécifique de chaque enfant (Bartelet et al., 2014; Carroll et al., 2016).

Néanmoins, une limite importante de cette étude réside dans le fait que les enfants présentant de faibles performances à la fois en lecture et en mathématiques ont été inclus dans les deux analyses. Il est donc possible qu'une partie de l'hétérogénéité cognitive observée au sein de chaque groupe reflète la présence simultanée d'enfants avec des difficultés isolées dans un domaine et d'enfants avec difficultés co-occurrentes. Dans ce contexte, l'étude suivante visait à examiner de manière distincte les caractéristiques cognitives des enfants présentant des difficultés en lecture seulement, en mathématiques seulement, ou dans les deux domaines.

Etude 4

La dernière étude de cette thèse avait pour objectif d'examiner séparément les enfants présentant des difficultés en lecture seulement, en mathématiques seulement, ou dans les deux domaines, tout en caractérisant la variabilité interindividuelle au sein de chaque groupe.

La plupart des études ayant porté sur les difficultés académiques en lecture et en mathématiques ont considéré ces domaines séparément, négligeant le fait qu'une proportion importante d'enfants présente des difficultés cumulées dans les deux domaines (L. Peters & Ansari, 2019; Starling-Alves et al., 2025). Par conséquent, les facteurs contribuant à l'émergence de difficultés co-occurrentes en lecture et en mathématiques restent encore très peu compris. Plusieurs modèles théoriques ont été proposés pour expliquer l'apparition de difficultés touchant simultanément les deux domaines, notamment : le modèle additif, selon lequel la co-occurrence résulte de l'addition des faiblesses cognitives propres à chacun des groupes avec difficultés isolées ; le modèle des trois troubles indépendants, qui postule un profil d'atteintes cognitives distinctes et/ou plus sévères chez les enfants avec difficultés co-occurrentes ; et le modèle du risque accru, suggérant que des difficultés en lecture et une faible conscience phonologique augmenteraient le risque de développer des difficultés en mathématiques, en raison de l'implication de tels processus dans certaines tâches mathématiques comme la résolution de problème verbaux ou la récupération de faits arithmétiques (Ashkenazi et al., 2013; Starling-Alves et al., 2025). Toutefois, les données empiriques actuelles ne convergent pas vers l'une ou l'autre de ces hypothèses, et une limite des études antérieures est que peu d'entre elles ont intégré simultanément des compétences cognitives spécifiques à chaque domaine et des compétences domaine-générales dans l'étude des facteurs impliqués dans les difficultés co-occurrentes versus isolées en lecture et en mathématiques (L. Peters et al., 2020; Starling-Alves et al., 2025). Par ailleurs, aucune étude n'a encore exploré l'existence d'une variabilité interindividuelle dans les faiblesses cognitives présentes au sein de chacun des trois groupes (enfants avec difficultés en lecture seulement, en mathématiques seulement, ou dans les deux domaines).

Dans ce contexte, cette étude avait pour objectif d'examiner les facteurs cognitifs contribuant aux difficultés en lecture seulement, en mathématiques seulement, et dans les deux domaines, tout en contrôlant pour des covariables importantes telles que le sexe, l'âge, le QI non-verbal et le SES. Elle visait également à analyser la prévalence et la combinaison de différentes faiblesses cognitives au sein de chacun des trois groupes, afin de caractériser l'hétérogénéité cognitive existant chez des enfants présentant le même type de difficultés académiques.

De la même manière que pour l'étude 3, les enfants présentant des difficultés isolées ou co-occurrentes ont été identifiés sur la base d'un score inférieur ou égal au 30ème percentile du score composite de fluence de lecture et du score composite de calcul. Les enfants obtenant un score inférieur ou égal au 30ème percentile dans les deux domaines constituaient le groupe

avec difficultés co-occurrentes. Par ailleurs, un groupe d'enfants contrôle, performant au-dessus du 30ème percentile dans les deux domaines, a été inclus comme référence.

Un modèle de régression logistique multinomiale a tout d'abord été réalisé afin d'examiner les prédicteurs de l'appartenance à chacun des trois groupes en difficulté par rapport au groupe contrôle. Les résultats ont montré que la RAN, l'empan visuo-attentionnel et le transcodage prédisaient significativement les difficultés isolées en lecture. De leur côté, les difficultés isolées en mathématiques étaient prédites par la mémoire de travail, la comparaison symbolique et le transcodage. Enfin, ces cinq facteurs cognitifs (RAN, empan visuo-attentionnel, transcodage, comparaison symbolique et mémoire de travail) prédisaient l'appartenance au groupe présentant des difficultés co-occurrentes en lecture et en mathématiques.

Par la suite, afin d'examiner la variabilité interindividuelle dans les faiblesses cognitives au sein de chaque groupe, la prévalence de faiblesses dans les cinq facteurs cognitifs susmentionnés a été analysée pour chaque groupe. Une faiblesse cognitive a été définie comme un score inférieur au 10ème percentile de la distribution du groupe contrôle pour une compétence donnée (Valdois et al., 2021). Les résultats ont révélé une hétérogénéité cognitive marquée au sein de chaque groupe, avec une prévalence particulièrement élevée de faiblesses cumulées sur plusieurs compétences chez les enfants présentant des difficultés co-occurrentes en lecture et en mathématiques.

Ainsi, ces résultats mettent en évidence que les difficultés co-occurrentes en lecture et en mathématiques se caractérisent par la combinaison des facteurs contribuant aux difficultés isolées dans chaque domaine, soutenant ainsi le modèle additif (Ashkenazi et al., 2013; Starling-Alves et al., 2025). De manière notable, le transcodage prédisait de manière significative l'appartenance à chacun des trois groupes, y compris à celui des enfants présentant des difficultés isolées en lecture, suggérant que cette compétence pourrait mobiliser des mécanismes communs aux apprentissages de la lecture et des mathématiques (Cirino et al., 2018; Jöbstl et al., 2023). Enfin, cette étude montre qu'une variabilité interindividuelle importante existe même au sein d'enfants partageant des difficultés académiques similaires. Ces résultats corroborent des recherches antérieures ayant mis en évidence une absence de correspondance stricte entre profil cognitif et type de difficultés académiques rencontrées (Astle et al., 2019), soulignant l'importance de proposer des interventions individualisées pour répondre aux besoins spécifiques de chaque enfant.

Conclusion

Cette thèse avait pour objectif d'approfondir la compréhension des multiples facteurs associés aux faibles performances scolaires en lecture et en mathématiques à l'école primaire. En adoptant une démarche intégrative et en mobilisant différentes approches méthodologiques, elle a examiné de manière conjointe les influences cognitives (domaine-spécifiques et domaine-générales), émotionnelles (MA) et socio-économiques des performances académiques, tout en prenant en compte la variabilité interindividuelle observée chez les enfants présentant des difficultés en lecture et/ou en mathématiques.

Dans une première approche dimensionnelle menée sur l'ensemble de l'échantillon, les résultats ont montré que le SES était significativement associé aux performances en lecture et en mathématiques, et que diverses compétences cognitives jouaient un rôle médiateur dans cette relation. Par ailleurs, la MA a également été identifiée comme un facteur émotionnel impactant les performances en mathématiques, indépendamment du SES, avec également un rôle médiateur de facteurs cognitifs. Ces résultats suggèrent que des interventions ciblant le renforcement de certaines compétences cognitives clés pourraient contribuer à réduire les inégalités associées au SES et à atténuer l'impact négatif de la MA sur les apprentissages en mathématiques. Néanmoins, des recherches complémentaires sont nécessaires afin de mieux comprendre les mécanismes par lesquels le SES et la MA sont liés à ces compétences cognitives. De manière plus générale, ces résultats soulignent l'importance d'adopter une approche multi-niveaux dans l'étude des facteurs influençant les performances scolaires en lecture et en mathématiques (Bonte & Brem, 2024).

Dans un second temps, une approche catégorielle centrée sur les enfants en difficulté a permis de compléter cette perspective en montrant, au niveau du groupe, que les difficultés en lecture étaient principalement associées à des faiblesses domaine-spécifiques, tandis que celles en mathématiques impliquaient à la fois des facteurs domaine-généraux et domaine-spécifiques. Ces résultats invitent ainsi à reconsidérer la pertinence d'une dichotomie stricte entre facteurs domaine-généraux – apparus comme prédictifs uniquement des performances en mathématiques – et facteurs domaine-spécifiques – semblant pour certains pouvoir intervenir dans les deux domaines (Cartwright & Palian, 2024; Gilmore, 2023).

Enfin, l'adoption d'une approche interindividuelle a révélé que les faiblesses cognitives identifiées en moyenne au niveau du groupe ne se manifestent pas de manière uniforme chez tous les enfants, soulignant la nécessité de concevoir des stratégies d'intervention personnalisées plutôt que fondées uniquement sur le type de difficulté académique (Astle et

al., 2019; Starling-Alves et al., 2025). Dans cette optique, des supports numériques pourraient constituer une piste prometteuse, permettant d'adapter de manière dynamique les interventions aux besoins spécifiques et à la progression individuelle de chaque enfant (Butterworth & Laurillard, 2010; Pasqualotto et al., 2022).

Néanmoins, cette thèse présente certaines limites qu'il convient de souligner. En premier lieu, le design corrélationnel adopté ne permet pas d'établir de relations causales entre les variables étudiées, ce qui souligne la nécessité de conduire de futures études longitudinales et interventionnelles. Celles-ci permettraient d'examiner plus finement les trajectoires développementales d'enfants présentant de faibles performances en lecture et/ou en mathématiques, ainsi que d'évaluer l'efficacité d'interventions personnalisées. Par ailleurs, bien que cette thèse ait cherché à articuler plusieurs niveaux d'explication rarement considérés conjointement, elle n'est pas exhaustive à cet égard. Des travaux futurs pourraient ainsi prolonger ces résultats en intégrant d'autres dimensions cognitives et émotionnelles non explorées, ainsi que des niveaux d'analyse supplémentaires, tels que les corrélats neuronaux ou l'influence de facteurs génétiques (Bonte & Brem, 2024).

En conclusion, cette thèse constitue une première étape vers une compréhension intégrative des différences individuelles dans les performances en lecture et en mathématiques. Elle met en évidence la nécessité d'adopter une approche multi-niveaux, articulant des dimensions cognitives, émotionnelles et environnementales, tout en tenant compte de la variabilité interindividuelle. Une telle perspective apparaît essentielle pour appréhender la complexité des interactions entre ces facteurs et, in fine, concevoir des interventions éducatives plus adaptées aux besoins spécifiques de chaque enfant.