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Arithmetic strategy development and its domain-specific and domain-general cognitive correlates: A longitudinal study in children with persistent mathematical learning difficulties

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A B S T R A C T

Deficits in arithmetic fact retrieval constitute the hallmark of children with mathematical learning difficulties (MLD). It remains, however, unclear which cognitive deficits underpin these difficulties in arithmetic fact retrieval. Many prior studies defined MLD by considering low achievement criteria and not by additionally taking the persistence of the MLD into account. Therefore, the present longitudinal study contrasted children with persistent MLD (MLD-p; mean age: 9 years 2 months) and typically developing (TD) children (mean age: 9 years 6 months) at three time points, to explore whether differences in arithmetic strategy development were associated with differences in numerical magnitude processing, working memory and phonological processing. Our longitudinal data revealed that children with MLD-p had persistent arithmetic fact retrieval deficits at each time point. Children with MLD-p showed persistent impairments in symbolic, but not in nonsymbolic, magnitude processing at each time point. The two groups differed in phonological processing, but not in working memory. Our data indicate that both domain-specific and domain-general cognitive abilities contribute to individual differences in children's arithmetic strategy development, and that the symbolic processing of numerical magnitudes might be a particular risk factor for children with MLD-p.

1. Introduction

Children with mathematical learning difficulties (MLD) experience difficulties acquiring basic arithmetical skills (Butterworth, Varma, & Laurillard, 2011; Geary, 2004; Mazzocco, 2007). Given that arithmetic comprises a building block for subsequent growth in mathematics (e.g., Kilpatrick, Swafford, & Findell, 2001) and that difficulties in storing and recalling arithmetic facts (e.g., Berch & Mazzocco, 2007; Jordan, Hanich, & Kaplan, 2003) constitute the hallmark of children with MLD (e.g., Geary, Hoard, & Bailey, 2012), it is crucial to reveal the origin of difficulties in arithmetic strategy development. In the past decade, most studies on MLD have focused on the cognitive origins of mathematical difficulties in general, i.e. by studying how numerical magnitude processing (De Smedt, Noël, Gilmore, & Ansari, 2013, for a review), working memory (see Friso-van den Bos, van der Ven, Kroesbergen, & van Luit, 2013, for a meta-analysis) and phonological processing

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(e.g., Vukovic & Siegel, 2010) are related to children's performance on general mathematics achievement tests. Yet only a few studies investigated the association of these cognitive abilities with specific types of mathematical skill, such as arithmetic strategy development. This more narrow focus is, however, needed, because it will allow us to explore how numerical magnitude processing, working memory and phonological processing might contribute to difficulties in children's acquisition of adequate strategies for solving single-digit arithmetic. This is precisely the aim of the current study. Further, in many prior studies children with MLD were defined by considering low achievement criteria and not by additionally taking into account the persistence of the mathematical difficulties. Against this background, we conducted a longitudinal study in which arithmetic strategy development, numerical magnitude processing, working memory and phonological processing were investigated in children with persistent MLD (MLD-p) and typically developing (TD) children.

In the remainder of this introduction, we first describe the arithmetic strategy development in TD children and children with MLD. Next, we discuss how numerical magnitude processing, working memory and phonological processing may contribute to difficulties in acquiring adequate arithmetic solving strategies. Finally, we present the specific goals of the present study.

1.1. Arithmetic strategy development

Many studies have examined arithmetic strategy use during the solution of single-digit arithmetic in TD children (e.g., Bailey, Littlefield, & Geary, 2012; Barrouillet, Mignon, & Thevenot, 2008). At the earliest stages of arithmetic strategy development, children count all the numbers in a problem (e.g., 1, 2, 3, 4, 5, 6, 7 to solve 3 + 4) and gradually move on to more advanced counting procedures, such as counting on from the larger number in the problem (e.g., 4, 5, 6, 7 to solve 3 + 4) (Geary, Bow-Thomas, & Yao, 1992). Through repeated use of counting strategies, children develop representations of basic arithmetic facts, which are stored in their long-term memory (Siegler & Shrager, 1984). Children (and also adults) rely on these stored fact representations when they evolve to more advanced strategies for solving single-digit additions and subtractions. These problems are then typically solved either by using an advanced procedural strategy, such as decomposition (e.g., 7 + 8 = 7 + 3 = 10 + 5 = 15), or by directly retrieving the correct answer from long-term memory (Siegler, 1996).

Studies comparing children with and without MLD observed impaired procedural strategy skills in children with MLD (e.g., Geary, 2004, for a review). This impairment is marked by a developmental delay in the shift from immature counting strategies, such as finger counting, to more advanced procedural strategies, such as decomposing the problem into smaller facts. Growth modeling data have shown that children with MLD catch up with their typically developing peers over time, narrowing the initial learning gap in procedural strategy skills (Chong & Siegel, 2008).

One of the most robust findings is that children with MLD have difficulties in storing and recalling simple arithmetic facts (e.g., Geary, Hoard, et al., 2012), even despite intensive instructional interventions (e.g., Howell, Sidorenko, & Jurica, 1987). These arithmetic fact retrieval difficulties do not ameliorate with time and constitute persistent deficits in children with MLD (e.g., Geary, Hoard, Nugent, & Bailey, 2012; Jordan et al., 2003; but see Torbeyns, Verschaffel, & Ghesquière, 2004). Although, there is a lack of universally accepted screening tools for defining MLD, knowledge on classification criteria for MLD is growing and it has been suggested that arithmetic fact retrieval deficits may be a useful indicator to include in a diagnostic definition of MLD (Geary, 2011).

Questions have been raised about the origin of children's difficulties in developing adequate arithmetic solution strategies. Therefore the aim of this study was to investigate how numerical magnitude processing, working memory and phonological processing contribute to difficulties in arithmetic strategy development.

1.2. Numerical magnitude processing

It is amply evidenced that the ability to represent numerical magnitudes contributes to individual differences in children's mathematical development (see De Smedt et al., 2013; for a review). This ability has typically been investigated by means of Arabic digit and dot comparison tasks, in which children have to identify the larger of two numerosities. Several researchers have proposed that MLD arise from a fundamental impairment in this ability to represent numerical magnitudes (Andersson & Ostergren, 2012; Iuculano, Tang, Hall, & Butterworth, 2008; Landerl & Kölle, 2009; Mazzocco, Feigenson, & Halberda, 2011; Piazza et al., 2010). Two hypotheses have been put forward to explain how deficient representations of numerical magnitude are related to MLD. According to the defective number module hypothesis (Butterworth, 2005), MLD originate from a specific deficit in the innate ability to understand and represent numerical magnitudes. By contrast, the access deficit hypothesis (Rousselle & Noël, 2007) argues that MLD are due to impairments in accessing semantic numerical representations from Arabic symbols, rather than from difficulties in processing numerical magnitudes per se. To date, findings remain inconclusive whether the defective number module or the access deficit hypothesis explains MLD (see De Smedt et al., 2013; Noel & Rousselle, 2011, for a review). This may be so because the existing research investigated these hypotheses in the context of children's general mathematics achievement, yet it is likely that various forms of numerical magnitude processing impact more on some specific aspects of mathematical skill more than others.

Interestingly, Vanbinst, Ghesquière, and De Smedt (2012) have recently addressed this issue in typically developing third graders. More specifically, these authors showed that symbolic, but not nonsymbolic, magnitude processing was related to