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Number magnitude processing and basic cognitive functions in children with mathematical learning disabilities[☆]

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A R T I C L E I N F O

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The study sought out to extend our knowledge regarding the origin of mathematical learning disabilities (MLD) in children by testing different hypotheses in the same samples of children. Different aspects of cognitive functions and number processing were assessed in fifth- and sixth-graders (11–13 years old) with MLD and compared to controls. The MLD group displayed weaknesses with most aspects of number processing (e.g., subitizing, symbolic number comparison, number-line estimation) and two cognitive functions (e.g., visual–spatial working memory). These findings favor the defective approximate number system (ANS) hypothesis, but do not fit well with the access deficit hypothesis. Support is also provided for the defective object-tracking system (OTS) hypothesis, the domain general cognitive deficit hypothesis and to some extent the defective numerosity-coding hypothesis. The study suggests that MLD might be caused by multiple deficits and not a single core deficit.

1. Introduction

Research demonstrates that acquiring basic mathematical skills is important not only for the individual's future academic and professional success but also in order to manage many common tasks in everyday life such as paying bills, developing a monthly budget or purchasing a place to live (Bottge, 2001; see McCloskey, 2007 for a review). Moreover, prevalence studies show that 4–7% of school-age children have mathematical disabilities (MLD), that is, have severe difficulties with acquiring these important basic mathematical skills (Badian, 1999; Geary, 2004; Lewis, Hitch, & Walker, 1994). The corresponding number for children with reading disabilities is 6–9% (Badian, 1999). Although both types of learning disabilities are equally common considerably less systematic research has been conducted to identify the origins of MLD in children. Still, a number of hypotheses have been proposed (Berch & Mazzocco, 2007).

1.1. The hypothesis of a domain general cognitive deficit

This hypothesis (Geary, 2004; Geary & Hoard, 2005) emanates from converging evidence showing that cognitive functions such as working memory, executive functions, semantic memory and processing speed are involved in mathematical performance in both adults and children (Andersson, 2007; 2008a; Fuchs et al., 2005; Swanson, Jerman, & Zheng, 2008). During mathematical performance, working memory and executive functions provide a flexible and efficient mental workspace capable of processing and storing information simultaneously, inhibiting irrelevant information from gaining access to working memory and shifting from one strategy or operation to another (Andersson, 2008a; Fürst & Hitch, 2000; Logie, Gilhooly, & Wynn, 1994; Seitz & Schumann-Hengsteler, 2000; Swanson, 2004). Semantic long-term memory is obviously important for learning and storing knowledge of mathematical concepts and procedures, and of course storing and retrieving arithmetic facts (D'Amico & Passolunghi, 2009; Geary, 1993; Logie & Baddeley, 1987). These findings have made researchers propose that children with MLD might have a deficit in their underlying cognitive system that prevents them from developing age-adequate skills in mathematics (e.g., Geary, 1993; 2004; Geary & Hoard, 2005; McLean & Hitch, 1999).

A fairly large number of studies have examined working-memory in children with MLD, and a number of these studies, but not all, support the hypothesis of a domain general cognitive deficit by showing that children with MLD perform poorly on working memory tasks requiring simultaneous storage and processing of information (D'Amico & Passolunghi, 2009; Geary, Hoard, Byrd-Craven, & DeSoto, 2004; Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; 2008; Geary, Hoard, Nugent, & Byrd-Craven, 2008; Siegel & Ryan, 1989; see Raghubar, Barnes, & Hecht, 2010; Swanson & Jerman, 2006 for reviews). However, it is difficult to draw any firm conclusions regarding what aspect of working memory is impaired, because few studies have employed a sufficiently broad spectrum of tasks tapping both verbal and visual–spatial working memory. Furthermore, previous

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studies have included different age groups and used different methods to identify children with MLD (see Raghubar et al., 2010).

In spite of this, recent studies using a broad spectrum of working memory tasks (verbal and visual–spatial) demonstrate that children with MLD have deficits with both verbal and visual–spatial working memory functions (Andersson & Lyxell, 2007; Kyttälä, Aunio, & Hautamäki, 2010; Passolunghi & Cornoldi, 2008; Wilson & Swanson, 2001), whereas a few studies have found that MLD children only have a deficiency with visual–spatial working memory but not with verbal working memory (Andersson, 2010; Schuchardt, Maehler, & Hasselhorn, 2008).

The majority of studies have focused only on verbal working memory functions in children with MLD. Some of these provide further evidence that MLD children have a deficiency related to simultaneous storage and processing of both linguistic information (words, sentences) and numerical information (digits, dot counting; D'Amico & Guarnera, 2005; Geary et al., 2007; 2008; Passolunghi & Siegel, 2004). In contrast, other findings suggest that children with MLD only have problems with working-memory tasks involving numerical material (digits) but not with tasks involving verbal material (words; Hitch & McAuley, 1991; Siegel & Ryan, 1989).

Impaired executive functions appear to be associated with MLD in children as a few studies report problems with shifting ability and attention functions among these children (Bull & Johnston, 1997; Bull, Johnston, & Roy, 1999; McLean & Hitch, 1999; van der Sluis, de Jong, & van der Leij, 2004). Passolunghi and colleagues have demonstrated that deficiencies with inhibition control might be another serious executive function problem for children with MLD (D'Amico & Passolunghi, 2009; Passolunghi & Siegel, 2001; 2004). Furthermore, difficulties with updating and strategic planning might be associated with MLD as suggested by studies performed by Swanson and Beebe-Frankenberger (2004) and Sikora, Haley, Edwards, and Butler (2002), respectively.

Findings observed in a few studies are that MLD children display impairment with rapid and automatic access to information in long-term memory (Andersson & Lyxell, 2007; D'Amico & Passolunghi, 2009; Landerl, Bevan, & Butterworth, 2004). In addition, there are some indications that children with MLD have problems with controlled retrieval of semantic information from long-term memory and are slower with respect to general processing speed (Andersson, 2008; Andersson & Lyxell, 2007; Bull & Johnston, 1997; Swanson & Beebe-Frankenberger, 2004).

Although these studies are consistent with the domain general cognitive deficit hypothesis, it is important to note that not all studies have found deficits in cognitive functions (see above). The MLD children in the Landerl, Fussenegger, Moll, and Willburger (2009) study did not show any domain general cognitive problems (see also Landerl et al., 2004). Some studies have found that children with MLD do not display a processing speed deficiency (Chan & Ho, 2010; van der Sluis et al., 2004; Willburger, Fussenegger, Moll, Wood, & Landerl, 2008), whereas other studies report normal inhibition control (Andersson & Lyxell, 2007), shifting ability (Andersson, 2008b; 2010) and visual–spatial working memory (Andersson, 2008b). Thus, the empirical pattern regarding which cognitive processes are impaired in children with MLD, if there is a deficit, is far from straightforward. As such, strong evidence in favor of the domain general cognitive deficit hypothesis is still sparse (see also Raghubar et al., 2010). In view of this, one aim of the present study was to examine long-term memory, a function that few studies have examined in children with MLD. In addition, verbal and visual–spatial working memory was targeted by using two tasks similar in demand and procedure and neither of them included numerical material.

1.2. Hypotheses of domain specific deficits in number processing

It is widely recognized that humans are born with a preverbal ability to identify, represent and manipulate quantities (Dehaene, 1997; Gallistel & Gelman, 1992; Gelman & Butterworth, 2005; Starkey & Cooper, 1980; Wynn, 1992; 1995; Xu & Spelke, 2000). This innate sense of number constitutes the foundation for the acquisition and development of the symbolic number system used for counting and arithmetic (Butterworth, 1999; Feigenson, Dehaene, & Spelke, 2004; Piazza, 2010).

According to one theoretical account, the innate quantity ability consists of an approximate number system (ANS) for representing large, approximate quantities (i.e., numerosities) and an object-tracking system (OTS) for precise representations of up to four objects (Cordes & Brannon, 2008; de Hevia, Girelli, Bricolo, & Vallar, 2008; Feigenson, Carey, & Hauser, 2002; Feigenson et al., 2004; Piazza, 2010). The ANS represents numerosities via an analog magnitude, a mental number line (de Hevia, Vallar, & Girelli, 2006; Feigenson et al., 2004; Le Corre & Carey, 2007). As numerosities are mapped onto the number line, increasing magnitudes are represented in ascending order, from left to right. As a consequence, each number is associated with a spatial location (de Hevia et al., 2006; Previtali, de Hevia, & Girelli, 2010). The ANS is also approximate and imprecise and imprecision increases with numerical size (Dehaene, 1992; de Hevia et al., 2006). The imprecision is thought to arise due to a) that the mapping of large numbers are more variable than the mapping of small numbers resulting in a larger overlap between two large numbers than two small ones (Ashkenazi, Mark-Zigdon, & Henik, 2009; Gallistel & Gelman, 1992), or b) the logarithmic nature of ANS, so that larger numbers are closer together than smaller numbers (Dehaene, 1992).

The OTS is a visual–spatial object-based attention system for precisely keeping track of small sets of objects (3–4 objects). It represents objects as distinct individuals in working memory by constructing a one-to-one correspondence between real world objects and individual mental representations (object files; Feigenson et al., 2004; Piazza, 2010). As such, the OTS does not represent the cardinal value of arrays of objects, but it can be used for a precise discrimination/comparison between arrays of objects in the small number range by using a one-to-one correspondence evaluation (Cantlon, Safford, & Brannon, 2010; Cordes & Brannon, 2009; van Herwegen, Ansari, Xu, & Karmiloff-Smith, 2008; Xu, 2003). The OTS matures with development; the capacity is limited to a single object until at approximately 12-months of age, when full capacity is reached of three to four objects (Piazza, 2010). A further characteristic of the OTS is that each individual representation contains information about the real world object's continuous quantitative properties (e.g., shape, Cantlon et al., 2010; Feigenson et al., 2004; Xu, 2003).

It is assumed that the ability to represent numbers in a symbolic, exact fashion develops through an integration of the two core number systems by first using number words and later symbols (Wilson & Dehaene, 2007; Wilson, Dehaene, Dubois, & Fayol, 2009). The symbolic system becomes mapped onto pre-existing core quantity representations, rather than replacing the pre-existing ANS and OTS (De Smedt & Gilmore, 2011; Mundy & Gilmore, 2009; Piazza, 2010). The mapping of the symbolic system onto the innate number systems generates a logarithmic symbolic ANS (Feigenson et al., 2004; Gallistel & Gelman, 1992; Mundy & Gilmore, 2009; Siegler & Booth, 2004). However, it is believed that with increasing experience with the symbolic system children learn to compensate for the logarithmic nature of the symbolic ANS or that ANS is sharpened through the acquisition of the exact symbolic number system (Feigenson et al., 2004; Halberda & Feigenson, 2008; Mundy & Gilmore, 2009).

Proponents of the two core system account of number representation suggest that MLD in children is caused by deficits in the ANS and/or the OTS (Dehaene, 1997; Piazza, 2010; Piazza et al., 2010; Wilson & Dehaene, 2007). If MLD in children is caused by a defective OTS, they should display impairment in the ability to precisely keep track of small sets of objects (3–4 objects), for example, problems with subitizing, the immediate and exact apprehension of small numbers of objects (Burr, Turi, & Anobile, 2010; Revkin, Piazza, Izard, Cohen, &