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Numerical matching judgments in children with mathematical learning disabilities

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ABSTRACT

Both deficits in the innate magnitude representation (i.e. representation deficit hypothesis) and deficits in accessing the magnitude representation from symbols (i.e. access deficit hypotheses) have been proposed to explain mathematical learning disabilities (MLD). Evidence for these hypotheses has mainly been accumulated through the use of numerical magnitude comparison tasks. It has been argued that the comparison distance effect might reflect decision processes on activated magnitude representations rather than number processing per se. One way to avoid such decisional processes confounding the numerical distance effect is by using a numerical matching task, in which children have to indicate whether two dot-arrays or a dot-array and a digit are numerically the same or different. Against this background, we used a numerical matching task to examined the representation deficit and access deficit hypotheses in a group children with MLD and controls matched on age, gender and IQ. The results revealed that children with MLD were slower than controls on the mixed notation trials, whereas no difference was found for the non-symbolic trials. This might be in line with the access deficit hypothesis, showing that children with MLD have difficulties in linking a symbol with its quantity representation. However, further investigation is required to exclude the possibility that children with MLD have a deficit in integrating the information from different input notations.

1. Introduction

It is estimated that 3–8% of the elementary school children have mathematical learning disabilities (MLD) (Desoete, Roeyers, & De Clercq, 2004). Individuals with MLD experience specific problems in arithmetic and mathematics, which are not caused by general intellectual impairment or the lack of educational opportunities (American Psychiatric Association, 2000; see Butterworth, Varma, & Laurillard, 2011 for a review). Low mathematical competence has been shown to negatively impact upon important aspects of life, such as educational and employment attainment (Duncan et al., 2007; Reyna, Nelson, Han, & Dieckmann, 2009). Therefore, several studies have tried to unravel the causes of MLD in order to develop appropriate intervention strategies. Some studies proposed that deficits in domain-general cognitive capacities (e.g. working memory, visuospatial abilities) cause MLD (Geary, 2004, 2005; McLean & Hitch, 1999; Passolunghi & Siegel, 2001; Rourke & Conway, 1997). Other researchers suggested that MLD are due to a domain-specific numerical deficit (see Rubinsten & Henik, 2009 for

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a review). In this study, we focus on the two main hypotheses that have been put forward to explain MLD in terms of a domain-specific numerical deficit.

It has been demonstrated that humans have an innate non-symbolic number sense, which supports the manipulation and comparison of numerosities (Feigenson, Dehaene, & Spelke, 2004; Izard, Sann, Spelke, & Streri, 2009). When symbols are learned, these are thought to acquire their meaning through the mapping onto this pre-existing non-symbolic magnitude representation (Barth, La Mont, Lipton, & Spelke, 2005; Mundy & Gilmore, 2009). Accordingly, one hypothesis states that MLD are caused by a deficit in this innate ability to mentally represent and process numerical magnitudes (Butterworth, 2005). This *representation deficit hypothesis* is mainly supported by studies showing that children with MLD perform more poorly than controls on non-symbolic (e.g. dot-arrays) (Mazzocco, Feigenson, & Halberda, 2011; Piazza, 2010; Price, Holloway, Raesaenen, Vesterinen, & Ansari, 2007) or both symbolic (e.g. digits) and non-symbolic (e.g. dot-arrays) (Landerl, Fussenegger, Moll, & Willburger, 2009; Mussolin, De Volder, et al., 2010; Mussolin, Mejias, & Noël, 2010) numerical magnitude comparison tasks. In these tasks, participants need to judge which of two magnitudes (e.g. digits or dot-arrays) represents the larger number. Typically, a numerical distance or ratio effect emerges which indicates faster and more accurate responses when the numerical distance or ratio is larger. These effects are assumed to originate from the mental representation of magnitude. A particular magnitude does not only activate its corresponding representation, but also to a lesser extent the representations of numerically close magnitudes, according to a Gaussian distribution (Moyer & Landauer, 1967; Restle, 1970). It is therefore more difficult to discriminate between magnitudes that are numerically close as there is more representational overlap between them. Studies supporting the representation deficit hypothesis have shown that children with MLD had a larger comparison distance effect than controls. The children with MLD were significantly slower and/or made more errors than controls when comparing magnitudes that were close together. This suggests that children with MLD have a less precise magnitude representation compared to controls (e.g. Mussolin, De Volder, et al., 2010; Mussolin, Mejias, et al., 2010; Price et al., 2007).

By contrast, other studies have demonstrated that children with MLD do not perform more poorly during the comparison of non-symbolic stimuli, but only show impairments when comparing symbolic stimuli (De Smedt & Gilmore, 2011; Iuculano, Tang, Hall, & Butterworth, 2008; Landerl & Kölle, 2009; Rousselle & Noël, 2007). This latter finding gave rise to the second hypothesis, referred to as the *access deficit hypothesis* (Rousselle & Noël, 2007). According to this hypothesis, children with MLD do not have a deficient magnitude representation. Instead, they have problems in accessing the magnitude representation from symbolic magnitudes.

One caveat, however, is that evidence for both hypotheses is mainly accumulated by means of number comparison tasks (e.g. Price et al., 2007; Rousselle & Noël, 2007). It has been recently questioned to which extent these number comparison tasks index the magnitude representation. Indeed, several studies have argued that the comparison distance effect might rather be explained by more general decision processes on activated representations (Cohen Kadosh, Brodsky, Levin, & Henik, 2008; Holloway & Ansari, 2008; Van Opstal, Gevers, De Moor, & Verguts, 2008; Van Opstal & Verguts, 2011). For example, Holloway and Ansari (2008) reported a developmental decrease in the distance effect for both numerical (e.g. digits) and non-numerical (e.g. brightness) comparisons, suggesting that the comparison distance effect might reflect a general decisional mechanism. More evidence was provided by a study from Van Opstal et al. (2008), in which it was shown that the CDE can be explained by response competition (indicating the left or right magnitude as 'larger'), which decreases with increasing distance and is common for numerical and non-numerical comparisons. These authors suggested that representational overlap is not required for the CDE to emerge, see (Van Opstal et al., 2008) for a more detailed description.

One way to avoid such confounds due to decisional processes is by using a numerical matching task (Cohen Kadosh et al., 2008; Van Opstal & Verguts, 2011). In this task, participants have to judge whether two simultaneously presented magnitudes are numerically the same or different. Typically, also here a numerical distance effect is observed: matching magnitudes is more difficult when they are close to each other; for example, indicating that 5 and 7 dots are numerically the same or different is more difficult than deciding whether 5 and 9 dots are numerically the same or different. In contrast to the comparison task, the distance effect in a numerical matching task has shown to reflect the underlying mental representation of magnitude, without being confounded by decisional processes (Cohen Kadosh et al., 2008; Van Opstal & Verguts, 2011). For example, Van Opstal and Verguts (2011) observed a numerical distance effect in the comparison task when both numbers (which have representational overlap) and letters (which have no representational overlap) had to be compared. By contrast, a distance effect in the matching task only emerged with numbers and not letters, suggesting this task directly indexes the magnitude representation (Van Opstal & Verguts, 2011). Defever, Sasanguie, Vandewaetere, and Reynvoet (2012) recently examined non-symbolic (i.e. two dot-arrays) and mixed notation (i.e. digit and dot-array) matching judgments in a group of typically developing kindergartners, first-, second- and third graders. As expected, a numerical distance effect was observed but the size of this effect was not related to individual differences in mathematics achievement. This indicates that the preciseness of the mental representation of magnitudes does not differ as a function of mathematical achievement in children. However, poor mathematics achievement was associated with slower reaction times on the matching task, particularly when a digit and a dot-array had to be matched. This suggests that the speed with which a digit can activate its magnitude representation is related to mathematics achievement, which is in line with the access deficit hypothesis (Defever et al., 2012; Rousselle & Noël, 2007).

In the current study, we aimed to further address the abovementioned hypotheses about a specific deficit to number processing in children with MLD using a numerical matching task. This allowed us to investigate the replicability of the findings on comparison tasks, in which general-decision processes could have an effect on the numerical distance effect. We