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Research paper

(Non-)symbolic magnitude processing in children with mathematical difficulties: a meta-analysis

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ABSTRACT

Symbolic and non-symbolic magnitude representations, measured by digit or dot comparison tasks, are assumed to underlie the development of arithmetic skills. The comparison distance effect (CDE) has been suggested as a hallmark of the preciseness of mental magnitude representations. It implies that two magnitudes are harder to discriminate when the numerical distance between them is small, and may therefore differ in children with mathematical difficulties (MD), i.e., low mathematical achievement or dyscalculia. However, empirical findings on the CDE in children with MD are heterogeneous, and only few studies assess both symbolic and non-symbolic skills. This meta-analysis therefore integrates 44 symbolic and 48 non-symbolic response time (RT) outcomes reported in 19 studies (N = 1,630 subjects, aged 6–14 years). Independent of age, children with MD show significantly longer mean RTs than typically achieving controls, particularly on symbolic (Hedges' g = 0.75; 95% CI [0.51; 0.99]), but to a significantly lower extent also on non-symbolic (g = 0.24; 95% CI [0.13; 0.36]) tasks. However, no group differences were found for the CDE. Extending recent work, these meta-analytical findings on children with MD corroborate the diagnostic importance of magnitude comparison speed in symbolic tasks. By contrast, the validity of CDE measures in assessing MD is questioned.

What this paper adds

This meta-analysis adds substantially to the existing body of research on numerical cognition in children with low mathematical achievement and dyscalculia (i.e., children with mathematical difficulties, MD). Being the first quantitative meta-analysis that explicitly focuses on this clinically relevant population, it sheds light on the diagnostic meaning of different measures of magnitude processing. Most importantly, it corroborates the significance of mainly symbolic (i.e., digit) comparison speed as a measure that identifies children with MD compared to typical achievers. This result is in line with the access-deficit hypothesis rather than with the assumption that MD up to dyscalculia arise from problems with the innate Approximate Number System (ANS) per se. Moreover, the meta-analytical results support the recent discussion

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criticizing the CDE as an index of the symbolic magnitude representation (Lyons, Nuerk, & Ansari, 2015). The meta-analytical model explicitly controlled for statistical dependencies between multiple effects derived from the same study by using robust variance estimation. A main benefit of this procedure, compared to other approaches such as stratification, within-study pooling or selecting only one outcome per study, is that all the available outcomes are taken into account (Hedges, Tipton, & Johnson, 2010). Taken together, this study extends the current state of research on numerical cognition in school-aged children with MD, both in respect of the clinically relevant population it focuses on and the meta-analytical methodology employed.

1. Introduction

Numerical processing skills and broader mathematical competencies help children deal with many everyday tasks and future professional activities (e.g., Ancker & Kaufman, 2007). In contrast, low mathematical skills negatively impact quality of life (Parsons & Bynner, 2005) and economic well-being (Ritchie & Bates, 2013). Importantly, a substantial number of primary school children experience learning difficulties in mathematics, which are referred to as developmental dyscalculia (DD) when causing an atypical numerical development despite normal intelligence and educational opportunities. Prevalence estimates of DD vary between 3 and 7% (Butterworth, 2005; Reigosa et al., 2008; Rubinsten & Henik, 2009).

During the past two decades, an increasing number of studies aimed at unravelling the cognitive mechanisms behind the development of mathematical difficulties, and consistently revealed that children with MD are impaired in numerical magnitude processing tasks (see De Smedt, Noël, Gilmore, & Ansari, 2013 for a literature review). However, it remains unclear to what extent the processing of symbolic (i.e., digits) or non-symbolic (i.e., arrays of dots or other objects) magnitudes or both, is affected. Heterogeneous results in this regard have led to two different etiological hypotheses: the ANS deficit hypothesis (Wilson & Dehaene, 2007) versus the access deficit hypothesis (Rousselle & Noël, 2007).

According to the *ANS deficit hypothesis*, the impairments originate from deficits in the Approximate Number System (ANS), an internal analogue magnitude system which allows humans to represent and manipulate approximate numerosities (Feigenson, Dehaene, & Spelke, 2004). Evidence for this hypothesis has been provided by studies demonstrating that children with MD have problems with non-symbolic magnitude processing (e.g., Mazzocco, Feigenson, & Halberda, 2011; Piazza et al., 2010) or both non-symbolic and symbolic magnitude processing (e.g., Landerl, Fussenegger, Moll, & Willburger, 2009; Mussolin, Mejias, & Noël, 2010), as symbolic magnitudes are assumed to be mapped onto the ANS (Mundy & Gilmore, 2009; for an alternative view see Noël & Rousselle, 2011; Sasanguie, De Smedt & Reynvoet, 2017). By contrast, the *access deficit hypothesis* assumes that children with MD do not have an ANS dysfunction per se, but rather a problem with accessing the ANS when magnitudes are expressed symbolically (Rousselle & Noël, 2007). This idea emerged from studies reporting deficient symbolic, but intact non-symbolic, magnitude processing in children with MD (e.g., Andersson & Östergren, 2012; De Smedt & Gilmore, 2011; Landerl & Kölle, 2009).

To integrate the findings mentioned above, a quantitative meta-analysis is necessary. Recently, three meta-analyses reviewed the associations between magnitude processing and mathematical competencies in unselected populations. Because some authors argue that MD up to DD form part of a continuum of ability (e.g., Dowker, 2009), we here briefly summarize these meta-analyses: Chen and Li (2014) and Fazio, Bailey, Thompson and Siegler (2014) included non-symbolic outcomes only. Both meta-analyses report a weak but reliable association with mathematical competence (i.e., a correlation of $r = .20$ and $r = .22$, respectively). Schneider et al. (2016) extended these findings by also including symbolic magnitudes. Based on 284 effect sizes, their analyses showed a significantly larger effect for symbolic ($r = .30$) than for non-symbolic ($r = .24$) magnitude processing, which decreased slightly with age. Furthermore, they observed the highest correlations for response times (RT) and Weber fractions (i.e., the smallest ratio of two numerosities that one can reliably judge as larger or smaller; Halberda, Mazzocco, & Feigenson, 2008). However, the abovementioned meta-analyses do not offer satisfying evidence to evaluate the two etiological hypotheses about the magnitude processing impairments observed in children with MD. The current meta-analysis therefore closes this gap for this clinically relevant group.

Numerical magnitude processing is most frequently assessed by comparison tasks (Ansari, 2008; Lyons et al., 2015). In such tasks, participants are instructed to select as quickly and accurately as possible which of two visually presented magnitudes is numerically larger. Visual stimuli can either be symbolic or non-symbolic. Typically, a comparison distance effect (CDE), or a conceptually similar ratio effect, is observed: Error rates and RT decrease with increasing distance between the magnitudes at comparison (or a ratio between the magnitudes that substantially differs from 1). This has traditionally been explained by assuming a cognitive magnitude representation on a mental number line, with small magnitudes on the left and larger magnitudes on the right. Each magnitude is represented with certain noise, expressed as a Gaussian distribution around the corresponding quantity (i.e., the mental number line hypothesis, Dehaene, 1997). Consequently, the CDE is thought to reflect the activation of magnitude representations on the mental number line, or in other words, the ANS (Price & Ansari, 2013; but see van Opstal, Gevers, de Moor & Verguts, 2008, modelling the CDE as a decisional process). The size of the CDE has even been assumed to index ANS precision: A smaller CDE was regarded as a more precise, and a larger effect as a less precise underlying representation (cf. Lyons et al., 2015). This assumption has led to several major theoretical claims, one of which is that children with MD should show a larger CDE because they have more noisy mental magnitude representations than typically achieving peers (e.g., Mussolin et al., 2010).

Against this background, we meta-analyzed the CDE of children with MD on comparison tasks. In line with Lyons et al. (2015), we chose RT instead of the popular Weber fractions, which focus exclusively on error rates, as measure of performance