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Cognitive mechanisms underlying the relation between nonsymbolic and symbolic magnitude processing and their relation to math

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ABSTRACT

Recent studies suggest that the relation between nonsymbolic magnitude processing skills and math competence is mediated by symbolic number processing. However, less is known about whether mapping between nonsymbolic and symbolic magnitude representations also mediates that relation, and whether the mediating role of symbolic number processing is explained by domain-general executive functions. Therefore, the current study examines whether symbolic comparison, mixed-format comparison, and executive function each mediate the relation between nonsymbolic magnitude processing and math. Furthermore, we investigate whether the relation between nonsymbolic and symbolic magnitude comparison is mediated by mapping between the formats and/or domain-general executive functions. Results indicate that symbolic processing mediates the relation between nonsymbolic processing and math, even after controlling for multiple components of executive function, which were also significant mediators. Cross-format comparison (i.e. mapping), on the other hand, did not mediate the relation between nonsymbolic comparison and math, but did mediate the relation between nonsymbolic and symbolic magnitude processing, even after controlling for executive function, which also mediated that relation. Taken together, our results suggest that both domain-specific and domain-general cognitive mechanisms account for the link between nonsymbolic and symbolic magnitude processing and their relation to math.

1. Introduction

Mathematical competence is an important predictor of success in modern life, including educational achievement, employment, financial stability, and physical and mental health (Bynner & Parsons, 1997; Gross, Hudson, & Price, 2009; Parsons & Bynner, 2005). However, a large number of individuals fail to acquire the math skills necessary to function optimally in today's society (Gross et al., 2009; NCES, 2007). Over the past decade, a growing body of research has elucidated important links between basic numerical processing abilities and the development of school level mathematical skills. In particular, it has been suggested that the ability to efficiently process numerical magnitude information in both nonsymbolic (e.g. sets of dots) and symbolic (e.g. Arabic digits) formats is an important foundational competence for math development (for a review see De Smedt, Noël, Gilmore, & Ansari, 2013). However, the extent to which they scaffold math development independently of one another, and independently of domain-general cognitive mechanisms, such as executive function, remains unclear. The current study addresses this uncertainty by investigating the interrelations between nonsymbolic and symbolic magnitude processing and executive function as they relate to math competence in

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a large sample of middle-school children. Also unclear are the cognitive mechanisms which support the mapping between nonsymbolic and symbolic representations of numerical magnitude. The second aim of this study, therefore, is to investigate the role of domain-specific and domain-general cognitive processes in the relation between nonsymbolic and symbolic representations of numerical magnitude.

1.1. Mechanisms underlying the relation between numerical magnitude processing and math

Nonsymbolic magnitude processing is typically measured using tasks that require participants to judge which of two sets of dots or other objects contains more items. Performance on this task has been suggested to reflect the precision of the so-called 'approximate number system' (ANS) (Feigenson, Dehaene, & Spelke, 2004). Nonsymbolic magnitude comparison performance has been shown to predict math competence in typically developing children and adults (Halberda, Mazzocco, & Feigenson, 2008; Libertus, Odic, & Halberda, 2012; Mazzocco, Feigenson, & Halberda, 2011a,b) and to be impaired in children with mathematical learning difficulties (Mazzocco et al., 2011a,b; Piazza et al., 2010). It should also be noted, however, that a number of studies have tested for and not observed a significant relation between nonsymbolic magnitude comparison and math performance in both children and adults (e.g. Holloway & Ansari, 2009; Mundy & Gilmore, 2009; Price, Palmer, Battista, & Ansari, 2012). At the same time, a number of studies have reported significant relations between symbolic magnitude comparison tasks, in which participants compare the relative numerical size of two Arabic digits, and math competence (e.g. Bugden & Ansari, 2011; De Smedt, Verschaffel, & Ghesquière, 2009; Holloway & Ansari, 2009). However, again it should be noted that some studies have tested for and not observed any such relation (e.g. Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013). Thus, the exact pattern of relations between these basic competencies and math outcomes are not yet fully resolved.

Therefore, as an alternative to contrasting the independent relations between nonsymbolic and symbolic magnitude processing and math competence, it may be fruitful to consider the interplay between them and how that interplay relates to math. Specifically, recent evidence suggests that the relation between nonsymbolic magnitude processing and math may be mediated by symbolic number processing (Fazio, Bailey, Thompson, & Siegler, 2014; Lyons & Beilock, 2011; Price & Fuchs, 2016), numeral knowledge (Peng, Yang, & Meng, 2017) and 'number-numerosity mapping' as indexed by dot set estimation (Wong, Ho, & Tang, 2016). According to these studies, nonsymbolic magnitude processing may influence math outcomes by facilitating the acquisition of numerical symbols, which in turn influences the acquisition of basic math skills. Additionally, recent studies have shown that the relation between nonsymbolic magnitude processing and math performance is non-significant when controlling for domain-general factors such as inhibitory control (Fuhs & McNeil, 2013; Gilmore et al., 2013). Thus, both domain-general factors and domain-specific mechanisms have been suggested to influence the relation between numerical magnitude processing and math. While previous mediation studies have controlled for working memory and inhibitory control in their models, it is unclear whether those cognitive processes also serve as mediators of the relation between nonsymbolic magnitude processing and math.

Therefore, in the current study we take multiple approaches to investigate the factors underlying the relation between magnitude processing mechanisms and math. First, we examine whether symbolic comparison and different components of executive function each mediate the relation between nonsymbolic magnitude processing and math, and whether any mediating role of symbolic number processing is accounted for by executive function. Second, we test the mediating role of cross-format magnitude comparison (i.e. comparing the magnitude of a set of dots to an Arabic digit) as a measure of the mapping between nonsymbolic and symbolic representations. This allows us to further test the hypothesis that it is the *mapping* between nonsymbolic and symbolic number representations that scaffolds the acquisition of math skills. Lastly, a growing body of evidence also suggests that there may be a bidirectional influence between nonsymbolic and symbolic magnitude processing whereby the acquisition of numerical symbols refines the representation of nonsymbolic magnitude (Mussolin, Nys, Leybaert, & Content, 2015; Piazza, Pica, Izard, Spelke, & Dehaene, 2013). Therefore, we also examine whether nonsymbolic comparison, mixed-format comparison, and executive function each mediate the relation between symbolic magnitude processing and math.

1.2. Mechanisms underlying the relation between nonsymbolic and symbolic magnitude processing

The apparent importance of the relation between nonsymbolic and symbolic magnitude processing and math development gives rise to a second important question. Specifically, what are the cognitive mechanisms underlying the relation between Arabic digits and the quantities they represent? The most prominent current theory, the 'mapping hypothesis', suggests that Arabic digits are associated with or 'mapped onto' the innate ANS over the course of learning (Dehaene, 2007; Piazza, 2011; for a review see Leibovich & Ansari, 2016). Evidence for this theory comes largely from the fact that across studies, number comparison tasks using both nonsymbolic and symbolic stimuli demonstrate numerical ratio effects, whereby comparison performance declines as the ratio of the larger to the smaller number increases (for a review see: Mussolin et al., 2015). However, the extent to which symbolic numbers are rooted in an underlying representation of nonsymbolic numerical magnitude is still an open empirical question (Matejko & Ansari, 2016; Leibovich & Ansari, 2016).

An alternative explanation may be that the overlap in performance profiles is accounted for by shared domain-general cognitive resources used for comparing the magnitudes of both nonsymbolic and symbolic numbers. The most likely mechanisms in our opinion are executive function, including inhibitory control, task switching, and working memory, all of which are known to play an important role in math development (e.g. Blair, Knipe, & Gamson, 2008; Blair & Razza, 2007). Therefore, in the current study we examine whether the relation between nonsymbolic and symbolic numerical magnitude comparison is mediated by performance on a mixed-format magnitude comparison task, as a measure of the mapping between symbolic and nonsymbolic numbers, and/or by