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Nonsymbolic and symbolic magnitude comparison skills as longitudinal predictors of mathematical achievement

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A B S T R A C T

What developmental roles do nonsymbolic (e.g., dot arrays) and symbolic (i.e., Arabic numerals) magnitude comparison skills play in children's mathematics? We assessed a large sample in kindergarten, grade 1 and 2 on two well-known nonsymbolic and symbolic magnitude comparison measures. We also assessed children's initial IQ and developing Working Memory (WM) capacities. Results demonstrated that symbolic and nonsymbolic comparison had different developmental trajectories; the first underwent larger developmental improvements. Both skills were longitudinal predictors of children's future mathematical achievement above and beyond IQ and WM. Nonsymbolic comparison was moderately predictive only in kindergarten. Symbolic comparison, however, was a robust and consistent predictor of future mathematics across all three years. It was a stronger predictor compared to nonsymbolic, and its predictive power at the early stages was even comparable to that of IQ. Furthermore, the present results raise several methodological implications regarding the role of different types of magnitude comparison measures.

1. Introduction

The question of what underlies the development of mathematical achievement has attracted a lot of attention the last decades. The reason is simple: mathematical skills play a prominent role in our cognitive development and life success (e.g., Dougherty, 2003; Reyna & Brainerd, 2007). Numbers are everywhere and they can take many forms: for example, there is the *nonsymbolic* representation consisting of five dots on a screen and the *symbolic* representation of the number "5" in its Arabic form. What both of these representations have in common is the "fiveness" of the numerosities' magnitude. Extensive focus has been placed on the early markers of numerical cognition, particularly on the role that nonsymbolic and symbolic magnitude comparison skills play as building blocks of numerical cognition (for reviews see De Smedt, Noël, Gilmore, & Ansari, 2013; Feigenson, Libertus, & Halberda, 2013). Findings so far have been contradictory, and in the literature one notices three striking gaps: a) There is a shortage of longitudinal developmental studies examining whether and how the different magnitude processing *predictors' power dynamically changes* from one grade to another (De Smedt et al., 2013; Noël & Rousselle, 2011). b) *Tasks* with fundamentally different design characteristics and number ranges, have been used interchangeably (De Smedt et al., 2013; Gilmore, Attridge, De Smedt, & Inglis, 2014). c) Domain-general capacities such as *working memory* resources and IQ are rarely controlled for (Hornung, Schiltz, Brunner, & Martin, 2014; Xenidou-Dervou, van Lieshout, & van der Schoot, 2014). The present study strived to fill in these gaps and thereby resolve the existing conflicting findings.

1.1. Nonsymbolic and symbolic magnitude processing

Research has indicated that human and non-human primates may be born with an ability to estimate and manipulate abstract quantities in nature. The Approximate Number System (ANS;

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Dehaene, 2011) is thought to be a pre-linguistic cognitive system where magnitudes are represented and processed. The ANS enables humans to compare and manipulate nonsymbolic numerosities already from infancy onwards (for reviews see Dehaene, 2011; Feigenson et al., 2013; De Smedt et al., 2013). Of course, as humans we also develop higher-order mathematical skills with symbols. So, how does this "innate" ability affect the development of our symbolic processing and what predicts the development of mathematical achievement, nonsymbolic, symbolic processing or both? These questions have generated intense scientific debate since they have important theoretical as well as educational implications (e.g., De Smedt et al., 2013; Noël & Rousselle, 2011). Establishing which early cognitive predictors play an important role, when and how, in the development of mathematics achievement, can inform educational practice, curricula contents and guide early intervention designs (De Smedt et al., 2013). For example, should educational practice focus on training children's nonsymbolic or symbolic skills or perhaps place different focus at different ages?

Some studies suggest that symbolic representations of number directly map onto ones readily accessible nonsymbolic representations, i.e., the ANS (e.g., Lipton & Spelke, 2005; Piazza & Izard, 2009). In this respect, the ANS is viewed as the cognitive foundation that fosters and enhances the development of general mathematics achievement. This has been a compelling theory and several studies have demonstrated relations between ANS measures and general mathematics achievement (Gilmore, McCarthy, & Spelke, 2010; Inglis, Attridge, Batchelor, & Gilmore, 2011; Libertus, Feigenson, & Halberda, 2011; Starr, Libertus, & Brannon, 2013; for a review see; Feigenson et al., 2013). At the same time, however, many studies have failed to find such relations between the ANS and symbolic processing or mathematics achievement (e.g., Bartelet, Vaessen, Blomert, & Ansari, 2014; Holloway & Ansari, 2009; Lyons, Price, Vaessen, Blomert, & Ansari, 2014; Sasanguie, Defever, Maertens, & Reynvoet, 2014; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013). The latter findings seem to suggest that symbolic numbers are processed and acquire meaning in a fundamentally different way (e.g., Lyons, Ansari, & Beilock, 2012). Within this framework, symbolic magnitude processing is viewed as the best predictor of mathematical achievement, not the ANS (De Smedt et al., 2013; Lyons et al., 2014). Perhaps the predominance of symbolic processing as a predictor of children's individual differences in mathematical achievement, may reflect the fact that children may differ in their ability to access the number magnitude of symbols, rather than processing numerosity in itself (Rouselle & Noël, 2007). Nevertheless, if symbolic processing does not directly map one-to-one onto ones pre-existing nonsymbolic representations, then we may expect them to demonstrate different developmental growth rates (Matejko & Ansari, 2016). As an assumed innate ability, nonsymbolic processing is expected to demonstrate less developmental growth compared to symbolic processing, given that the latter focuses on children assessing the magnitude of Arabic digits, and school mathematics instruction primarily teaches children to use digits to conduct basic arithmetic.

As various contradicting results come forth, the predictive roles of nonsymbolic and symbolic magnitude processing across development remain unclear. In a recent review of findings concerning the relationship between mathematics achievement and nonsymbolic and symbolic magnitude processing, De Smedt et al. (2013) acknowledged two factors that may give rise to the patchwork of contradictory results that characterizes the extant literature: a) The age of the participants assessed, and b) The measures used to assess magnitude comparison.

1.2. Inconsistent findings: Possible sources

1.2.1. Age of participants

In order to identify the role that nonsymbolic and symbolic magnitude skills play, longitudinal and developmental studies are clearly necessary. ANS acuity (Halberda & Feigenson, 2008) and symbolic magnitude precision have been shown to increase with age (Holloway & Ansari, 2009; Sasanguie, De Smedt, Defever, & Reynvoet, 2011). Several longitudinal studies have demonstrated ANS acuity before the start of formal school instruction to correlate with or be predictive of later mathematics achievement (Gilmore et al., 2010; Libertus et al., 2011; Mazzocco, Feigenson, & Halberda, 2011; Starr, Libertus, & Brannon, 2013). Furthermore, Inglis et al. (2011) found that ANS acuity correlates with mathematical achievement in childhood but not in adulthood.

These studies, however, did not assess symbolic magnitude processing. With cross-sectional designs, Lyons et al. (2014) and Sasanguie et al. (2013) assessed various nonsymbolic and symbolic measures simultaneously across *primary school children* and found no evidence for nonsymbolic magnitude processing predicting unique variance in children's arithmetic abilities. Instead, only symbolic magnitude processing played a unique role. On the basis of these findings, we expected that the ANS, as a readily accessible system, may play a unique role primarily in kindergarten, before formal mathematics instruction starts (e.g., Gilmore et al., 2010). From grade 1 and onwards, however, the predictive role of symbolic processing would take over (Lyons et al., 2014; Sasanguie et al., 2013). Thus, we hypothesized that the predictive roles of nonsymbolic and symbolic magnitude comparison skills would dynamically change over time. To our knowledge, this is the first study, which – due to its longitudinal design – allowed the examination of whether and how the predictive roles of magnitude comparison skills change across grades.

In contrast to our aforementioned hypothesis, however, Bartelet et al. (2014) demonstrated that in kindergarten only symbolic magnitude skills predicted children's grade 1 mathematics above and beyond nonsymbolic skills. Notably, though, in this study, children's WM capacities were not controlled for. Also, the measures used in this study differed on several aspects from certain other kindergarten studies; for example, the (non)symbolic stimuli were presented simultaneously, not sequentially (e.g. Gilmore et al., 2010; Xenidou-Dervou et al., 2014). In general, one notable difference across the various studies conducted so far is the measures used to assess nonsymbolic and symbolic magnitude processing skills.

1.2.2. Different magnitude comparison measures

Measures used across the literature can differ both on design characteristics as well as numerosity/number ranges but have nevertheless been used interchangeably. Specifically, in one well-known magnitude comparison measure, the stimuli to be compared (*nonsymbolic or symbolic*) are presented *simultaneously* (see for example Fig. 1A). This measure usually entails *small numerosities* within the range of 1 up to 9 (e.g., De Smedt, Verschaffel, & Ghesquière, 2009; Holloway & Ansari, 2008, 2009; Sasanguie et al., 2013; Sasanguie, Van den Bussche, & Reynvoet, 2012). In contrast, another well-known magnitude comparison measure comprises *large numerosities* ranging for example from 6 up to 70. Also, this measure entails several *sequential* steps (see Fig. 1B): the child sees a blue (nonsymbolic or symbolic) numerosity dropping down on the left side of the screen, this is then covered by an occluder, and then a comparison red quantity drops down on the right side of the screen (Barth et al., 2006; Barth, La Mont, Lipton, & Spelke, 2005; De Smedt & Gilmore, 2011;