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Children's representation of symbolic and nonsymbolic magnitude examined with the priming paradigm

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ABSTRACT

How people process and represent magnitude has often been studied using number comparison tasks. From the results of these tasks, a comparison distance effect (CDE) is generated, showing that it is easier to discriminate two numbers that are numerically further apart (e.g., 2 and 8) compared with numerically closer numbers (e.g., 6 and 8). However, it has been suggested that the CDE reflects decisional processes rather than magnitude representation. In this study, therefore, we investigated the development of symbolic and nonsymbolic number processes in kindergartners and first, second, and sixth graders using the priming paradigm. This task has been shown to measure magnitude and not decisional processes. Our findings revealed that a priming distance effect (PDE) is already present in kindergartners and that it remains stable across development. This suggests that formal schooling does not affect magnitude representation. No differences were found between the symbolic and nonsymbolic PDE, indicating that both notations are processed with comparable precision. Finally, a poorer performance on a standardized mathematics test seemed to be associated with a smaller PDE for both notations, possibly suggesting that children with lower mathematics scores have a less precise coding of magnitude. This supports the defective number module hypothesis, which assumes an impairment of number sense.

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Introduction

Complex numerical processing is a product of education, but nonsymbolic processes such as the discrimination between nonsymbolic magnitudes (e.g., arrays of dots) is suggested to be innate and can already be observed in infants as well as in animals (Dehaene, Dehaene-Lambertz, & Cohen, 1998; Feigenson, Dehaene, & Spelke, 2004; Izard, Sann, Spelke, & Streri, 2009; Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005). This basic understanding of quantity is thought to lie at the basis of the development of symbolic mathematics (Barth, La Mont, Lipton, & Spelke, 2005). The development of mental representations of magnitude has been frequently studied using the magnitude comparison task, where participants are presented with two numbers and need to judge which number is numerically larger. When the distance between the numbers decreases, participants respond more slowly and make more errors (Moyer & Landauer, 1967). This behavioral effect is referred to as the comparison distance effect (CDE) and is suggested to originate from partially overlapping neural representations of nearby numbers (Moyer & Landauer, 1967; Restle, 1970). This means that a specific number (e.g., 4) will activate not only its corresponding representation but also the representations of numbers that are numerically close (e.g., 3 and 5), following a Gaussian distribution. Recently, however, several studies have demonstrated that the CDE is not the result of a representational overlap but instead is due to decisional processes (Cohen Kadosh, Brodsky, Levin, & Henik, 2008; Holloway & Ansari, 2008; Van Opstal, Gevers, De Moor, & Verguts, 2008). A CDE has been shown to be common to both numerical and nonnumerical comparisons, suggesting that the CDE reflects a domain-general comparison mechanism (Holloway & Ansari, 2008) or a general sensorimotor transformation (Cohen Kadosh et al., 2008). In addition, it has been argued that the CDE can be dissociated from a more direct behavioral measure of magnitude representation, namely the priming distance effect (PDE) (van Opstal et al., 2008). In the priming task, two numbers are presented consecutively: the prime and the target. The distance between the prime and the target is directly related to the behavioral response, the PDE, meaning faster responses for numerically close prime–target pairs than for pairs that are numerically more distant. Unlike the CDE, this PDE cannot be explained on the basis of response processing; representational overlap is necessary to allow the prime to elicit activation of the target representation to shorten reaction times (Van Opstal et al., 2008). Therefore, the priming paradigm seems to be a better tool for investigating magnitude representation of numbers.

Studies with adults have shown that a PDE is observed not only when both the prime and target are symbolic numbers but also when they are presented as nonsymbolic magnitudes such as dot collections (e.g., Herrera & Macizo, 2008; Koechlin, Naccache, Block, & Dehaene, 1999; Roggeman, Verguts, & Fias, 2007). It is assumed that symbolic representations emerge after repeatedly linking a quantity with the number symbol to which it relates, resulting in the ability to automatically access symbolic representation (Dehaene, 1992). Using the numerical Stroop paradigm, it has been shown that an association between Arabic digits and their meaning gradually develops in children and is fully automated at around 7 or 8 years of age (Gebuis, Cohen Kadosh, de Haan, & Henik, 2009; Gebuis, Herfs, Kenemans, de Haan, & van der Smagt, 2009; Girelli, Lucangeli, & Butterworth, 2000; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002). Some authors suggest a deficit in this automatic access to number magnitude from symbols in children with dyscalculia (Holloway & Ansari, 2009; Landerl, Bevan, & Butterworth, 2004; Rousselle & Noël, 2007; Rubinsten & Henik, 2005), whereas others propose an impairment of the nonsymbolic representations (e.g., Butterworth, 2005; Halberda, Mazzocco, & Feigenson, 2008; Mundy & Gilmore, 2009; Mussolin, Mejias, & Noël, 2010). In the latter case, mathematical competence has been suggested to relate to differences in the internal magnitude representation (Butterworth, 2005). However, evidence for this hypothesis is based on the CDE and has not yet been investigated with the PDE. Therefore, it is not clear to what extent these individual differences in mathematics relate to differences in magnitude processes, decisional processes, or both.

To date, the majority of research using the PDE as a measure for number representation has focused on adults. Only recently did Reynvoet, De Smedt, and Van den Bussche (2009) conduct a cross-sectional study to examine the PDE in first graders (mean age = 6.7 years). They demonstrated that the PDE for symbolic numbers (i.e., digits) was already present at this age but also, more important, that the size of this effect was similar to that found in older children and adults, suggesting a rather