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Symbolic and non-symbolic distance effects in children and their connection with arithmetic skills

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ABSTRACT

The ability to compare numerical magnitudes is assumingly related to children's arithmetic skills. The role of symbolic and non-symbolic number representations in this relationship is, however, still a matter of debate. To address this issue we assessed addition and subtraction skills of 8–10-year-old children ($n = 35$) and asked them to compare numerical magnitudes of dot patterns and Arabic digits in different numerical ranges. Results revealed that the relationship between numerical magnitude comparisons and arithmetic skills is not restricted to symbolic stimuli, but that it can also be detected for non-symbolic dot patterns. The range of numerosities for which this relationship was found and the manner in which the magnitude comparison was related to arithmetic skills differed regarding the dots and digits. These findings highlight the role of both symbolic and non-symbolic number representations in the development of arithmetic skills and strengthen the view of different developmental trajectories underlying these representations.

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1. Introduction

Magnitude comparison is a crucial ability for everyday life that we share with other species (e.g. Brannon, 2005). Human infants can compare sets represented by dot arrays on the basis of number. At six months of age children seem to be sensitive to the difference between 8 and 16, but fail to discriminate between 8 and 12 dots (Xu & Spelke, 2000). Similar to our performance in discriminating other physical dimensions like line length or pitch (e.g. Henmon, 1906) comparing numerical magnitudes depends on the proportion by which magnitudes differ. We are faster and more accurate in comparing dot arrays with respect to their magnitude the further apart they are (e.g. van Oeffelen & Vos, 1982). This so-called distance effect (DE) is also found for symbolic number magnitude representations like Arabic numerals (Moyer & Landauer, 1967), which is ascribed to a mapping of symbolic representations onto approximate non-symbolic number magnitude representations (Verguts & Fias, 2004). In contrast, it has been proposed that non-symbolic and symbolic number representations might draw on different processes (Zorzi & Butterworth, 1999). According to this view, the DE emerges as a consequence of a nonlinear decision process rather than from an approximate representation of numerical magnitude.

Sekuler and Mierkiewicz (1977) reported a DE for Arabic numerals in children. The strength of this effect was found to decrease with age (see also Holloway & Ansari, 2008). While the effect's strength for older children (grades four and seven) was comparable to that of adults, it was more pronounced for younger children (kindergarten and first grade). The decreasing size of the DE may represent an increase in the precision of children's numerical representations (Holloway & Ansari, 2009). These numerical magnitude representations assumingly serve as a foundation on which mathematical competences like arithmetic skills are built (Butterworth, 2005). In three recent studies, the association between symbolic as well as non-symbolic DE's and mathematical skills was explored (Holloway & Ansari, 2009; Mussolin, Mejias, & Noël, 2010; Rousselle & Noel, 2007). Rousselle and Noel (2007) demonstrated that second graders with mathematical disabilities are impaired regarding symbolic but not with regard to non-symbolic numerical magnitude comparison. The authors claimed that children with mathematical disabilities do not have difficulties in processing numerical magnitudes per se but rather in accessing the meaning of symbolic numerals. These findings are similar to the ones by Holloway and Ansari (2009), reflecting a relationship between symbolic, but not non-symbolic numerical magnitude comparison and mathematical skills in six to eight year old children. It is important to note a difference between these two studies with respect to the manner in which the DE was related to performance on tests of mathematical competence. While children with mathematical disabilities had smaller distance effects than typically developing children (Rousselle & Noel, 2007), children with lower mathematical skills were shown to have larger DE's in the study by Holloway and Ansari (2009). Rousselle and Noel (2007) assumed that children with mathematical disabilities used peculiar strategies for comparing Arabic digits in order to compensate for their impaired ability in extracting the meaning from Arabic numerals. On the other hand, Holloway and Ansari (2009) claimed that children with less efficient, but not impaired, strategies to access the meaning of numerical symbols show relatively lower mathematical skills as well as larger DE's. In sum, both findings seem to converge on the access deficit hypothesis by Rousselle and Noel (2007), implying that the efficiency with which children access and use the meaning of symbolic numerals is related to their mathematical competence. Objection to this interpretation has been raised by Cohen Kadosh and Walsh (2009), who claimed that a better mapping between a numerical symbol and its meaning can explain overall faster reaction times in children with better mathematical achievement, but cannot explain differences in the DE, as the symbolic DE occurs at a point in time (e.g. at the level of representation or during response selection) when such a mapping should already have taken place. In a recent study, however, Mussolin et al. (2010) revealed that children with mathematical disabilities showed a greater numerical distance effect than control children, irrespective of the number format, favoring the idea of a representation rather than an access deficit in children with dyscalculia.

An important issue that has to be addressed when comparing symbolic and non-symbolic magnitude comparison tasks is that qualitatively different mechanisms seem to be involved in apprehending dot patterns of different quantities. While estimation or counting processes are involved in processing large sets of dots, quantities from 1 to 3 are supposedly apprehended by automatic quantification processes called 'subitizing' (e.g. Trick & Pylyshyn, 1994). The performance pattern in the