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What can the same–different task tell us about the development of magnitude representations?

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ABSTRACT

We examined the development of magnitude representations in children (Exp 1: kindergartners, first-, second- and sixth graders, Exp 2: kindergartners, first-, second- and third graders) using a numerical same–different task with symbolic (i.e. digits) and non-symbolic (i.e. arrays of dots) stimuli. We investigated whether judgments in a same–different task with digits are based upon the numerical value or upon the physical similarity of the digits. In addition, we investigated whether the numerical distance effect decreases with increasing age. Finally, we examined whether the performance in this task is related to general mathematics achievement. Our results reveal that a same–different task with digits is not an appropriate task to study magnitude representations, because already late kindergarteners base their responses on the physical similarity instead of the numerical value of the digits. When decisions cannot be made on the basis of physical similarity, a similar numerical distance effect is present over all age groups. This suggests that the magnitude representation is stable from late kindergarten onwards. The size of the numerical distance effect was not related to mathematical achievement. However, children with a poorer mathematics achievement score seemed to have more difficulties to link a symbol with its corresponding magnitude.

1. Introduction

There is consistent evidence that humans have an innate capacity to represent magnitude (e.g., Feigenson, Dehaene, & Spelke, 2004; Izard, Sann, Spelke, & Streri, 2009). This ability to represent magnitude develops over time and is thought to be fundamental for acquiring the meaning of numerals. By repeatedly linking a numeral with its associated quantity, children acquire a symbolic system that is mapped onto this pre-existing representation (Barth, La Mont, Lipton, & Spelke, 2005; Mundy & Gilmore, 2009). In the last couple of years, many different studies investigated the development of magnitude representations (e.g., Holloway & Ansari, 2009; Reynvoet, De Smedt, & Van den Bussche, 2009; Soltész, Szücs, & Szücs, 2010). A task that is commonly used to study this development is the comparison task (e.g., Bugden & Ansari, 2011; Mundy & Gilmore, 2009). This task typically results in a comparison distance effect (CDE) which implies that it is easier to discriminate two magnitudes that are numerically further apart (e.g., "1" and "7") compared to numerically closer magnitudes (e.g., "5" and "7"). The distance effect is usually thought to be caused by partially overlapping representations of nearby magnitudes. A particular magnitude does not only activate its corresponding representation, but also the representations of numerically close magnitudes, according to a Gaussian distribution (Moyer & Landauer, 1967), making it more difficult to discriminate between two close magnitudes. Studies investigating the development of the CDE in children found that its size decreases with increasing age. This observation has been explained by magnitude representations that become more precise when schooling advances (Holloway & Ansari, 2009). In addition, the size of the comparison distance effect was found to be correlated with mathematics achievement, showing larger CDEs being associated with poorer mathematical ability (De Smedt, Verschaffel, & Ghesquière, 2009; Holloway & Ansari, 2009; Mussolin, Mejias, & Noël, 2010). Recent studies, however, argued that one should be careful with interpreting the CDE as reflecting the characteristics of the magnitude representation (Cohen Kadosh, Brodsky, Levin, & Henik, 2008; Holloway & Ansari, 2008; Van Opstal, Gevers, De Moor, & Verguts, 2008; Van Opstal & Verguts, 2011). For instance, Van Opstal et al. (2008) argued that the CDE can

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be explained on the basis of decision processes rather than from magnitude representations. These authors constructed a connectionist model that was trained to select the largest of two numbers. After training the model, it was shown that the CDE can be explained by monotonically increasing or decreasing connections weights between the magnitude layer and the response nodes and crucially, that the CDE does not require representational overlap as was assumed before (see Van Opstal et al., 2008 for a more detailed description). Also the finding of Holloway and Ansari (2008) that a developmental decrease of the CDE is common to both numerical and non-numerical comparisons, supports the idea of the CDE reflecting a decisional mechanism. More evidence came from a study of Cohen Kadosh et al. (2008), who found that comparisons of music pitches were similar to other magnitude response functions, again implying that the CDE reflects a general sensorimotor transformation rather than the mental representation of magnitudes.

Therefore, in this study we chose an alternative task that is assumed to address the magnitude representation directly, i.e. a numerical same–different task. In this task, participants have to decide whether two magnitudes are numerically the same or different. Similar to comparison tasks a numerical distance effect is typically observed which implies that it becomes easier to classify two magnitudes as numerically different when the numerical distance between the magnitudes increases. This numerical distance effect is also explained by overlapping magnitude representations. Van Opstal and Verguts (2011) simulated the numerical distance effect in a same–different task and found that, in contrast to comparison tasks, the effect is only present when overlapping representations are assumed. On the basis of these simulations, the authors argued that a same–different task is more appropriate to investigate the mental representations of magnitudes (see also Cohen Kadosh et al., 2008).

The only developmental work so far using the same–different task was carried out by Duncan and McFarland (1980). They conducted a symbolic same–different task with kindergartners, first-, third-, fifth graders and adults. These authors observed a similar symbolic distance effect over all age groups, a finding in contrast with the observation of a decreasing distance effect with increasing age observed in a comparison task. This suggests, in contrast to the conclusion based on comparison performance, that children's magnitude representation does not get more precise with increasing age from late kindergarten onwards. Recently, however, Cohen (2009) argued that the numerical distance between two numerals correlates strongly with the physical similarity between those two numerals, which may have lead researchers in previous studies to confuse the effects of physical similarity for those of numerical distance. In the study of Cohen (2009), adults were presented with digits that had to be classified as the same as or as different than five. The data revealed that the participants based their decisions entirely on the physical characteristics of the Arabic digits and not on the numerical value. It therefore remains unclear whether the previous developmental results of Duncan and McFarland (1980) tell us something about how symbolic magnitudes are represented. It can be questioned whether children use numerical value or, similar to adults, use the physical similarity to make their decisions in symbolic same–different judgments (Cohen, 2009).

In the present study, we wanted to shed light upon the contribution of numerical distance and physical similarity in a symbolic same–different task conducted in children. In addition, we examined whether the numerical distance effect in symbolic and non-symbolic same–different judgments decreases with increasing age, which would be an indication of a more precise magnitude representation with increasing age. Finally, we examined whether the performance in a numerical same–different task is related to individual differences in mathematics achievement. Therefore, in the first experiment we examined the performance of children from four different age groups (Exp 1: kindergartners, first-, second-, and sixth graders) using a symbolic and a non-symbolic same–different task. In the second experiment, in addition to a pure non-symbolic same–different task, we used a same–different task in which a digit and an array of dots had to be matched.

2. Experiment 1

2.1. Method

2.1.1. Participants

Participants were 140 typically developing children recruited from a primary school in Belgium. The sample consisted of 30 kindergartners (16 males, mean age = 5.067 years, SD = .254), 32 first graders (12 males, mean age = 6.125, SD = .336), 38 second graders (14 males, mean age = 7.079, SD = .273) and 40 sixth graders (15 males, mean age = 11.175, SD = .385). None was aware of the purpose of the experiment. All children received a small reward for their participation.

2.1.2. Stimuli

Number knowledge test: Before starting the same–different experiments, all kindergartners and first graders needed to conduct a simple task to measure their knowledge of the digits 1 to 9 and the magnitude they represent. First, children were asked to read aloud the digits 1 to 9 (that were printed on the left side of the sheet), to ensure that they recognized the digits. Next they had to connect the numbers to pictures on the right hand side of the sheet where collections with different numbers of clowns were presented. Children who did not score 9 out of 9 were excluded from further analyses.

Mathematics achievement: The mathematical skills of the kindergartners were assessed by the 'Toeters' (CLB Haacht, 2005). The subtest mathematics of this test covers items on counting, mathematics language and conservation. Cronbach's α for this test is .89 (CLB Haacht & Department of Psychology of the Lessius Hogeschool, 2005). Mathematical skills of the elementary school children were assessed using a curriculum-based standardized achievement test for mathematics from the Flemish Student Monitoring System (Deloof, 2005; Dudal, 2000, 2001). The scores on the test administered halfway the school year were used. The reliability index of Kuder–Richardson (KR 20) for the test is .90, .89 and .88 for first, second and sixth grades, respectively. This test includes 60 items covering number knowledge, understanding of operations, (simple) arithmetic, word problem solving, measurement and geometry. For the analyses, we transformed the raw mathematics achievement scores to z-scores per grade.

Symbolic same–different task: The task was administered using notebooks with 14-inch screens. In each trial, two Arabic digits ranging from 1 to 9 were displayed simultaneously in white on a black background using E-prime 1.0 (www.pstnet.com; Psychology Software Tools). The digits were presented in Arial font and subtended 0.57° visual angle (= .05 cm) in width and 0.69° (= .06 cm) visual angle in height from a viewing distance of about 50 cm. Trials with a numerical distance up to 5 of all possible combinations were presented. This choice was motivated based on previous research in which it was shown that the decrease in reaction times is limited for distances larger than 5 (Sasanguie, Defever, Van den Bussche, & Reynvoet, 2011). The 9 'same' trials (i.e. trials with two numerically same stimuli) were presented twice, resulting in a final list of 78 trials (60 'different' trials and 18 'same' trials).

Non-symbolic same–different task: In each trial, two white-filled circles (diameter 7 cm, 8.01° visual angle from a viewing distance of about 50 cm) containing arrays of 1 to 9 black dots were shown simultaneously. The physical properties of the stimuli (i.e. total area occupied and individual dot size) were controlled using the MatLab program as described in Dehaene, Izard, and Piazza (2005). On half of the trials dot size was held constant whereas on the other half