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Single-digit Arabic numbers do not automatically activate magnitude representations in adults or in children: Evidence from the symbolic same–different task☆

Becky Wong *, Dénes Szücs **

Centre for Neuroscience in Education, Department of Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, United Kingdom

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ABSTRACT

We investigated whether the mere presentation of single-digit Arabic numbers activates their magnitude representations using a visually-presented symbolic same–different task for 20 adults and 15 children. Participants saw two single-digit Arabic numbers on a screen and judged whether the numbers were the same or different. We examined whether reaction time in this task was primarily driven by (objective or subjective) perceptual similarity, or by the numerical difference between the two digits. We reasoned that, if Arabic numbers automatically activate magnitude representations, a *numerical* function would best predict reaction time; but if Arabic numbers do not automatically activate magnitude representations, a *perceptual* function would best predict reaction time. Linear regressions revealed that a perceptual function, specifically, subjective visual similarity, was the best and only significant predictor of reaction time in adults and in children. These data strongly suggest that, in this task, single-digit Arabic numbers do not necessarily automatically activate magnitude representations in adults or in children. As the first study to date to explicitly study the developmental importance of perceptual factors in the symbolic same–different task, we found no significant differences between adults and children in their reliance on perceptual information in this task. Based on our findings, we propose that visual properties may play a key role in symbolic number judgements.

1. Introduction

Most cultures employ the use of symbolic numbers, such as Arabic digits, to convey numerical magnitudes. Several researchers assume that the mere presentation of symbolic numbers automatically activates corresponding mental representations of magnitude in humans (Girelli, Lucangeli, & Butterworth, 2000; Tzelgov & Ganor-Stern, 2005). This contention was largely based on the results of behavioural studies that tested only one numerical hypothesis (e.g. Dehaene & Akhavein, 1995; Duncan & McFarland, 1980; Ganor-Stern & Tzelgov, 2008). These studies assumed that their experimental effects could only be explained by the numerical properties of the stimuli. In contrast, Cohen (2009) contrasted the numerical hypothesis with an alternative perceptual hypothesis. His approach examined whether the experimental effects could be explained by non-numerical (i.e. perceptual) rather than numerical properties of the stimuli. Recent studies based on this new approach have found evidence for the argument that the mere presentation of symbolic numbers does not automatically activate their magnitude representations (e.g., Defever, Sasanguie, Vandewaetere, & Reynvoet, 2012; Garcia-Orza, Perea, Abu Mallouh, & Carreiras, 2012; Lyons, Beilock, & Ansari, 2012). In this study, we further investigated whether single-digit Arabic numbers automatically activate magnitude representations in adults or in children by substantially extending the original experimental task (Cohen, 2009), stimuli, participants, explanatory functions tested, and analyses.

1.1. Background

It is widely thought that humans possess imprecise internal representations of magnitudes (henceforth referred to as magnitude representations) that correspond to symbolic numbers in the external environment (Domahs et al., 2012; Lyons & Ansari, 2008; Verguts & Fias, 2004; Young & Opfer, 2011; Zhang & Wang, 2005). Certainly, it seems that symbolic numbers may activate such magnitude representations. The classic evidence for this argument comes from the comparison distance effect that appears in the numerical comparison task with symbolic numbers (e.g., Buckley & Gillman, 1974; Moyer & Landauer, 1967). But, do symbolic numbers *automatically* activate magnitude representations? A strong test of an automatic process is to examine whether it occurs even when it is not directly relevant to the demands of the task at hand (Bugden & Ansari, 2011; Ganor-Stern &

* Corresponding author. Tel.: +65 68319609.
** Corresponding author. Tel.: +44 (0)1223 333500.
E-mail addresses: beckyw@singnet.com.sg (B. Wong), ds377@cam.ac.uk (D. Szücs).

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Table 1
A list of functions and their corresponding abbreviations in this paper.

Abbreviation	Name of function	Previously used by	Formula (for details, refer to individual paragraphs)
P_C	Perceptual function by Cohen (2009)	Cohen (2009)	$P_C = O/D$
P_{GP}	Perceptual function by Garcia-Orza et al. (2012) for Persian–Indian numbers	Garcia-Orza et al. (2012)	Spanish students' reaction time for Persian–Indian numbers
P_{GA}	Perceptual function by Garcia-Orza et al. (2012) for Arabic–Indian numbers	Garcia-Orza et al. (2012)	Spanish students' reaction time for Arabic–Indian numbers
P_{CM}	Perceptual function by Cohen (2009) after modification	Novel	$P_{CM} = O/T$
P_P	Perceptual function based on pixel overlap	Novel	$P_P = O/T$
P_{SA}	Perceptual function based on subjective visual similarity ratings of adults	Campbell and Clark (1988) (adapted)	Adult participants' ratings of subjective visual similarity
P_{SC}	Perceptual function based on subjective visual similarity ratings of children	Novel	Child participants' ratings of subjective visual similarity
N_W	Numerical function based on the Welford function	Cohen (2009) and Garcia-Orza et al. (2012)	$RT = a + k * \lg(L/L–S)$
N_D	Numerical function based on the distance effect	Defever et al. (2012)	$N_D = L–S$
N_R	Numerical function based on the ratio effect	Novel	$N_R = S/L$

Note: O refers to the amount of overlap between any two given numbers; D refers to the difference between these two numbers; T refers to total area covered by the numbers; L refers to the larger number; S refers to the smaller number; RT refers to reaction time; a and k are constants.

Tzelgov, 2008; Rubinsten, Henik, Berger, & Sharhar-Shalev, 2002; Tzelgov, Meyer, & Henik, 1992; Zhang, Si, Zhu, & Xu, 2010).

Early studies seemed to suggest that symbolic numbers may indeed automatically activate magnitude representations. One strand of evidence came from the matching distance effect in symbolic same–different tasks (e.g. Dehaene & Akhavein, 1995; Duncan & McFarland, 1980; Ganor-Stern & Tzelgov, 2008; Van Opstal & Verguts, 2011; Verguts & van Opstal, 2005). However, the matching distance effect does not appear to be highly reliable, as other studies have not found this effect in the same–different task (Cohen, 2009; Defever et al., 2012; Goldfarb, Henik, Rubinsten, Bloch-David, & Gertner, 2011; Sasanguie, Defever, Van den Bussche, & Reynvoet, 2011). A second strand of evidence came from the size congruity effect in the physical size decision Stroop paradigm (e.g. Cohen Kadosh et al., 2007; Girelli et al., 2000; Mussolin & Noel, 2008; Szűcs & Soltesz, 2007, 2008; Szűcs, Soltesz, Jarmi, & Csepe, 2007; Tzelgov et al., 1992; Zhou et al., 2007). The current study only deals with the symbolic same–different task.

1.2. Perceptual vs. numerical factors in the same–different task

In 2009, Cohen proposed a more nuanced approach to tackle the question of whether symbolic numbers automatically activate their magnitude representations. Although a relationship between numerical distance and reaction time clearly exists, Cohen (2009) suggested that there may be a relationship between the physical form of symbolic numbers and reaction time. To the extent that visual similarity and magnitude representations are correlated, Cohen (2009) contended that the studies of the symbolic same–different task, which investigated only one (numerical) hypothesis, might have missed a potential perceptual confound. He thus argued that researchers investigating this question should test two hypotheses: a numerical hypothesis and a perceptual hypothesis.

Cohen (2009) conducted a 5-or-not-5 task, in which adult participants were presented with single-digit Arabic numbers (henceforth referred to as probes) and made a button-press response as to whether each probe was 5 or not 5. As a measure of visual similarity between 5 and the probe, Cohen (2009) codified a perceptual function, abbreviated as P_C (Table 1). The formula was $P_C = O/D$, where O is the number of lines that the two digits share (i.e. overlapping lines), and D is the number of unshared lines between the two digits (i.e. difference) (Fig. 1). As a measure of magnitude processing, Cohen (2009) employed the well-known Welford (1960) function, abbreviated as N_W (Table 1). The formula for N_W was $RT = a + k * \lg(L/L–S)$, where RT is the reaction time, L is the larger number, S is the smaller number, and a and k are constants.

Cohen (2009) then ran two separate linear regressions with reaction time as the criterion variable and either P_C or N_W as the predictor variable. To the extent that Arabic numbers automatically activate their corresponding magnitude representations, Cohen (2009) argued that the numerical function would dominate participants' responses even in a task which required no explicit magnitude judgements, i.e., N_W would be the best predictor of reaction time. Cohen (2009) further argued that Arabic numbers, minus the semantic (numerical) meaning they convey, are essentially symbolic shapes. Thus, to the extent that Arabic numbers do not automatically activate their corresponding magnitude representations, the function based on visual similarity, i.e., P_C, would best predict reaction time. Both P_C and N_W separately and significantly predicted reaction time; however, P_C was a better fit for the data and accounted for a substantial percentage of the variance (93%). Thus, Cohen (2009) concluded that Arabic numbers do not automatically activate magnitude representations.

Garcia-Orza et al. (2012) applied Cohen's (2009) logic to investigate whether Persian and Arabic versions of Indian numbers automatically activate magnitude representations. The researchers recruited three

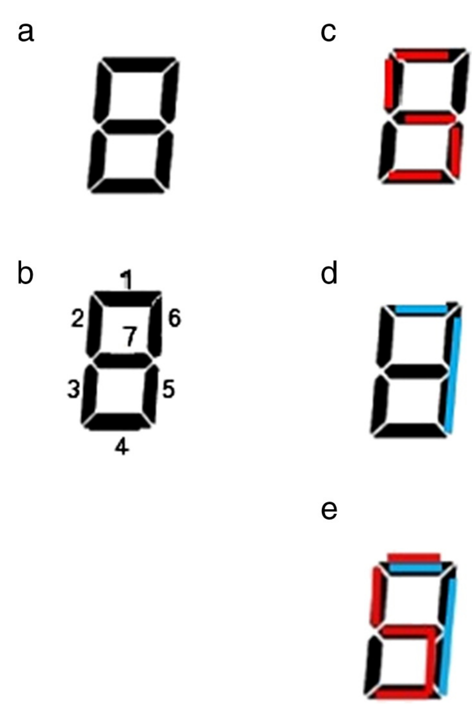

Fig. 1. (a) The figure 8 structure as used in Cohen's (2009) perceptual function (P_C). (b) This structure is made up of 7 lines. (c) The digit 5 is imposed on the structure. (d) The digit 7 as imposed on the structure. (e) A minimum of 6 lines are needed to form the digits 5 and 7. Two lines overlap. Four lines are used only once.