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Spatial and numerical processing in children with high and low visuospatial abilities

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ABSTRACT

In the literature on numerical cognition, a strong association between numbers and space has been repeatedly demonstrated. However, only a few recent studies have been devoted to examine the consequences of low visuospatial abilities on calculation processing. In this study, we wanted to investigate whether visuospatial weakness may affect pure spatial processing as well as basic numerical reasoning. To do so, the performances of children with high and low visuospatial abilities were directly compared on different spatial tasks (the line bisection and Simon tasks) and numerical tasks (the number bisection, number-to-position, and numerical comparison tasks). Children from the low visuospatial group presented the classic Simon and SNARC (spatial numerical association of response codes) effects but showed larger deviation errors as compared with the high visuospatial group. Our results, therefore, demonstrated that low visuospatial abilities did not change the nature of the mental number line but rather led to a decrease in its accuracy.

Introduction

In the literature on numerical cognition, it has been suggested that humans and nonhuman animals present two distinct elementary systems for representing numerosities. One of these is precise and

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limited by its absolute set size (up to 3 or 4) (e.g., Scholl, 2001; Trick & Pylyshyn, 1994; Uller, Huntley-Fenner, Carey, & Klatt, 1999); the other is extensible to very large quantities and allows the discrimination and approximate representation of large visual and auditory numerosities without verbal counting (Butterworth, 1999; Dehaene, 1992; Feigenson, Dehaene, & Spelke, 2004; Nieder & Miller, 2003, 2004; Wynn, 1995).

The most widespread model used to account for this approximate number system is the mental number line hypothesis. According to this model, the representation of numerosities presents two major features reflecting the fact that numerical processing obeys Weber's law (Dehaene, 2001).[1] First, numbers are represented on the mental number line by equal distributions of activation. Therefore, the larger the distance between the quantities being compared, the more distant their distributions of activation on the mental number line are and the easier it is to discriminate between them (i.e., distance effect; Buckley & Gillman, 1974; Dehaene, 1996; Gallistel & Gelman, 1992; Moyer & Landauer, 1967; van Oeffelen & Vos, 1982). Second, the mental number line is logarithmically scaled, so that small numerical magnitudes are farther apart on the number line than large numerical magnitudes. For equal numerical distance, discrimination of two numerosities, therefore, worsens as their numerical size increases (i.e., the size effect; Aschcraft & Battaglia, 1978; Buckley & Gillman, 1974; Gallistel & Gelman, 1992; Moyer & Landauer, 1967; van Oeffelen & Vos, 1982).

A developmental transition from logarithmic to linear numerical representation has, however, been documented in several studies, suggesting that children's representation of numbers changes over time with age and increasing numerical experience (Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Booth & Siegler, 2006; Siegler & Booth, 2004; Siegler & Opfer, 2003). In these studies, children and adults needed to place different numbers on a visual number line with 0 at one end and either 10, 20 (Berteletti et al., 2010), 100 (Siegler & Booth, 2004), or 1000 (Booth & Siegler, 2006; Siegler & Opfer, 2003) at the other end. All of these studies reported consistent results; the youngest children (e.g., second graders) positioned numbers logarithmically when the experimental condition was unfamiliar (e.g., 1000) but positioned them linearly when the experimental condition was familiar (e.g., 100). In contrast, older children and adults positioned numbers linearly in both experimental conditions. The dissociation between familiar and unfamiliar conditions, therefore, reveals that children's performances change with age and shift from a logarithmic representation to a linear one. Interestingly, the linearity of the numerical representation appeared to be correlated to mathematical achievement (Booth & Siegler, 2008; Siegler & Booth, 2004).

In addition to obeying Weber's law, the mental number line is also thought to be spatially oriented. Much of the evidence used to support the fact that numbers and space interact with each other comes from studies that used the numerical counterpart of two spatial tasks: the Simon effect and the line bisection task. The Simon effect, on the one hand, refers to the fact that the response to a stimulus is faster and more accurate when the position of the stimulus is compatible with the side of the response (e.g., Simon, 1969; Simon & Rudell, 1967; Simon & Wolf, 1963). In a typical Simon task, participants see lateralized colored stimuli and are instructed to respond with a left side response key to one color and with a right side response key to the other color. Although the stimulus location is completely irrelevant to the task, participants' reaction times are faster on spatially corresponding trials (left stimulus position–left side response and right stimulus position–right side response) than on spatially non-corresponding trials (left stimulus position–right side response and right stimulus position–left side response). Several studies provided evidence of a similar compatibility effect between number and space. The so-called SNARC (spatial numerical association of response codes) effect indicates that (in occidental cultures) small numbers are preferentially responded to the left, whereas larger numbers are preferentially responded to the right (Dehaene, Bossini, & Giraux, 1993). As with the Simon effect, the SNARC effect appears even if participants cross their hands, indicating that both effects originate from the mapping of an input stimulus onto an allocentric frame of reference (for the

[1] Two major theoretical models have been proposed to conceptualize how numerical processing obeys Weber's law: the mental number line model and the accumulator model. In this article, we detail only the first model, which suggests that numbers are logarithmically represented on a line by equal distributions of activation. However, the accumulator model, which suggests that numerosities are represented by magnitudes on an analogue linear representation with scalar variability (Gallistel & Gelman, 1992, 2000; Whalen, Gallistel, & Gelman, 1999), produces similar behavioral expectations.