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Spontaneous orientation towards irrelevant dimensions of magnitude and numerical acuity

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ABSTRACT

When comparing collections of objects on the basis of their number, children can be influenced by non-numerical dimensions of magnitude such as size or density. By devising a new tool for assessing children's spontaneous orientation towards different dimensions of magnitude (SOMAG), we investigated the role of non-symbolic dimensions of magnitude in the development of numerical representations from a perspective of individual differences. Ninety-three kindergarteners and first graders were asked to sort cards representing sets of dots that could be matched in number, size and total surface area or in the field area and spacing/density of the dots. Children's orientation towards different dimensions of magnitude was correlated with their performance in a non-symbolic numerical comparison task. Taken together, these results suggest that children's capacity to overcome interference when making numerical judgments can be related, in part, to individual differences in their orientation towards irrelevant non-numerical dimensions.

1. Introduction

Before entering school, children possess intuitions about numbers (Izard, Sann, Spelke, & Streri, 2009; Xu & Spelke, 2000). In particular, they have the capacity to estimate the number of objects in a set (referred to as the “numerosity” of the set), an approximate “number sense” (Dehaene, 1997) that can further be used to compare or perform approximate calculations (McCrink & Wynn, 2004). Although the way in which this capacity relates to formal mathematics is still under debate (De Smedt, Noël, Gilmore, & Ansari, 2013; Fazio, Bailey, Thompson, & Siegler, 2014), it is widely accepted that our number sense provides the foundation for arithmetic knowledge (see Libertus, 2015 for a review).

Given its foundational aspects, many researchers are attempting to characterize and better understand the processes underlying numerical estimation. One of the most debated questions regarding numerical estimation abilities relates to the non-numerical (and thus irrelevant) dimensions of magnitudes present in the stimuli and their impact on observed performances. For instance, when comparing the number of toys in two boxes, a child perceives not only the approximate number of objects but also their size, how much space they occupy in the box, and the space between each object (an observation made long ago by Piaget in number conservation tasks with preschoolers and school-aged children: Piaget, 1952; see also Houdé, 2000). These non-numerical dimensions of magnitude can be congruent with number (e.g., when a set of five large toys is compared to a set of three small ones) or incongruent with number (e.g., when a set of three large toys is compared to a set of five small ones).

1.1. The impact of non-numerical dimensions on numerical estimation

The precision of the number sense is classically assessed by numerical estimation tasks such as the non-symbolic comparison task, in which a comparative numerical judgment has to be made on rapidly flashed stimuli (usually collections of dots). As for the

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example mentioned above, these stimuli contain non-numerical dimensions of magnitude, which can co-vary with numerosity, and thus be used by the participants when performing the task. While many studies have attempted to control for these non-numerical dimensions of magnitude to isolate the participants' numerical abilities (Brannon, 2002; Lipton & Spelke, 2003; Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005), some researchers have also attempted to evaluate the impact of the non-numerical dimensions on estimation performances.

In adults, estimation performances are affected by a variety of magnitude dimensions such as the total surface area occupied by the stimuli (Gebuis & Reynvoet, 2013; Nys & Content, 2012), the individual sizes of items in the estimated set (Hurewitz, Gelman, & Schnitzer, 2006), the density of the items forming the set (Anobile, Cicchini, & Burr, 2014; Dakin, Tibber, Greenwood, Kingdom, & Morgan, 2011; Gebuis & Reynvoet, 2012; Tibber, Greenwood, & Dakin, 2012), or the space occupied by the set (Gebuis & Gevers, 2011; Sophian & Chu, 2008). In infants, the relative sensitivity to number vs. non-numerical dimensions of magnitude has been commonly investigated by pitting these dimensions against each other using looking time paradigms (Cordes & Brannon, 2008, 2009, 2011; Brannon, Lutz, & Cordes, 2006; Clearfield & Mix, 2001; Feigenson, Carey, & Spelke, 2002; Libertus, Starr, & Brannon, 2014; Mix, Huttenlocher, & Levine, 2002; Starr & Brannon, 2015; Starr, Libertus, & Brannon, 2013).

In preschoolers and school-aged children, several studies in past few years have investigated the impact of non-numerical dimensions of magnitude on numerical estimation by analyzing children's performance on congruent vs. incongruent trials (Defever, Reynvoet, & Gebuis, 2013; Fuhs & McNeil, 2013; Fuhs, McNeil, Kelley, O'Rear, & Villano, 2016; Gilmore, Cragg, Hogan, & Inglis, 2016; Szűcs, Nobes, Devine, Gabriel, & Gebuis, 2013). For instance, Szűcs et al. (2013) observed that these congruency effects were driving 7-year-old children's level of precision of their numerical estimation capacities, and that these congruency effects were larger than the ones observed in adults.

So far, most of these studies have focused on the influence of either the total surface area of the dots (correlated with average dot size) or the space occupied by the dots (often measured by convex hull). Thus far, studies have demonstrated that the total surface area of the dots affects the perception of numerosity in three-year-old children (Rousselle, Palmers, & Noël, 2004) and that three- to six-year-old children have greater precision in discriminating surface area than numerosity (Odic, Libertus, Feigenson, & Halberda, 2013). In addition, the numerical estimation of children between the ages of seven and nine is affected by the space occupied by the dots (i.e., convex hull, Clayton & Gilmore, 2015). Finally, the influence of convex hull and dot area on numerical estimation follows different developmental trajectories, with a decreasing influence of dot area, but a stable influence of convex hull with age (Gilmore et al., 2016). While these results suggest that the influence of the size of items might be more easily overcome than that of the total occupied space, in line with Piaget's work on the interference between number and length in the number conservation task, further studies are needed to fully describe the dynamics between the different dimensions of magnitude and their developmental trajectory.

1.2. The underlying mechanisms of numerical estimation

All of these studies converge in showing that performance in numerical estimation tasks can be affected by irrelevant non-numerical dimensions, and that these effects depend on the nature of the dimensions (Gebuis, Cohen Kadosh, & Gevers, 2016), the participant's age (Gilmore et al., 2016; Szűcs et al., 2013; Tokita & Ishiguchi, 2013), the numbers of presented dots (Clayton & Gilmore, 2015), and the experimental procedure used (Defever et al., 2013). These studies improved our understanding of the dynamics between these factors. For instance, the salience of non-numerical dimensions of magnitude has been shown to increase with the numerosities to be estimated in seven to nine-year-old children (Clayton & Gilmore, 2015).

New models of the development of numerical representations have been proposed to account for the interactions between numerical and non-numerical dimensions of magnitude (Gebuis et al., 2016; Leibovich, Katzin, Harel, & Henik, 2016), with some assuming the existence of a shared system of representation for several dimensions of magnitude (Leibovich et al., 2016; Mix, Levine, & Newcombe, 2016). For instance, several studies support the idea that the perception of numerosity relies on a system of representation of density (Dakin et al., 2011). However, other authors suggest that number and density rely on distinct systems, which are activated depending on the density level of the processed stimuli (Anobile et al., 2014). In line with this view, one study reported that the psychophysical law describing the participants' performance switched from a Weber's law – typical of the number sense - for densities below a certain threshold to a square root law for higher densities, interpreted as a processing of the collections of dots as texture (Anobile et al., 2014; see also Cicchini, Anobile, & Burr, 2016).

Regardless of debates about the existence of a distinct, innate number sense, these models also differ in terms of the exact mechanisms leading to the observed performance in numerical estimation tasks, i.e., the way the participants process the interference between numerical and non-numerical dimensions of magnitude when making a numerical judgment. Several authors have proposed that domain-general processes, such as inhibitory control, play a role in numerical estimation. This manifests as either a competing process with our innate sense of number (Clayton & Gilmore, 2015), or as a process that isolates numerosity from a general sense of magnitude (Leibovich et al., 2016). The congruency effects reported in number of numerical estimation tasks with a variety of dimensions of magnitude provide evidence for the role of inhibitory control in numerical judgment (Fuhs & McNeil, 2013; Fuhs et al., 2016), as well as studies investigating the number/size interferences using numerical Stroop paradigms (Rousselle & Noël, 2008). This assumption regarding the role of inhibition in numerical estimation is of particular relevance for education, given the current debate on the relation between non-symbolic numerical capacities and formal arithmetic (De Smedt et al., 2013). Some studies have indeed reported that the association between numerical estimation and math could be explained by individual difference in inhibitory control efficiency (Fuhs & McNeil, 2013; Gilmore et al., 2013 but see Keller & Libertus, 2015; for contradictory results).

1.3. The present study

Our study examines the development of numerical estimation by studying individual differences in spontaneous orientation towards various dimensions of magnitude (numerical or non-numerical) in a stimulus.

Recently, studies have started to investigate individual differences in children's spontaneous focus on numerosity (SFON, Hannula & Lehtinen, 2005), which is defined as a "self-initiated process of focusing attention on the aspect of exact number of a set of items or incidents" (Hannula, Lepola, & Lehtinen, 2010). For instance, in one SFON task, a child is asked to imitate a scene performed by the experimenter (e.g., feeding a toy parrot with a given number of red and/or blue candies). The SFON scores are calculated