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Plane thinking: Mental representations in number line estimation as a function of orientation, scale, and counting proficiency

Victoria Simms [a,*], Kevin Muldoon [b], John Towse [c]

[a] Department of Health Sciences, University of Leicester, Leicester LE1 6TP, UK
[b] School of Life Sciences, Heriot Watt University, Edinburgh EH14 4AS, UK
[c] Department of Psychology, University of Lancaster, Lancaster LA1 4YF, UK

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ABSTRACT

Young children typically show strong biases when estimating the placement of numbers on or along a scale. Number line estimation changes in accuracy and linearity across development. However, existing research is almost entirely based on a horizontal number line, which presupposes that numbers are scaled on a horizontal plane only. We present data that broaden our understanding of number line estimation by also including vertically oriented scales. This study presented 4- to 7-year-olds with the number line estimation task presented in both horizontal and vertical orientations and on different scales. Our results suggest that children store numbers as accurately in the vertical plane as in the horizontal plane, although some developmental changes are observed. Our results highlight how even simple experimental manipulations can reveal the complexities of internal representations of number.

Introduction

There is general agreement that early numerical skills and abilities are contingent on internal (i.e., mental) representations of number (e.g., De Smedt, Verschaffel, & Ghesquière, 2009; Gilmore, McCarthy, & Spelke, 2010; Siegler & Booth, 2004). Such representations envisage a horizontal number line (e.g., Fias & Fischer, 2005; Restle, 1970) along which numbers are "located" in mental space. A

* Corresponding author. Current address: School of Psychology, University of Ulster, Coleraine, BT52 1SA, UK. Fax: +44 0116 252 3272.
E-mail addresses: vrs3@le.ac.uk, v.simms@ulster.ac.uk (Victoria Simms).

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consistent finding is that for speakers of non-Semitic languages, small numbers are positioned on the left and large numbers are positioned on the right.

However, experimental stimuli used to investigate numerical representations predominantly involve the horizontal plane (for a review, see Fias & Fischer, 2005), potentially constraining conclusions about the spatial nature of numerical representations. In the current article, we look at whether the patterns of data found using a horizontal number line are evident when the number line is presented in a different orientation. After all, having a number scale located on a vertical axis might be just as important and advantageous for making everyday judgments as having representations stored on a horizontal scale; for example, being able to judge the height of a tree might be just as consequential as the ability to judge the distance of the tree from the nearest building.

Why the focus on the horizontal plane?

The theoretical notion of the mental representations of number places particular emphasis on the horizontal orientation, mainly due to evidence from empirical examinations of the spatial–numerical association of response codes (SNARC) effect. In the original SNARC tasks, participants were typically asked to indicate whether a number was odd or even by pressing a key with either the left or right hand (e.g., Dehaene, Bossini, & Giraux, 1993). Although participants were not asked to make any judgment based on the magnitude of the number, a consistent finding was that small numbers are responded to more quickly using the left hand and, conversely, large numbers are responded to more quickly using the right hand (e.g., Dehaene et al., 1993). Hence, it appears that small numbers are automatically associated with the left side of mental space and large numbers are automatically associated with the right side of mental space in adult samples (see Fias & Fischer, 2005). Consequently, being asked to respond, for example, with the right hand to small numbers provokes cognitive conflict due to the mental "siting" of those numbers on the left. The suggestion that this spatial orientation is linked to writing systems is supported by findings that participants who read from right to left (e.g., Arabic) have numerical representations that are oriented right to left and show the converse pattern of response times on SNARC tasks (Shaki, Fischer, & Petrusic, 2009).

However, it is possible that number is represented in more than one plane. Gevers, Lammertyn, Notebaert, Verguts, and Fias (2006) proposed a more complex representation of number, such that numerical association with space is evident in both horizontal and vertical planes. Results from studies using the SNARC task with vertically orientated response keys (i.e., participants are asked to indicate whether a number is odd or even by pressing either an upper or lower key) have shown that small numbers are associated with the lower end of space and large numbers are associated with the upper end of space (Gevers et al., 2006; Holmes & Lourenco, 2012; Ito & Hatta, 2004; Schwarz & Keus, 2004). This vertical indexing of number is reflected in many environmental stimuli; for example, when liquid is added to a glass, the relationship between quantity and level are clearly observable—the more liquid, the higher the level (Lakoff, 1987). On the other hand, larger numbers/objects might be associated with being heavier, which would lead them to be *lower* in the vertical axis. In other words, there might be multiple space–size correspondences in the vertical plane, not all of which act in the same way. This complex representation seems reasonable when considering human behavior; everyday tasks involve the judgment of distances and heights, often using the self as a datum from which measurements are made. Moreover, the ability to map number with space along three dimensions might confer an evolutionary advantage in estimating distances from prey or dangerous animals, the height of trees, or the depth of holes or drops in order to pick fruit, procure birds' eggs, and so forth. If this were the case, then we may expect numerical representations to run from small numbers (on the ground/where I am now) to large numbers (up high/down low/far away) as well as from left to right (or from right to left).

Estimating: Another way of understanding mental representations of number

More recently, the use of the number line estimation paradigm has provided researchers with quite striking data on the development of number representations during childhood (Siegler & Opfer, 2003). In these tasks, children are asked to mark various numbers on a blank horizontal number line (of a