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Research report

The effect of hand movements on numerical bisection judgments in early blind and sighted individuals

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ABSTRACT

Recent evidence suggests that in representing numbers blind individuals might be affected differently by proprioceptive cues (e.g., hand positions, head turns) than are sighted individuals. In this study, we asked a group of early blind and sighted individuals to perform a numerical bisection task while executing hand movements in left or right peripersonal space and with either hand. We found that in bisecting ascending numerical intervals, the hemi-space in which the hand was moved (but not the moved hand itself) influenced the bisection bias similarly in both early blind and sighted participants. However, when numerical intervals were presented in descending order, the moved hand (and not the hemi-space in which it was moved) affected the bisection bias in all participants. Overall, our data show that the operation to be performed on the mental number line affects the activated spatial reference frame, regardless of participants' previous visual experience. In particular, both sighted and early blind individuals' representation of numerical magnitude is mainly rooted in world-centered coordinates when numerical information is given in canonical orientation (i.e., from small to large), whereas hand-centered coordinates become more relevant when the scanning of the mental number line proceeds in non-canonical direction.

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1. Introduction

Consistent work has shown the existence of a tight and bidirectional coupling between the spatial representation of numbers (the so-called "mental number line", Dehaene, 1992; for a review, de Hevia, Vallar, & Girelli, 2008) and the representation of physical space. For instance, individuals tend to respond faster to smaller numerosities with the left hand and to larger numerosities with the right hand (at least in Western societies who read in the left-to-right direction), a phenomenon known as SNARC (Spatial Numerical Association of Response Codes) effect (Dehaene, Bossini, & Giraux, 1993). Furthermore, processing numerical magnitude can orient attention to different portions of external space (small numbers biasing attention to the left, while large numbers bias to the right) (e.g., Cattaneo, Fantino, Tinti, Silvanto, & Vecchi, 2010; Di Luca, Pesenti, Vallar, & Girelli, 2013; Fischer, 2001; Goffaux, Martin, Dormal, Goebel, & Schiltz, 2012; Schuller, Hoffmann, Goffaux, & Schiltz, 2014). Accordingly, Loetscher, Bockisch, Nicholls, and Brugger (2010) measured participants' eye position during a random number generation task and found that a leftward and downward change in eye position predicted that the next number would be smaller than the last. Conversely, a rightward and upward change in eye position predicted that the next number would be larger than the last. At the same time, moving the hand in the left space (Cattaneo, Fantino, Silvanto, Vallar, & Vecchi, 2011) or turning the head leftwards (Loetscher, Schwarz, Schubiger, & Brugger, 2008) biases attention to small numbers, with the reverse tendency for hand movements or head towards the right. Although it is important to stress that the mental number line can be evoked based on a purely attentional basis without any obvious motor component (Nicholls, Loftus, & Gevers, 2008), the analogies consistently reported between movements along the mental number line and physical space suggest that our mental representations may be grounded, at least to a certain extent, in sensorimotor experience (Fischer, 2012).

When sensory experience is altered such as in case of blindness, there is the potential that resulting mental representations are affected. In particular, converging evidence suggests that blind individuals' spatial representations rely more on body/hand centered coordinates compared to the sighted (Noordzij, Zuidhoek, & Postma, 2006; Röder, Kusmierek, Spence, & Schicke, 2007; for a review, see Cattaneo et al., 2008). The lack of prior visual experience has led to mixed reports in terms of its effect on the representation of external space and (at least to a certain extent) on the mental representation of numerical magnitude (Crollen, Dormal, Seron, Lepore, & Collignon, 2013; Pasqualotto, Taya, & Proulx, 2014). For example, prior evidence has found that blind individuals also tend to represent numbers in the form of a mental number line (Castronovo & Seron, 2007; Cattaneo et al., 2010; Szűcs & Csépe, 2005), showing attentional biases similar to those of sighted individuals when exploring it (Cattaneo, Fantino, Silvanto, Tinti, & Vecchi, 2011). However, blind individuals may use different reference frames in representing numbers compared to sighted individuals. For instance, Crollen et al. (2013) recently reported that crossing the hands reversed the typical SNARC effect in early blind but not in sighted individuals while performing a numerical comparison task, suggesting that in comparing magnitudes blind participants mainly adopted a hand-based reference frame (see also Röder, Rösler, & Spence, 2004, for similar findings in tactile temporal order judgments). However, in the same study, early blind participants' performance was unaffected by crossing the hands in a parity judgment task (i.e., judging whether a given numeral is odd or even) (Crollen et al., 2013). Other recent findings have questioned the canonical left-to-right orientation of the mental number line in blind individuals in light of their performance in a random number generation task. In particular, while sighted individuals typically generate more small numbers when turning the head left, and more large numbers when turning the head right, early blind participants appear to show the opposite behavior (Pasqualotto et al., 2014).

Overall, prior evidence suggests that mental representation of numbers may be affected differently by proprioceptive cues (e.g., hand position, head turn) in blind than in sighted individuals, at least under specific task conditions (Crollen et al., 2013; Pasqualotto et al., 2014). In particular, the results by Crollen et al. (2013) suggest that blind individuals may anchor their mental representations more to the hands, and less to world-centered reference frame. The aim of this study was to shed further light on this issue. In a prior study by our group carried out in sighted participants, we found that hand movements performed in the left peripersonal space (irrespective of the hand used) accentuated underestimation (i.e., a leftward bias) in numerical bisection, whereas movements in the right peripersonal space (irrespective of hand used) had the opposite tendency (Cattaneo, Fantino, Silvanto, Vallar, et al., 2011). These results suggest that the correspondence between physical space and the mental number space in sighted individuals is anchored to a world-based reference frame centered on the body (i.e., left in physical space and left on the mental number line). Such representation is not sensitive to which hand is actually moved, but rather to the hand's position in peripersonal space. However, following the results reported by Crollen et al. (2013), we hypothesized that in the case of early blindness, the effect of hand movement would be more evident given the reliance on egocentric frames of reference.

In order to investigate this issue, we asked a group of early blind and sighted individuals to perform a numerical bisection task while executing hand movements in left or right peripersonal space with either hand. If indeed early blind individuals rely more on hand-centered coordinates when representing numerical intervals, then the hand used (more than the space in which the hand is moved) should lead to biases in estimation along the mental number line.

2. Methods

2.1. Participants

Sixteen early-blind participants (8 males; mean age = 42.3 ys, *SD* = 10.2, range: 27–62 ys; mean education: 14.7 ys, *SD* = 2.5)