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Bisecting the mental number line in near and far space

Matthew R. Longo [a,*], Stella F. Lourenco [b]

[a] Institute of Cognitive Neuroscience, University College London, United Kingdom
[b] Department of Psychology, Emory University, Atlanta, GA, USA

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ABSTRACT

Much evidence suggests that common posterior parietal mechanisms underlie the orientation of attention in physical space and along the *mental number line*. For example, the small leftward bias (*pseudoneglect*) found in paper-and-pencil line bisection is also found when participants "bisect" number pairs, estimating (without calculating) the number midway between two others. For bisection of physical lines, pseudoneglect has been found to shift rightward as lines are moved from near space (immediately surrounding the body) to far space. We investigated whether the presentation of stimuli in near or far space also modulated spatial attention for the mental number line. Participants bisected physical lines or number pairs presented at four distances (60, 120, 180, 240 cm). Clear rightward shifts in bias were observed for both tasks. Furthermore, the rate at which this shift occurred in the two tasks, as measured by least-squares regression slopes, was significantly correlated across participants, suggesting that the transition from near to far distances induced a common modulation of lateral attention in physical and numerical space. These results demonstrate a tight coupling between number and physical space, and show that even such prototypically abstract concepts as number are modulated by our on-line interactions with the world.

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1. Introduction

Numbers are commonly conceptualized with the metaphor of the *mental number line*, smaller numbers on the left and larger numbers on the right. An increasing body of evidence supports the theory that numerical information is represented spatially (e.g., Dehaene, Bossini, & Giraux, 1993; Fischer, Castel, Dodd, & Pratt, 2003; Göbel, Calabria, Farnè, & Rossetti, 2006; Loetscher, Bockisch, & Brugger, 2008; Loftus, Nicholls, Mattingley, & Bradshaw, 2008; Longo & Lourenco, 2007a; Zorzi, Priftis, & Umiltà, 2002; for reviews see Hubbard, Piazza, Pinel, and Dehaene (2005), de Hevia, Vallar, and Girelli (2008), Umiltà, Priftis, and Zorzi (2009)). For example, Zorzi et al. (2002) asked patients with hemineglect for the left side of space following a posterior parietal lesion to 'bisect' numerical intervals by indicating the number midway between two others, without overtly computing the correct answer. These patients showed a 'rightward' bias when bisecting number pairs (i.e., overestimating the true midpoint of the numerical interval), analogous to their rightward bias when bisecting physical lines. More recently, Pia, Corazzini, Folegatti, Gindri, and Cauda (2009) reported a patient with right neglect following a left hemisphere stroke who showed a leftward bias both when bisecting physical lines and numbers. Similarly, the small leftward bias (*pseudoneglect*) found in healthy adults on line bisection (Bowers & Heilman, 1980; Jewell & McCourt, 2000) also appears for number bisection (Göbel et al., 2006; Loftus, Nicholls, Mattingley, Chapman, & Bradshaw, 2009; Loftus et al., 2008; Longo & Lourenco, 2007a; Lourenco & Longo, 2009b), and, importantly, is correlated across the two tasks (Longo & Lourenco, 2007a). Together, these data suggest that common mechanisms, likely in posterior parietal regions, underlie directional attention in physical and numerical space.

Recently, Loetscher, Schwarz, Schubiger, and Brugger (2008) found that turning one's head to the left or right modulated random number generation; specifically, right head turning led to larger numbers being generated more frequently than did left head turning. These results provide an intriguing demonstration of a relation between attention to numerical information and the position and orientation of body parts with respect to each other. However, it is unknown whether, in addition to the internal spatial *configuration* of the body, attention along the mental number line is also affected by the external spatial *relations* of the body to objects in the world. Numerous studies have found that lateral attention in physical space is different in the near space immediately surrounding the body than in more distant (far) space. When participants bisect lines with a laser pointer in near space, the same leftward bias found on paper-and-pencil tasks is observed; as lines are moved farther away, however, this bias gradually shifts

* Corresponding author. Address: Institute of Cognitive Neuroscience, University College London, 17 Queen Square, London WC1 N 3AR, United Kingdom.
E-mail address: m.longo@ucl.ac.uk (M.R. Longo).

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rightward (Longo & Lourenco, 2006, 2007b; Varnava, McCarthy, & Beaumont, 2002). Here, we tested whether viewing distance also affects spatial attention to mental representations of number, producing rightward shifts in attentional bias with increasing distance. To the extent that common mechanisms of spatial attention operate along physical lines as well as the mental number line, modulation of lateral attention by presenting stimuli in near or far space should produce comparable modulation of bisection biases for physical lines and the mental representation of numbers.

Participants bisected physical lines and number pairs presented at four distances from 60 and 240 cm. We quantified the effect of distance on spatial attention by regressing rightward bias on distance for physical line bisection and number bisection for each participant. The *y*-intercept of these regressions provides a measure of lateral attentional bias at hypothetical distance 0 cm, analogous to paper-and-pencil responses; the slope of these regressions provides a measure of how bias changes with increasing distance. Thus, pseudoneglect should manifest itself as a negative intercept in each task, and a rightward shift with increasing distance should manifest itself as a positive slope. Furthermore, there is strong test–retest correlation of these slopes for physical line bisection (Longo & Lourenco, 2007b) indicating consistent individual differences not only in lateral attentional biases (cf. Levy, Heller, Banich, & Burton, 1983), but also in their modulation by viewing distance. Thus, if the transition from near to far space has a common effect on both tasks, the rightward shift with increasing distance as indexed by the regression slopes should be correlated as well.

2. Experiment 1

2.1. Methods

Twenty-five students at Emory University (15 female), between 18 and 23 years, participated. All participants had normal or corrected-to-normal vision. Participants were on average right handed as assessed by the Edinburgh Inventory (*M*: 63.65, range: −68.42 to 100), and received payment or course credit for their participation. Procedures were approved by the local ethics committee.

Participants bisected physical lines and number pairs in sequential blocks, counterbalanced across participants. Physical lines were printed on legal-size (8.5″ × 14″) sheets of white paper, and measured 1 mm in height and either 10, 20, or 30 cm in length. Sheets were suspended from the wall with a pair of paper clips, at a height of 145.3 cm. Participants bisected 60 lines, five of each length at each of four distances (60, 120, 180, and 240 cm). A laser pointer, constantly activated, was attached to the head of a tripod, with the height of the tripod adjusted for each participant's comfort. On all trials, the tripod was positioned to the participant's right and equally far from the wall as his/her feet. Participants used their right hand to move the head of the tripod to bisect the line with the laser beam. Responses were marked by an experimenter (blind to the hypotheses of the study), who, until then, remained behind the participant. Two coders measured bisection responses off-line, never disagreeing by more than 0.25 mm. Mean percent deviations were calculated for each participant at each distance.

Participants were instructed to bisect each numerical interval by estimating the number midway between the two presented numbers, without explicitly computing the answer. Number pairs were presented on a computer monitor using a custom MATLAB script (Mathworks, Natick, MA). The font size of the numbers was increased in proportion to increases in distance, such that visual angle size was held constant across conditions (0.645° in height). Participants made untimed verbal responses, but were instructed to respond quickly, giving the answer that seemed immediately intuitive. There were 128 trials, in four blocks of 32 trials each. Within each block, there were eight trials at each distance, counterbalanced for left/right position of the smaller and larger numbers in each pair.

Number pairs were generated by randomly selecting numbers between 11 and 99, with the constraint that the interval between numbers be 11 or greater and not a multiple of 10. The same 128 number pairs were used for all participants, but were randomly assigned to the different distances for each participant. The range of smaller numbers was 11–83, and for larger numbers it was 28–98. The interval size between the numbers was, on average, 33.7 (range: 11–75).

2.2. Results and discussion

We quantified effects of distance on spatial attention by regressing rightward bias on distance for physical lines and number pairs for each participant. As indicated above, the intercept of these analyses provides a measure of attentional bias at hypothetical distance zero and the slope provides a measure of change in bias with increasing distance.

Fig. 1 shows the raw data for physical line (Fig. 1a) and number (Fig. 1b) bisection. Analyses of intercepts show overall leftward

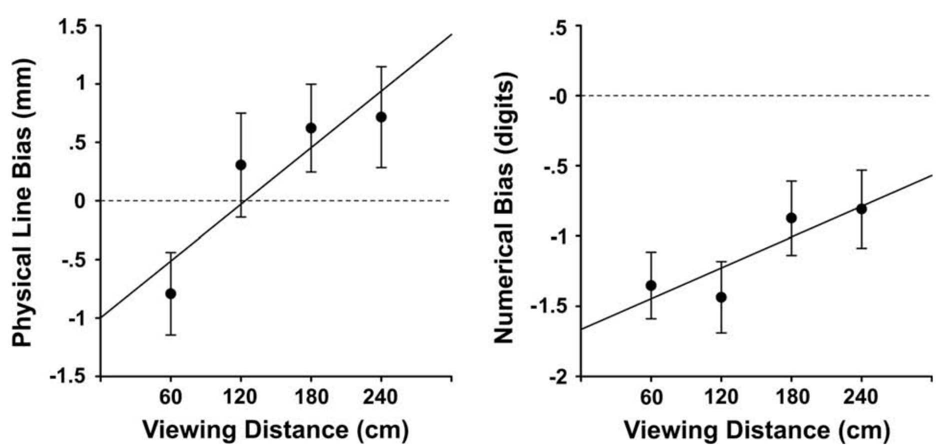

Fig. 1. Effect of viewing distance on physical line bisection (left panel) and numerical bisection (right panel) in Experiment 1. Bias for physical lines indicates the mean distance (in mm) between the true midpoint and participants' response; positive values indicate rightward bias, negative values leftward bias (pseudoneglect). Bias for numerical bisection indicates the mean difference between participants' responses and the true mean of the number pairs to be bisected; positive values indicate overestimation, negative values underestimation (pseudoneglect). Error bars are one SEM.

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