Approaching stimuli bias attention in numerical space

Journal Article

Citation:

Longo, M.R.; Lourenco, S.F.; Francisco, A. (2012)
Approaching stimuli bias attention in numerical space
Acta Psychologica 140 (2), 2012

RUNNING HEAD: Bisecting Approaching Numbers

Approaching Stimuli Bias Attention in Numerical Space

Matthew R. Longo[1], Stella F. Lourenco[2], and Alex Francisco[1,3]

[1]Department of Psychological Sciences, Birkbeck, University of London

[2]Department of Psychology, Emory University

[3]Truman State University

Address correspondence to:

Matthew R. Longo

Department of Psychological Sciences

Birkbeck, University of London

Malet Street

London WC1E 7HX

United Kingdom

m.longo@bbk.ac.uk

Word count:

Keywords: Number Line, Looming, Pseudoneglect, Laterality

Abstract

Increasing evidence suggests that common mechanisms underlie the direction of attention in physical space and numerical space, along the *mental number line*. The small leftward bias (*pseudoneglect*) found on paper-and-pencil line bisection is also observed when participants ‘bisect’ number pairs, estimating (without calculating) the number midway between two others. Here we investigated the effect of stimulus motion on attention in numerical space. A two-frame apparent motion paradigm manipulating stimulus size was used to produce the impression that pairs of numbers were approaching (size increase from first to second frame), receding (size decrease), or not moving (no size change). The magnitude of pseudoneglect increased for approaching numbers, even when the final stimulus size was held constant. This result is consistent with previous findings that pseudoneglect in numerical space (as in physical space) increases as stimuli are brought closer to the participant. It also suggests that the perception of stimulus motion modulates attention over the mental number line and provides further support for a connection between the neural representations of physical space and number.

Increasing evidence suggests important functional connections between the representation of number and physical space, consistent with the common conceptualisation of a *mental number line* (e.g., Dehaene, Bossini, & Giraux, 1993; Fischer, Castel, Dodd, & Pratt, 2003; Göbel, Calabria, Farnè, & Rossetti, 2006; Loetscher & Brugger, 2007; Loetscher, Schwarz, Schubiger, & Brugger, 2008; Loftus, Nicholls, Mattingley, & Bradshaw, 2008; Longo & Lourenco, 2007a; Lourenco & Longo, 2009b; Zorzi, Priftis, & Umiltà, 2002). For example, patients with hemi-neglect following brain damage show biases when asked to 'bisect' numerical intervals analogous to those shown when they bisect physical lines (Zorzi et al., 2002; Pia, Corazzini, Folegatti, Gindri, & Cauda, 2009; Priftis, Zorzi, Meneghello, Marenzi, & Umiltà, 2006; but, for an alternate view, see Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005; van Dijck, Gevers, Lafosse, Doricchi, & Fias, 2011). Similarly, neurologically healthy adults show small leftward biases ('pseudoneglect') when bisecting physical lines and underestimation when bisecting numerical intervals, consistent with the left-to-right organization of the mental number line (Göbel et al., 2006; Longo & Lourenco, 2007a; Loftus et al., 2009). Other recent studies have also provided evidence for spatial representations of time, which are altered both in patients with hemi-neglect (Basso, Nichelli, Frassinetti, & di Pellegrino, 1996; Calabria et al., 2011) and in healthy adults by prism adaptation (Frassinetti, Magnani, & Oliveri, 2009), consistent with suggestions of a system of generalized magnitude representation (Walsh, 2003; also, Lourenco & Longo, 2010).

Several studies have found differential attentional biases in the space immediately surrounding the body (i.e., *near* or *peripersonal* space) and the space farther away (i.e., *far* or *extrapersonal* space), with leftward biases in near space and a consistent rightward shift with distance (e.g., Gamberini, Seraglia, & Priftis, 2008; Longo & Lourenco, 2006, 2007b; Lourenco & Longo, 2009a; Varnava, McCarthy, & Beaumont, 2002). We recently found that viewing distance has similar effects on mental representations of number, with clear rightward shifts in attention as visually-presented number pairs are moved from near to far space (Longo & Lourenco, 2010). When participants were asked to bisect numerical intervals in near space they showed the expected 'left' bias, that is, underestimation of the midpoint. In contrast, as number pairs were presented at farther distances from the observer, participants showed a rightward shift (i.e., significantly less underestimation of the midpoint), much as they do when bisecting physical lines in far space.

Here, we build on this result, investigating how perceived stimulus motion towards the observer affects attention over the mental number line. Several lines of evidence suggest important functional connections between approaching stimuli and near space. For example, Fogassi and colleagues (1996) described bimodal neurons in macaque premotor cortex with both tactile and visual receptive fields (RFs). When objects approached the tactile RF, the visual RF expanded, with the amount of expansion related to the velocity of the approaching object. In other research, Ono and Kitazawa (2010) recently investigated the effects of approaching motion on the perception of time, finding that when stimuli appeared to approach the observer temporal intervals were perceived as lasting a shorter duration than when objects appeared to recede. This result is consistent with the finding of Zäch and Brugger (2008) that time appears to run more slowly for stimuli judged as near to the observer.

Here, we adapted the logic of the paradigm of Ono and Kitazawa (2010) to investigate the effects of stimulus motion on attention in numerical space. This paradigm is based on the fact that stimuli increasing in size radially outward from an unmoving centre (i.e., 'looming' stimuli) provide a specific optical signal of stimulus approach (Schiff, Caviness, & Gibson, 1962). Thus, by presenting two stimuli in rapid succession, differing only in size, clear apparent motion of stimulus approach (e.g., small stimulus followed by large stimulus) or receding (e.g., large stimulus followed by small stimulus) can be produced. Pairs of numbers were presented at three different font sizes. By rapidly changing font size, we compared bisection of numerical intervals that appeared to be (1) approaching the participant, (2) receding from the participant, or (3) not moving at all. Given the relation between stimulus approach and representation of near space (cf. Fogassi et al., 1996) and our recent finding of increased leftward bias for numbers presented in near space, we predicted that approaching stimuli should bias attention leftward in numerical space.

Methods

Participants

Twenty-eight members of the University of London community (15 female), between 18 and 49 years of age, participated for payment. Participants were all right-handed, as assessed by the Edinburgh inventory, *M*: 77.4, range: 17.7 – 100. Three additional participants were excluded from analyses due to failure to follow instructions (i.e., computing, rather than estimating, responses as evidenced by the time taken to respond and implausibly large proportion of exactly correct responses; two participants), or a large proportion of trials with responses out of range of the intervals (43%; one participant). Participants gave written informed consent and procedures were approved by the local ethics committee.

Procedures

Participants were instructed to 'bisect' numerical pairs by estimating the number midway between the two stimulus numbers, without explicit computation. No explicit time constraints were used, but participants were asked to respond quickly, using whichever number seemed immediately intuitive. Numbers were displayed on a monitor (approximately 40 cm from the participant) controlled by a custom MATLAB script (Mathworks, Natick, MA) at three different font sizes: *small* (.95 cm in height, 1.36° visual angle), *medium* (1.90

cm, 2.72°), and *large* (3.80 cm, 5.44°). By presenting two font sizes in rapid succession, apparent motion percepts of the numbers approaching (i.e., looming) or receding from the observer were produced (see Figure 1), as in the study of Ono and Kitazawa (2010). Five trial types were used: two types of approach trials (small to medium; medium to large), two types of receding trials (large to medium; medium to small), and one type without movement (medium to medium).

On each trial, the initial size was presented for 200 ms, immediately followed by the second size, which remained on the screen until the participant responded. Responses were made verbally and recorded by an experimenter who then pressed a button to proceed to the next trial. A fixation cross was presented at the centre of the screen for 500 ms before the numbers appeared. There were a total of 160 trials (32 of each trial type), divided into eight blocks of 20 trials. Participants were allowed a short break between each block.

*** INSERT FIGURE 1 ABOUT HERE ***

Following our previous research (Longo & Lourenco, 2007a, 2010; Lourenco & Longo, 2009b), number pairs were generated by random selection of numbers between 11 and 99 with the constraints that the distance between the numbers be at least 11 and not a multiple of 10. The smaller numbers in the pairs ranged from 11 to 82 (*M*: 38.4, *SD*: 17.9), and the larger numbers from 26 to 98 (*M*: 72.7, *SD*: 18.2). Within each of the five trial types, the smaller number was presented on the left on half the trials and on the right on the other half.

Results

For each trial, bias was computed as the difference between the participant's response and the true centre (i.e., arithmetic mean) of the interval. Thus, negative numbers indicate underestimation of the true centre (a 'leftward' attentional bias), and positive numbers indicate overestimation (a 'rightward' attentional bias). While results are reported in terms of raw bias, all key results are also significant when bias is expressed as a percentage of the interval between the two numbers to be bisected. Trials on which the participant's response was outside the range of numbers to be bisected (1.79% of trials) were excluded from analyses. Overall, there was a clear bias for participants to give responses smaller than the true centre of the numerical intervals (*M*: -1.41), $t(27) = -4.81$, $p < .0001$, $d = .91$, consistent with several previous studies showing pseudoneglect for the mental number line (e.g., Loftus et al., 2008, 2009; Longo & Lourenco, 2007a, 2010; Lourenco & Longo, 2009b). Indeed, significant pseudoneglect was seen in all conditions: approaching (*M*: -1.67), $t(27) = -5.52$, $p < .0001$, $d = 1.04$; no movement: (*M*: -1.19), $t(27) = -4.03$, $p < .0005$, $d = .76$; receding: (*M*: -1.25), $t(27) = -4.10$, $p < .0005$, $d = .78$ (see Figure 2).

To investigate the effect of stimulus motion, we conducted an analysis of covariance (ANCOVA) with two within-subject factors of stimulus motion (approaching, no motion, receding) and number order (i.e., smaller number on left or on right). Because we previously found that the magnitude of pseudoneglect for number bisection increases with the magnitude of numbers to be bisected (Longo & Lourenco, 2007a, 2010; Lourenco & Longo, 2009b), the average of the number pairs was included as a covariate. There was a significant main effect of numerical magnitude, $F(1, 27) = 33.26$, $p < .0001$, $\eta^2_p = .55$, consistent with previous findings. More importantly, there was a significant main effect of motion condition, $F(2, 54) = 10.90$, $p < .0001$, $\eta^2_p = .29$. Post-hoc comparisons using Bonferroni correction for all pairwise comparisons among the three motion conditions revealed significantly greater leftward bias in the approaching condition than either the no movement, $t(27) = -3.80$, $p <$

.005, *d* = .72, or receding, *t*(27) = -3.77, $p < .005$, *d* = .78, conditions, which did not differ, *t*(27) = 0.32, *n.s.* There was no significant effect of number order, *F*(1, 27) = 0.00, *n.s.*, with comparable biases observed with the smaller number on the left (-1.37) and the right (-1.39), nor an interaction of order and motion, *F*(2, 54) = 0.81, *n.s.*

*** INSERT FIGURE 2 ABOUT HERE ***

Could increased pseudoneglect in the approaching condition be due to differences in stimulus size across conditions, rather than apparent motion per se? On average, the approaching stimuli end up larger than in the other conditions, which could potentially drive effects. To address this issue, we analysed the three conditions in which final size was 'medium' (i.e., approach: small to medium; no movement: medium to medium; receding: large to medium). On this subset of trials, the eventual size of stimuli is matched, so that no differences should be observed if stimulus size – rather than motion – is driving the effects. As in the full analysis above, there were significant effects of numerical magnitude, *F*(1, 27) = 25.01, $p < .0001$, $\eta^2_p = .48$, and motion, *F*(2, 54) = 6.87, $p < .005$, $\eta^2_p = .21$. Post-hoc tests with Bonferroni correction revealed significantly more leftward bias for the approaching condition than either the no movement, *t*(27) = -2.96, $p < .02$, *d* = .56, or receding, *t*(27) = -3.19, $p < .02$, *d* = .60, condition, which again did not differ from each other, *t*(27) = 0.39, *n.s.* It is also worth noting that the initial size of the numbers works, if anything, against finding this effect, since the initial size in the approach condition is small (i.e., apparently distant), which should lead to *reduced* pseudoneglect (cf. Longo & Lourenco, 2010). Thus, the present results cannot be interpreted in terms of stimulus size or apparent stimulus distance, but are specifically due to the apparent movement of stimuli towards the observer (i.e., looming or receding). As in the initial analysis, there was no significant effect of numerical order, $F(1, 27) = 0.31$, *n.s.*, nor an interaction of order and motion, $F(2, 54) = 1.50$, *n.s.*

To further investigate any potential effect of stimulus size, we conducted an ANOVA comparing the ‘small’ and ‘large’ versions of the approaching and receding conditions. As in the above analyses, there was a clear main effect of stimulus movement, $F(1, 27) = 14.19$, $p < .001$. There was no effect of stimulus size, $F(1, 27) = 1.21$, $p > .20$, nor an interaction of movements and size, $F(1, 27) = 1.40$, $p > .20$. Though there was no overall effect of stimulus size, there was a significant difference between the large and small receding trials, with significantly greater pseudoneglect on small (i.e., medium to small) trials than on large (i.e., large to medium) trials (-1.39 vs. -1.11), $t(27) = -2.07$, $p < .05$. No such effect was found for approaching trials (-1.68 vs. -1.66), $t(27) = -.06$, $p > .20$. Thus, there is some modest evidence that absolute size may affect performance. Crucially, however, the direction of this bias would work *against* finding the effect of movement we report, since approaching stimuli necessarily involve numbers increasing in size.

Discussion

Approaching numbers are bisected farther to the left along the mental number line than static or receding numbers. This relation holds even when stimuli are controlled for their final absolute size, suggesting that the effect of stimulus movement is not an artefact of approaching numbers being perceived as closer. This result dovetails with our recent finding of increased leftward bias for numerical bisection of numbers presented close to the body (Longo & Lourenco, 2010). Together, these results suggest that approaching objects are bound to representations of near space, as if the extent of near space expands to include approaching objects, consistent with neurophysiological findings in monkeys (Fogassi et al., 1996). They also provide additional evidence for functional links between the representations of space and the mental number line (cf. Hubbard, Piazza, Pinel, & Dehaene, 2005).

In our previous study showing modulation of numerical bisection in near and far space (Longo & Lourenco, 2010), we discussed the possibility that the shift in attention over the mental number line might be due to generic priming of increased magnitude (i.e., 'more' distance). Several studies report that perceiving magnitude in one dimension (e.g., numerosity, physical size) can modulate representations in other dimensions (e.g., Casasanto & Boroditsky, 2008; Lourenco & Longo, 2010; Oliveri et al., 2008; Xuan, Zhang, He, & Chen, 2007). Analogously, numbers in our previous study might have been influenced by the amount of distance, with 'more' distance priming increased numerical responses, and, consequently, less apparent pseudoneglect. The approaching and receding conditions involved the same *amount* of motion, differing only in the direction of that motion. Nevertheless, only the approaching condition differed from the no movement control condition. This result suggests that the total amount of movement does not have a substantial priming effect. Rather, approaching movement appears to have a unique influence, not paralleled by a complementary effect of receding movement.

Analogous to the generic priming of increased magnitude, it is possible that *changes* in stimulus size might also have affected responses. The change in stimulus size that we used produces clear percepts of stimulus approach and recession. We interpreted the effects of changing stimulus size on numerical estimation as resulting from this perceived motion. An alternative possibility is that seeing a change in stimulus size might have primed changes in numerical estimation in the same direction, an account closely related to the phenomenon of representational momentum (Kelly & Freyd, 1987). On this account, an increase in stimulus size would lead to greater numerical estimates, and, consequently, less apparent pseudoneglect. Crucially, however, this account works *against* our finding the pattern of results we did. Indeed, we report the exact opposite findings; smaller numerical estimates following increases in stimulus size (approaching condition). Together with the results from our previous study (Longo & Lourenco, 2010), the present study converge to provide evidence that the distinction between near and far space has clear influences on the direction of attention over the mental number line, just as it does over physical lines. Further research should attempt to clarify the circumstances under which attention in physical and numerical space appears to be associated (e.g., Zorzi et al., 2002; Longo & Lourenco, 2007a) or dissociated (e.g., Doricci et al., 2005; van Dijck et al., 2011).

One aspect of our data, however, does complicate the relation between physical and numerical space, namely the asymmetry in our results, such that approaching – but not receding – stimuli bias attention in numerical space. What might account for this asymmetry? Classically, looming stimuli are interpreted as specifying not only stimulus approach, but also threat and the need for defensive reactions. Indeed, looming stimuli elicit consistent defensive reactions in monkeys (Schiff et al., 1962), human infants (Ball & Tronick, 1971), and human adults (King, Dykeman, Redgrave, & Dean, 1992). While looming stimuli clearly signal threat, receding stimuli do not in the same way signal the opposite of threat. In terms of their threat value, the no movement and receding conditions are basically equal, but both clearly differ from the looming condition. Thus, we suggest that the asymmetry we observe in our results may reflect the specific threat value specified by looming stimuli, which activates representations of near space, producing leftward shifts of spatial attention analogous to those we recently found by actually presenting numbers in near space (Longo & Lourenco, 2010). Looming has generally been treated separately from the issue of near vs. far space. The present finding that looming induces attentional biases similar to those induced by presenting stimuli in near space (cf. Longo & Lourenco, 2010) suggests a potential link between these aspects of perception. Looming stimuli, regardless of their content, may be coded as potentially threatening and hence bound to representations of near space. This activation of near space, in turn, would be expected to lead to the overall leftward shift in attention seen for stimuli presented in near space, both for physical lines (Longo & Lourenco, 2006; Varnava et al., 2002) and the mental number line (Longo & Lourenco, 2010). More generally, this connection between the perception of looming stimuli and the representation of near space highlights the role of near space in serving as a defensive buffer surrounding the body (cf. Graziano & Cooke, 2006; Lourenco et al., 2011) in contrast to the more traditional focus in cognitive neuroscience on near space's function in guiding visuomotor action (e.g., Brain, 1941; Farnè, Iriki, & Làdavas, 2005).

The present results contribute to an expanding literature revealing that a wide-range of spatial manipulations affect attention over the mental number line. For example, prism adaptation has been found to bias attention in numerical space, both in neglect patients (Rossetti et al., 2004) and healthy adults (Loftus et al., 2008). Similarly, spatial cueing of the left or right side of space affects numerical attention, whether in the form of lateralised visual cues (Stoianov, Kramer, Umiltà, & Zorzi, 2008; Nicholls & McIlroy, 2010) or manual tapping in left or right hemispace (Cattaneo et al., 2011). While the effect of left-right spatial cues is clearly predicted by the left-to-right spatial orientation of the mental number line (at least in Western participants, cf. Dehaene et al., 1993), the present results add to the evidence that location along the proximo-distal axis is also relevant to numerical cognition. Both actual physical proximity of numbers (Longo & Lourenco, 2010) or their apparent approach (this study) bias numerical attention towards smaller numbers, consistent with the relative leftward shift in bisection of physical lines near the observer (Longo & Lourenco, 2006; Varnava et al., 2002). Finally, one recent study using TMS-adaptation revealed overlapping representations of numerical magnitude and (left-right) stimulus motion in the posterior parietal cortex (Renzi, Vecchi, Silvanto, & Cattaneo, 2011). The present result converges with this finding in revealing connections between the mental number line and motion perception, both in the left-right (Renzi et al., 2011) and proximo-distal (this study) orientations.

References

Ball, W., & Tronick, E. (1971). Infant responses to impending collision. *Science, 171*, 818-820.

Basso, G., Nichelli, P., Frassinetti, F., & di Pellegrino, G. (1996). Time perception in a neglected space. *NeuroReport, 7*, 2111-2114.

Brain, W. R. (1941). Visual disorientation with special reference to lesions of the right cerebral hemisphere. *Brain*, *64*, 244–272.

Calabria, M., Jacquin-Courtois, S., Miozzo, A., Rossetti, Y., Padovani, A., et al. (2011). Time perception in spatial neglect: A distorted representation? *Neuropsychology, 25*, 193-200.

Casasanto, D., & Boroditsky, L. (2008). Time in the mind: Using space to think about time. *Cognition, 106*, 579–593.

Cattaneo, Z., Fantino, M., Silvanto, J., Vallar, G., & Vecchi, T. (2011). Tapping effects on numerical bisection. *Experimental Brain Research, 208,* 21-28.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, *122*, 371-396.

Doricchi, F., Guariglia, P., Gasparini, M., & Tomaiuolo, F. (2005). Dissociation between physical and mental number line bisection in right hemisphere brain damage. *Nature Neuroscience, 8*, 1663-1665.

Farnè, A., Iriki, A., & Làdavas, E. (2005). Shaping multisensory action-space with tools: Evidence from patients with cross-modal extinction. *Neuropsychologia*, *43*, 238-249.

Fischer, M. H., Castel, A. D., Dodd, M. D., & Pratt, J. (2003). Perceiving numbers causes spatial shifts of attention. *Nature Neuroscience, 6*, 555-556.

Fogassi, L., Gallese, V., Fadiga, L., Luppino, G., Matelli, M., & Rizzolatti, G. (1996). Coding of peripersonal space in inferior parietal cortex (area F4). *Journal of Neurophysiology, 76*, 141-157.

Frassinetti, F., Magnani, B., & Oliveri, M. (2009). Prismatic lenses shift time perception. *Psychological Science, 20,* 949-954.

Gamberini, L., Seraglia, B., & Priftis, K. (2008). Processing of peripersonal and extrapersonal space using tools: Evidence from visual line bisection in real and virtual environments. *Neuropsychologia, 46*, 1298-1304.

Göbel, S. M., Calabria, M., Farnè, A., & Rossetti, Y. (2006). Parietal rTMS distorts the mental number line: Simulating 'spatial' neglect in healthy subjects. Neuropsychologia, 44, 860-868.

Graziano, M. S. A., & Cooke, D. F. (2006). Parieto-frontal interactions, personal space, and defensive behavior. *Neuropsychologia, 44,* 845-859.

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews Neuroscience, 6*, 435-448.

Kelly, M. H., & Freyd, J. J. (1987). Explorations of representational momentum. *Cognitive Psychology, 19*, 369-401.

King, S. M., Dykeman, C., Redgrave, P., & Dean, P. (1992). Use of a distracting task to obtain defensive head movements to looming visual stimuli by human adults in a laboratory setting. *Perception, 21*, 245-259.

Loetscher, T., & Brugger, P. (2007). Exploring number space by random digit generation. *Experimental Brain Research, 180,* 655-665.

Loetscher, T., Schwarz, U., Schubiger, M., & Brugger, P. (2008). Head turns bias the brain's internal random generator. *Current Biology, 18*, R60-R62.

Loftus, A. M., Nicholls, M. E., Mattingley, J. B., & Bradshaw, J. L. (2008). Left to right:

Representational biases for numbers and the effect of visuomotor adaptation. *Cognition, 107*, 1048-1058.

Loftus, A. M., Nicholls, M. E., Mattingley, J. B., Chapman, H. L., & Bradshaw, J. L. (2009). Pseudoneglect for the bisection of mental number lines. *Quarterly Journal of Experimental Psychology*, *62*, 925-945.

Longo, M. R., & Lourenco, S. F. (2006). On the nature of near space: Effects of tool use and the transition to far space. *Neuropsychologia, 44*, 977-981.

Longo, M. R., & Lourenco, S. F. (2007a). Spatial attention and the mental number line: Evidence for characteristic biases and compression. *Neuropsychologia, 45*, 1400-1407.

Longo, M. R., & Lourenco, S. F. (2007b). Space perception and body morphology: Extent of near space scales with arm length. *Experimental Brain Research, 177*, 285-290.

Longo, M. R., & Lourenco, S. F. (2010). Bisecting the mental number line in near and far space. *Brain and Cognition*, *72*, 362-367.

Lourenco, S. F., & Longo, M. R. (2009a). The plasticity of near space: Evidence for contraction. *Cognition*, *112*, 451-456.

Lourenco, S. F., & Longo, M. R. (2009b). Multiple spatial representations of number: Evidence for co-existing compressive and linear scales. *Experimental Brain Research, 193*, 151-156.

Lourenco, S. F., & Longo, M. R. (2010). General magnitude representation in human infants. *Psychological Science*, *21*, 873-881.

Lourenco, S. F., Longo, M. R., & Pathman, T. (2011). Near space and its relation to claustrophobic fear. *Cognition, 119*, 448-453.

Nicholls, M. E. R., & McIlroy, A. M. (2010). Spatial cues affect mental number line bisections. *Experimental Psychology, 57*, 315-319.

Oliveri, M., Vicario, C. M., Salerno, S., Koch, G., Turriziani, P., Mangano, R., et al. (2008). Perceiving numbers alters time perception. *Neuroscience Letters, 438*, 308-311.

Ono, F., & Kitazawa, S. (2010). The effect of perceived motion-in-depth on time perception. *Cognition, 115*, 140-146.

Pia, L., Corazzini, L. L., Folegatti, A., Gindri, P., & Cauda, F. (2009). Mental number line disruption in a right-neglect patient after a left-hemisphere stroke. *Brain and Cognition, 69*, 81-88.

Priftis, K., Zorzi, M., Meneghello, F., Marenzi, R., & Umiltà, C. (2006). Explicit versus implicit processing of representational space in neglect: Dissociations in accessing the mental number line. *Journal of Cognitive Neuroscience, 18,* 680-688.

Renzi, C., Vecchi, T., Silvanto, J., & Cattaneo, Z. (2011). Overlapping representations of numerical magnitude and motion direction in the posterior parietal cortex: A TMS-adaptation study. *Neuroscience Letters, 490*, 145-149.

Rossetti, Y., Jacquin-Courtois, S., Rode, G., Ota, H., Michel, C., & Boisson, D. (2004). Does action make the link between number and space representation? Visuo-manual adaptation improves number bisection in unilateral neglect. *Psychological Science, 15*, 426-430.

Schiff, W., Caviness, J. A., & Gibson, J. J. (1962). Persistent fear responses in rhesus monkeys to the optical stimulus of “looming.” *Science, 136*, 982-983.

Stoianov, I., Kramer, P., Umiltà, C., & Zorzi, M., (2008). Visuospatial priming of the mental number line. *Cognition, 106*, 770-779.

Umiltà, C., Priftis, K., & Zorzi, M. (2009). The spatial representation of numbers: Evidence from neglect and pseudoneglect. *Experimental Brain Research, 192*, 561-569.

van Dijck, J. P., Gevers, W., Lafosse, C., Doricchi, F., Fias, W. (2011). Non-spatial neglect for the mental number line. *Neuropsychologia, 49*, 2570-2583.

Varnava, A., McCarthy, M., & Beaumont, J. G. (2002). Line bisection in normal adults: Direction of attentional bias for near and far space. *Neuropsychologia*, *40*, 1372-1378.

Xuan, B., Zhang, D., He, S., & Chen, X. (2007). Larger stimuli are judged to last longer. *Journal of Vision, 7*, 1–5.

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space, and quantity. *Trends in Cognitive Sciences, 7*, 483-488.

Zäch, P., & Brugger, P. (2008). Subjective time in near and far representational space. *Cognitive and Behavioral Neurology*, *21*, 8-13.

Zorzi, M., Priftis, K., & Umiltà, C. (2002). Neglects disrupts the mental number line. *Nature, 417*, 138-139.

Acknowledgements

This research was supported in part by a Research Grant from the School of Science, Birkbeck, University of London to Matthew R. Longo, and by a Scholars award from the John Merck Fund to Stella F. Lourenco.

Figure Captions

Figure 1: Timelines showing the sequence of events. On each trial, a fixation cross was followed by a pair of numbers. On ‘receding’ trials, the numbers halved in size after 200 ms, creating the impression that the numbers were moving away from the observer. On ‘approaching’ trials, the numbers doubled in size after 200 ms, creating the impression that the numbers were moving towards the observer. On ‘no movement’ trials, the font size was held constant. Note that the three trial types shown here involve the final size of the numbers being constant across conditions (i.e., medium size). There were additional conditions involving receding (medium to small) and approaching (medium to large) stimuli.

Figure 2: Numerical bisection bias as a function of stimulus motion. Clear ‘leftward’ biases to underestimate the true centre were found in all conditions, consistent with previous results. This bias was significantly increased when stimuli appeared to approach the observer. Error bars are standard errors.

Figure 1

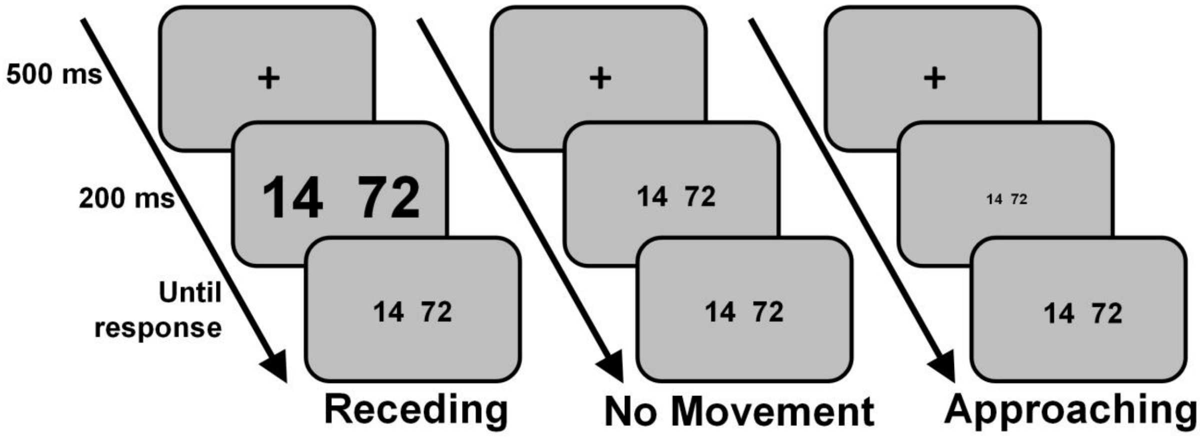
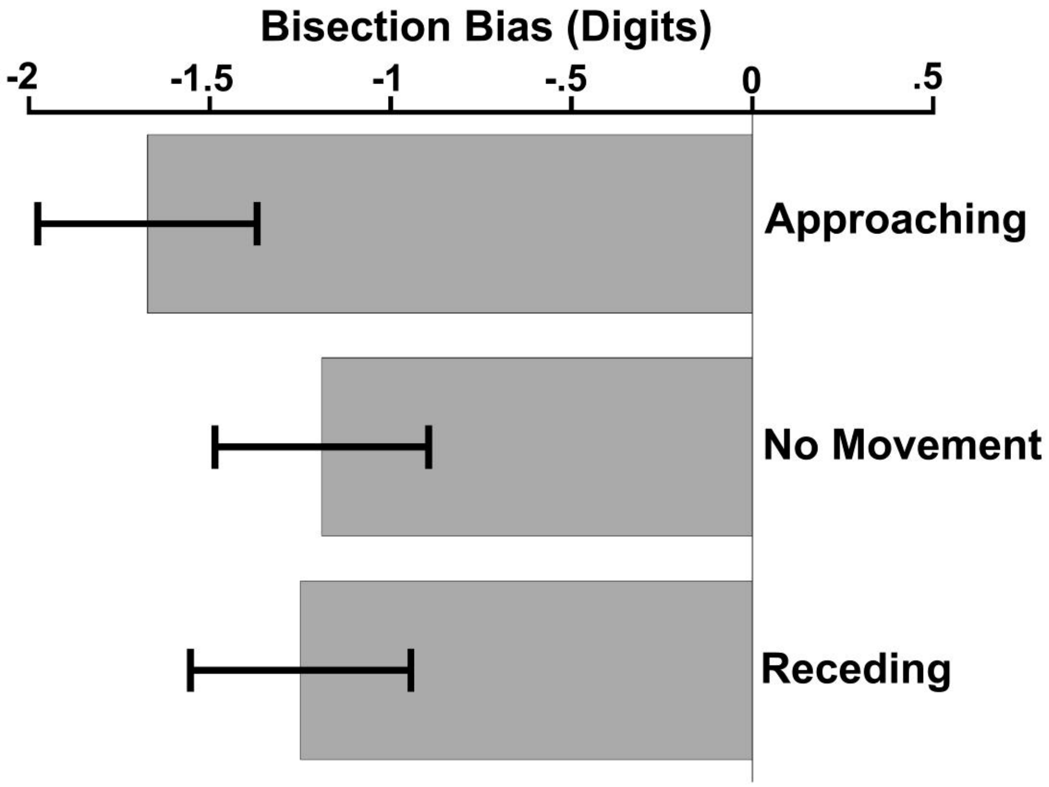

500 ms
200 ms
Until response
+
14 72
14 72
Receding
+
14 72
14 72
No Movement
+
14 72
14 72
Approaching

Figure 2


Bisection Bias (Digits)
-2
-1.5
-1
-.5
0
.5
Approaching
No Movement
Receding