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Orienting numbers in mental space: Horizontal organization trumps vertical

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While research on the spatial representation of number has provided substantial evidence for a horizontally oriented mental number line, recent studies suggest vertical organization as well. Directly comparing the relative strength of horizontal and vertical organization, however, we found no evidence of spontaneous vertical orientation (upward or downward), and horizontal trumped vertical when pitted against each other (Experiment 1). Only when numbers were conceptualized as magnitudes (as opposed to nonmagnitude ordinal sequences) did reliable vertical organization emerge, with upward orientation preferred (Experiment 2). Altogether, these findings suggest that horizontal representations predominate, and that vertical representations, when elicited, may be relatively inflexible. Implications for spatial organization beyond number, and its ontogenetic basis, are discussed.

Keywords: Number; Spatial organization; Mental number line; Spatial–numerical association of response codes (SNARC).

Much evidence suggests that mental representations of number are spatially organized, forming a mental number line (i.e., spatial-numerical association of response codes, or SNARC; for review, see Hubbard, Pinel, Piazza, & Dehaene, 2005). It has been claimed that the principal axis of organization is horizontal (Gertner, Henik, & Cohen Kadosh, 2009; Müller & Schwarz, 2007), with number increasing left to right (henceforth, rightward orientation) in Western cultures, mirroring various artefacts (e.g., rulers and measuring tapes). This proposal is difficult to evaluate, however, because evidence for vertical organization is open to alternative explanations. Here we provide a purer test of vertical organization to investigate whether one axis predominates in number representation.

The vertical axis is noteworthy because opposing forces might work against consistent organization. On the one hand, upright body position and gravity render vertical orientation inherently asymmetric, with the ground serving as a natural "zero" point from which magnitude increases upward (Clark, 1973). Linguistic metaphors (e.g., "prices *climb*" and "stocks *fall*") may also reinforce a

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conceptual mapping between greater magnitude and upward space. On the other hand, reading direction—a factor in horizontal organization (Shaki & Fischer, 2008)—is downward when, for example, scanning to the next row of text. There may also be downward attentional tendencies, given that the resting position of the eyes is lower than the true vertical midpoint (Collewijn, Erkelens, & Steinman, 1988).

Beyond general perceptual and attentional factors, specific numerical properties may also introduce competing influences. On cultural artefacts, both vertical directions—bottom-to-top and top-to-bottom—are widely depicted. Numbers increase upward on most calculators and computers with number keypads, but downward on most telephones and ordered lists, with orientation depending on whether symbols denote quantity (i.e., magnitude) or merely ordinal position. Numbers on calculators are essential for computations of magnitude. But on telephone keypads, there is no intrinsic magnitude; indeed, letters are ready replacements. Though not without exception, such symbolic conventions suggest that whether numbers are conceptualized as magnitudes may influence vertical organization.

Although extant findings suggest upward orientation when number is represented vertically, the property of magnitude may have inadvertently primed this orientation. Schwarz and Keus (2004) found that smaller numbers elicited faster downward saccades, and larger numbers elicited faster upward saccades. Similarly, Loetscher, Bockisch, Nicholls, and Brugger (2010) showed that downward and upward eye movements predicted smaller and larger number generation, respectively. Because upward saccades are slower, and potentially more effortful, than downward saccades (Collewijn et al., 1988), smaller and larger numbers may have mapped to less and more effortful actions, respectively. Other studies have used manual responses, but aligned on a tabletop (i.e., transverse plane) rather than with gravity. Ito and Hatta (2004) found that parity (odd/even) judgements were faster to smaller numbers on the "bottom" and larger numbers on the "top" (see also Gertner et al., 2009; Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006), but these locations are better characterized as near and far (i.e., proximo-distal). Although some have assumed that bottom/top and near/far locations are interchangeable with respect to spatial organization (Lidji, Kolinsky, Lochy, & Morais, 2007; Müller & Schwarz, 2007), the latter might encourage the mapping of number to another magnitude dimension (i.e., distance from the body), rather than to the vertical axis per se. Such "magnitude-on-magnitude" mappings may be more robust than organization along a spatial axis, as they are observed even in preverbal infants (Lourenco & Longo, 2010).

Given previous confounds, it remains unclear whether vertical organization occurs at all and, if so, whether it is as cognitively pervasive as its horizontal counterpart. To address these questions, we examined vertical organization in the absence of magnitude-related confounds, both in isolation and when pitted directly against horizontal organization (Experiment 1). To anticipate, our findings show that vertical organization is relatively weak, consistent with previous claims of horizontal dominance. We thus followed up by examining whether vertical organization depends on how numbers are conceptualized (Experiment 2).

EXPERIMENT 1: HORIZONTAL VERSUS VERTICAL ORGANIZATION

We tested horizontal and vertical orientations separately (Experiment 1A) and when pitted against each other (Experiment 1B). To avoid confounds with near/far distance, stimuli were presented to the frontal plane on a vertically mounted touchscreen (Keytec Magic Touch). In Experiment 1A, participants made parity judgements with left and right responses or top and bottom responses. In Experiment 1B, response locations were arranged diagonally such that horizontal and vertical orientations were either aligned or in conflict. Because diagonal locations combine horizontal and vertical axes (Schwarz & Keus, 2004), they may highlight the spatial nature of the task and hence may be especially likely to access spatial representations of number (as suggested for pitch; Lidji et al., 2007).

Method

Participants

Fifty-two undergraduates participated for course credit: 20 in Experiment 1A (15 female) and 32 in Experiment 1B (27 female). Most participants (47) were right-handed (Edinburgh Handedness Inventory, EHI: $M = 70.9$; range: −83.3 to 100; Oldfield, 1971), and all had normal or corrected-to-normal vision.

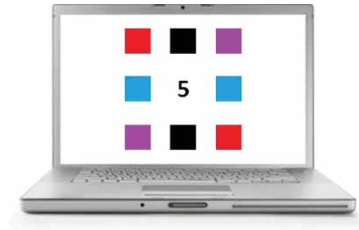

Figure 1. *Locations of response boxes in Experiment 1A and Experiment 2 (horizontal condition: blue; vertical condition: black), and in Experiment 1B (congruent condition: purple; incongruent condition: red). Each number (e.g., 5) appeared centrally. The figure is not to scale. Colours are merely for illustrative purposes. To view a colour version of this figure, please see the online issue of the Journal.*

Materials

Stimuli were black Arabic numerals (0–9), presented centrally on a white background (Calibri font, 3.3° × 2.4°) and surrounded by two boxes (each 11.8° × 11.0°). Boxes were separated 20° horizontally or vertically (Experiment 1A), or diagonally (Experiment 1B); see Figure 1.

Procedure

In Experiment 1A, participants completed horizontal and vertical conditions (within participants; order counterbalanced), each consisting of two blocks of trials. In one block, "even" and "odd" responses were assigned to left and right boxes, respectively (horizontal), or to top and bottom boxes, respectively (vertical). In the other block, these assignments were reversed (order counterbalanced). Each block consisted of 10 practice and 90 test trials (each number presented 9 times; random order). On each trial, a fixation cross was presented centrally for 500 ms, followed by a number, which remained on screen until participants responded manually.[1] Trials were separated by a 500-ms blank screen.

In Experiment 1B, participants completed congruent and incongruent conditions (within participants; order counterbalanced). For descriptive purposes, we assume rightward and upward orientations in these conditions. In the congruent condition, response boxes were located at the left/bottom and right/top of the screen, such that the two orientations were aligned (i.e., faster left/bottom responses to smaller numbers and faster right/top responses to larger numbers are consistent with both orientations, whereas the opposite mapping is inconsistent with both). In the incongruent condition, response boxes were at left/top and right/bottom locations, such that the two orientations were in conflict (i.e., faster left/top responses to smaller numbers and faster right/bottom responses to larger numbers is consistent with rightward orientation alone, whereas the opposite mapping is consistent with upward orientation alone). [Note that these descriptions reverse in the case of downward orientation; rightward and downward orientations are aligned in the incongruent condition, but in conflict in the congruent condition.][2] All other procedural aspects were identical to those in Experiment 1A.

Results and discussion

Test trials were trimmed for incorrect responses and reaction times (RTs) greater than 2.5 standard

[1] No explicit instructions were given concerning hand placement, but the vast majority of participants (polled immediately after the experiment) reported using two hands in both conditions.

[2] We do not consider leftward orientation in this description because there is no reason to expect that the participants in our experiments would represent number in this direction, given the wealth of prior research showing rightward orientation in Westerners (see Hubbard et al., 2005). Indeed, there was clear evidence of rightward orientation in all of the experiments reported here.

deviations from individual means (Experiment 1A: 8.3% of trials; Experiment 1B: 7.1%). Mean RT on remaining trials was 686 ms ($SD = 115$), with no differences across conditions in either experiment. For each participant, mean RTs were computed by response location (Experiment 1A: left, right, bottom, top; Experiment 1B: left/bottom, left/top, right/bottom, right/top), separately by number pair (cf. Dehaene, Bossini, & Giraux, 1993), and, following previous research (Fias, Brysbaert, Geypens, & d'Ydewalle, 1996), difference scores (dRT) were computed for each condition (horizontal = right − left; vertical = top − bottom; congruent: right/top − left/bottom; incongruent: right/bottom − left/top).

dRT values were regressed on number pairs, producing unstandardized slope coefficients. In Experiment 1A, slope differed from zero in the horizontal ($M = -10.55$ ms/digit, $SD = 10.81$), $t(19) = 4.36$, $p = .0003$, but not in the vertical ($M = 4.10$ ms/digit, $SD = 12.85$), $p > .1$, condition, indicating rightward orientation but no reliable upward or downward orientation (see Figure 2A). A 2 (condition) × 2 (condition order) analysis of variance (ANOVA) revealed no significant effects.

In Experiment 1B, the congruent condition yielded a negative slope ($M = -10.30$ ms/digit, $SD = 10.33$), $t(31) = 5.64$, $p < .0001$, consistent with both rightward and upward orientations (see Figure 2B). Slope in the incongruent condition did not differ significantly from zero. Importantly, however, a 2 × 2 ANOVA showed an interaction between condition and order, $F(1, 30) = 4.67$, $p = .04$, with follow-up analyses revealing an order effect only in the incongruent condition, $t(30) = 3.07$, $p = .005$. These results suggest that performance in the incongruent condition depended on whether it came first or second. Because the former provides a purer test of spontaneous spatial organization, uncontaminated by prior tasks, we focus on this context. When

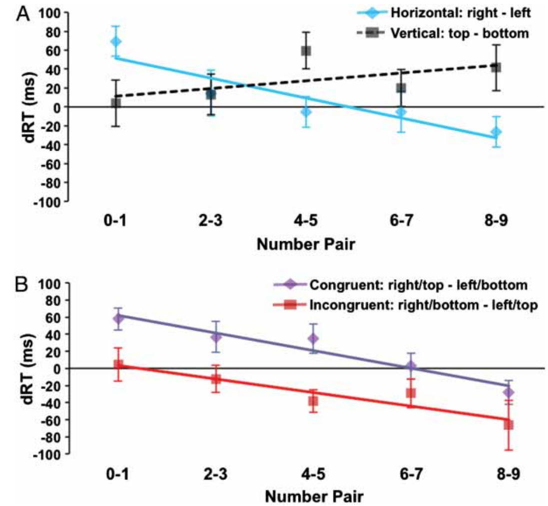

Figure 2. *Mean dRT (reaction time difference score) for number pairs in (A) Experiment 1A, and (B) Experiment 1B (incongruent task: when completed first). Negative dRT values indicate faster right (horizontal), top (vertical), right/top (congruent), and right/bottom (incongruent) responses in the respective conditions. Positive dRT values indicate faster left (horizontal), bottom (vertical), left/bottom (congruent), and left/top (incongruent) responses. Solid lines indicate statistically significant slopes; the dotted line is nonsignificant. Error bars are* ± SEM. *To view a colour version of this figure, please see the online issue of the Journal.*

completed first, the incongruent condition yielded a significant negative slope ($M = -7.94$ ms/digit, $SD = 13.73$), $t(15) = 2.31$, $p = .04$, consistent with rightward and downward orientations (see Figure 2B).[3] In contrast to reliable rightward orientation, upward versus downward orientation varied by condition, with rightward orientation trumping downward in the congruent condition and trumping upward in the incongruent condition, leaving no evidence for vertical organization (as in Experiment 1A when examined in isolation).

Although these findings suggest that the horizontal axis is relatively dominant, it remains possible that the two conditions were not fully equated. The

[3] When completed second, the incongruent condition yielded a marginally positive slope ($M = 5.60$ ms/digit), $t(15) = 2.03$, $p = .06$, unlike when completed first. This difference is difficult to interpret, perhaps reflecting a combination of carryover from the congruent condition and strategic switching of orientations in the incongruent condition following the change in response locations. Future research might consider how the underlying representation of number interacts with such task-related factors.

use of manual responses may have privileged horizontal organization over vertical, if such responses were additionally coded in terms of left and right hands (Müller & Schwarz, 2007). This explanation seems unlikely, however, given evidence that, at least for horizontal organization, orientation is based primarily on relative location in external space (e.g., Dehaene et al., 1993; Müller & Schwarz, 2007). Nevertheless, to address the possibility, we compared the variability of the slopes in the horizontal and vertical conditions in Experiment 1A. The rationale was that because the majority of participants responded bimanually, this would have produced more variability in vertical hand placement (i.e., for some participants, left hand on bottom and right hand on top; for others, the reverse positions) than in horizontal placement (i.e., for all participants, left hand on left and right hand on right). Standard deviations for the two slopes did not differ significantly, Pitman–Morgan $t(18) = 0.77$, $p > .4$, suggesting that hand-based coding was not solely responsible for the lack of spontaneous vertical organization. In the next study, we examined whether certain types of numerical representation might support vertical organization.

EXPERIMENT 2: PRIMING VERTICAL ORGANIZATION

Although Experiment 1 provided no evidence for spontaneous vertical organization, there may nevertheless be some propensity to organize number vertically, if, as suggested above, numbers are conceptualized along specific properties. In particular, conceptualizing numbers as magnitudes may elicit upward orientation absent under more neutral conditions. To investigate this possibility, we primed magnitude and nonmagnitude conceptualizations of number. Participants were told to think of numbers as floors in a building (e.g., 1st floor, 2nd floor, etc.), items on a shopping list (e.g., 1st item, 2nd item, etc.), or levels of depth in a swimming pool (e.g., 1 ft. from surface, 2 ft. from surface, etc.). We predicted that the building prime would trigger reliable vertical (upward) orientation, since buildings are associated with upward elevation. Less clear was what effect priming would have in the other conditions. The shopping prime might produce no consistent vertical orientation, since a list invokes no inherent sense of magnitude, or, if anything, downward orientation given symbolic conventions for depicting ordinality (see above). The swimming prime might similarly produce no consistent vertical orientation, but because of competing factors: While numbers denoting depth convey magnitude, the elevation is downward, not upward (i.e., numbers on the sides of pools typically increase downward, an exception to the conventional upward symbolic depiction of magnitude).

Method

Participants

Seventy-four undergraduates (51 female) participated for course credit. Most participants (69) were right-handed (EHI: $M = 68.2$; range: –100 to 100), and all had normal or corrected-to-normal vision.

Materials and procedure

Participants were exposed to one of three primes (building: $N = 16$; shopping: $N = 16$; swimming: $N = 42$), which differed only in how numbers were described (see above). Instructions included no explicit description of the spatial layout of numbers. As in Experiment 1A, participants completed both horizontal and vertical conditions (order counterbalanced). Each condition included numbers 1–8 (0 not included because not meaningful for all primes). There were eight practice and 80 test trials in each block of the two conditions (each number presented 10 times; random order). All other procedural aspects were identical to those in Experiment 1A.

Results and discussion

Using Experiment 1 criteria, 7.5%, 8.3%, and 8.9% of trials were excluded, and mean RT on remaining trials was 755 ms ($SD = 108$), 699 ms ($SD = 126$), and 692 ms ($SD = 112$) for building, shopping, and swimming primes, respectively, with no differences

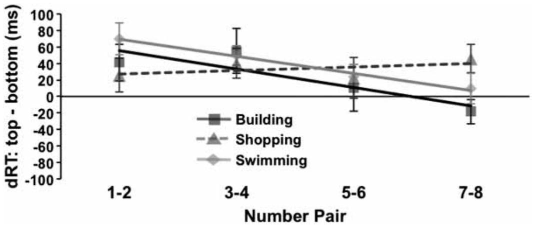

Figure 3. *Mean dRT (reaction time difference score) for number pairs in Experiment 2 (vertical condition) for building, shopping, and swimming (when completed first) primes. Negative dRT values indicate faster top responses, and positive dRT values indicate faster bottom responses. Solid lines indicate statistically significant slopes; the dotted line is nonsignificant. Error bars are* ±SEM.

across primes or conditions. dRT values were calculated by participant and were regressed on number pairs to produce slope coefficients. Slope data were analysed separately by prime.

For the building prime, slope differed from zero in both horizontal ($M = -11.61$ ms/digit, $SD = 19.06$), $t(15) = 2.44$, $p = .03$, and vertical ($M = -11.16$ ms/digit, $SD = 12.10$), $t(15) = 3.69$, $p = .002$ (see Figure 3), conditions, indicating rightward and upward orientations. For the shopping prime, slope was marginally significant in the horizontal condition ($M = -9.54$ ms/digit, $SD = 18.89$), $t(15) = 2.02$, $p = .06$, but did not differ from zero in the vertical condition ($M = 2.13$ ms/digit; $SD = 17.80$), $p > .6$ (see Figure 3), suggesting rightward orientation but no reliable vertical orientation. ANOVAs yielded no order effects or interactions for either prime.

For the swimming prime, slope differed from zero in the horizontal condition ($M = -6.95$ ms/digit, $SD = 16.76$), $t(41) = 2.69$, $p = .01$, indicating rightward orientation, but not in the vertical condition. However, an ANOVA revealed a significant order effect, $F(1, 40) = 6.28$, $p = .02$. Although the interaction between condition and order did not reach significance, the order effect was reliable only in the vertical condition, $t(40) = 2.52$, $p = .02$, suggesting that performance in the vertical condition depended on whether it came first or second. As in Experiment 1, we focus on the former as a purer test of spatial organization. When completed first, the vertical condition yielded a negative slope ($M = -10.37$ ms/digit, $SD = 22.27$), $t(20) = 2.13$, $p = .05$ (see Figure 3), indicating upward orientation.[4]

Additional analyses comparing slopes across primes yielded no significant differences in the horizontal condition; all three elicited rightward orientation. In the vertical condition, slope for the shopping prime differed significantly from that for the building prime, $t(30) = 2.47$, $p = .02$, and marginally from that for the swimming prime (when completed first), $t(35) = 1.84$, $p = .07$, but slopes for the building and swimming primes did not differ. These analyses are consistent with stronger vertical organization when magnitude was primed than when not, with upward orientation elicited in such contexts.

This study reveals that numbers can be organized along the vertical axis, but perhaps only when conceptualized as magnitudes. Particularly noteworthy is that priming magnitude elicited upward orientation even when a downward symbolic instantiation of number (i.e., depth) was invoked, suggesting that when number is represented vertically, upward orientation is preferred. Although no vertical organization was evident in the absence of magnitude priming, consistent downward orientation might be observed under conditions in which ordinal properties are rendered more salient (cf. Gevers, Reynvoet, & Fias, 2003).

GENERAL DISCUSSION

The present research is novel in three ways. First, we assessed organization of number along the true vertical axis, unlike previous studies in which near/far distance has been used as a proxy for vertical (e.g., Ito & Hatta, 2004). The lack of spontaneous vertical organization observed here

[4] When the vertical condition was completed second, the slope did not differ significantly from zero. It is possible that by the second half of the experiment, participants had disregarded the priming instructions (since they were irrelevant to judging parity). The attenuation of vertical orientation in this context is consistent with relatively weak vertical organization of number.

suggests that the two (i.e., vertical vs. near/far) may reflect fundamentally different phenomena. Second, we compared horizontal and vertical organization directly by pitting the two against each other, showing that horizontal trumps vertical under such conditions. Finally, we primed various vertical depictions of number to shed light on the numerical properties driving spatial organization. Priming produced clear vertical effects when numbers were conceptualized as magnitudes, with upward orientation elicited regardless of the primed symbolic instantiation. Our findings suggest a mental number line that is horizontal by default, but that may recruit the vertical axis when magnitude is a salient component of the representation.

Whereas perceptual, attentional, and symbolic factors converge on rightward direction along the horizontal axis, these factors are in opposition along the vertical. That upward orientation was preferred suggests that certain factors may carry more weight than others. The perceptual asymmetry of the vertical axis (Clark, 1973), though insufficient to support spontaneous vertical organization, may establish a propensity for upward orientation, such that number is invariably oriented upward when magnitude is highlighted. Indeed, vertical organization, when elicited, may be more inflexible than horizontal, which can reverse when leftward orientation is primed (Bächtold, Baumüller, & Brugger, 1998). Nonetheless, our findings suggest that spontaneous vertical organization may be rare, except perhaps in synaesthetes with vivid visuospatial representations of number (cf. Gertner et al., 2009).

Beyond number, there is evidence that other dimensions of experience, including duration (Vicario et al., 2008) and even emotional expression (e.g., more/less happy; Holmes & Lourenco, 2011), are represented spatially. Such dimensions, however, may differ from number with respect to which axis or orientation is dominant. Research on the representation of pitch suggests that vertical organization may be cognitively natural, even primary, for certain dimensions (Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006). Moreover, horizontal dominance, as observed for number, may not generalize. Although attentional factors (e.g., reading direction and orienting tendencies) might promote rightward orientation across dimensions, there is little, if any, cultural support for horizontal organization of dimensions such as duration or emotional expression. Future research might examine the precise contexts under which number and other dimensions are organized vertically, both in adults and over development. An intriguing possibility is that vertical organization, if driven by perceptual factors promoting the upward orientation of magnitude, may be earlier to develop than horizontal. At least for number, however, reading and symbolic depictions may contribute to the eventual dominance of horizontal organization. In showing that not all axes hold equal sway in representing number, our findings set the stage for exploring how different forms of magnitude come to be spatially organized in the mind.

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