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Horizontal Trumps Vertical in the Spatial Organization of Numerical Magnitude

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Abstract

The vast majority of research on the spatial nature of numerical representation has focused on the horizontal axis, highlighting the left-to-right orientation of increasing values (i.e., the *mental number line*). Recent evidence points to spatial organization along the vertical (bottom-to-top) axis as well. We argue, however, that these findings are better characterized as generalized magnitude mappings between number and other magnitude dimensions (e.g., near-far spatial extent), rather than genuine vertical orientation. Here we replicate generalized magnitude mappings for number (Exp. 1A) and show that they take precedence over left-to-right orientation (Exp. 1B), likely because of the direct mapping between dimensions. In contrast, we find no evidence of spontaneous organization along the true vertical axis (Exp. 2A), and left-to-right orientation trumped bottom-to-top orientation when the two were inconsistent with each other (Exp. 2B). Reliable bottom-to-top orientation was evident only after priming of magnitude relations among numbers (Exp. 3). Together, these findings demonstrate that number is more strongly represented horizontally than vertically. We suggest that experience with cultural tools may drive this asymmetry, and we highlight other cognitive and environmental factors that may influence the mental organization of magnitude dimensions beyond number.

Keywords: number; spatial organization; SNARC effect; mental magnitude line.

Introduction

Across a wide range of common cultural tools and artifacts, numbers are spatially organized. Many of these external symbolic representations depict numbers horizontally (e.g., rulers, measuring tapes), but some do so vertically (e.g., mercury thermometers, measuring cups). Despite this variation in spatial forms, the vast majority of research on the mental association between number and space has focused almost exclusively on the horizontal axis. Many such studies have suggested that numerical representations take the form of a *mental number line,* running from left to right in representational space (at least in Western cultures; for reviews, see Fias & Fischer, 2005; Hubbard et al., 2005), without examining other spatial axes on which number might also be mentally organized.

Recent findings suggest, however, that the vertical axis (specifically, bottom-to-top orientation) may also be recruited in the mental organization of number. In a parity judgment task, with response buttons arranged vertically on a tabletop, Ito and Hatta (2004) found that as numerical magnitude increased, “top” responses became faster relative to “bottom” responses (see also Gevers et al., 2006; Müller & Schwarz, 2007). Using saccadic latency as a dependent measure, Schwarz and Keus (2004) found that larger numbers elicited faster upward (relative to downward) saccades, and Loetscher et al. (2010) showed that vertical (not just horizontal) changes in participants’ eye position were predictive of the magnitude of numbers they subsequently generated.

While such findings have been regarded as evidence for vertical orientation of number, they are also compatible with the notion that number is but one component of a more general system of magnitude representation (Walsh, 2003). On this account, different dimensions of magnitude are spontaneously aligned, producing generalized mappings of more/less relations across dimensions (e.g., number, duration, size). As such mappings have been observed even in preverbal infants (Lourenco & Longo, 2010), they do not appear to require the same degree of cultural support as organization of number along spatial axes (e.g., left-to-right orientation), and hence may be especially robust. In the case of previous findings for vertical orientation, generalized magnitude mappings can fully account for the observed effects without invoking spatial axes, or a specific orientation, at all. That is, numerical magnitude may have been mapped to another magnitude dimension rather than to the vertical axis per se. In studies using tabletop responses, number may have been mapped to distance, given that response buttons were not arranged along the true vertical bottom-top axis (i.e., sagittal plane). Instead, they differed in relative spatial extent from the body (i.e., transverse plane; see Fig. 1); the “top” and “bottom” responses in these studies may be better characterized as “far” and “near” responses, respectively. Thus, larger numerical values may have been associated with greater distance, rather than upward locations in space.

Generalized magnitude mappings may also underlie the effects observed with saccadic measures. In these studies, number may be associated with effort, since upward and downward saccades may be considered more and less effortful, respectively. Vision research has shown that upward saccades are slower than downward saccades, and the resting position of the eyes is slightly lower than the actual vertical midpoint (Collewijn, Erkelens, & Steinman, 1988). Overall downward shifts in eye position have also been observed during number bisection tasks (Loetscher, Bockisch, & Brugger, 2008), suggesting that upward saccades may require greater effort, particularly during number processing. Thus, in studies using saccadic measures to examine vertical orientation, larger numerical values may have been associated with more effortful bodily actions (as has been shown for grasping; e.g., Lindemann et al., 2007).

Given that the vertical axis has been confounded with other magnitude dimensions in previous studies, whether number is represented vertically at all remains an open question. One reason to suspect that vertical orientation (if any) might be relatively weak is that vertical depictions of number on common cultural tools are often at odds with each other. For example, calculators display numbers in bottom-to-top orientation (i.e., smaller numbers on the bottom, larger numbers on the top), whereas telephone keypads display numbers in top-to-bottom orientation. These opposing orders may reflect a distinction between magnitude (i.e., more/less) and non-magnitude (e.g., ordinal position) properties of number. That is, the numbers on calculators are used in computations of magnitude, while the numbers on telephone keypads are merely ordinal. Importantly, calculators and telephone keypads are consistent with respect to the horizontal axis; on both, increasing values are displayed from left to right. Indeed, in Western cultures, left-to-right orientation is ubiquitous; there may be no common instantiation of number in which values increase from right to left.

For these reasons, we hypothesized that number might be more strongly represented horizontally than vertically. We examined this idea by comparing the relative strength of spatial organization along various axes, both separately (i.e., for horizontal or vertical alone) and when axes were at odds with each other (i.e., using response locations congruent with one axis and incongruent with another). First, to establish that generalized magnitude mappings are not interchangeable with the true vertical axis, we used tabletop keyboard responses to compare mappings of number to the horizontal axis (i.e., left-to-right orientation) and to near-far distance (i.e., generalized magnitude mapping), separately (Exp. 1A) and together (Exp. 1B). Second, we used responses on a vertically mounted touchscreen to tap true vertical, comparing horizontal and vertical orientation within (Exp. 2A) and across axes (Exp. 2B). Finally, we probed more directly the nature of vertical orientation by priming various vertical depictions of number and examining subsequent spatial organization along the vertical axis (Exp. 3).

Experiment 1: Horizontal vs. Near-Far

Method

Participants. A total of 42 Emory University undergraduates (22 in Exp. 1A; 20 in Exp. 1B) participated for course credit.

Materials. Stimuli were Arabic numerals (0-9), presented centrally on a computer screen in black font on a white background (Arial font, 6.5° × 5.5°).

Procedure. In Exp. 1A, participants completed Horizontal and Near-Far tasks (order counterbalanced). In both tasks, participants made parity (odd/even) judgments on each trial by pressing one of two keys on the numerical keypad of a computer keyboard (Horizontal: 4 and 6; Near-Far: 2 and 8; see Fig. 1). Keys were covered with opaque stickers. Each task consisted of two blocks of trials: one in which "even" responses were assigned to the left/near key and "odd" responses to the right/far key, and the other with the reverse assignment (order counterbalanced). Each block consisted of 10 practice trials and 90 test trials, with each number presented 9 times (random order). Each trial began with a fixation cross (presented centrally, 500 ms) and was followed by a number that remained onscreen until a response was made. Trials were separated by a blank screen (500 ms). Instructions emphasized both speed and accuracy.

Figure 1: Response keys in Exp. 1A (Horizontal task: blue; Near-Far task: red) and Exp. 1B (Congruent task: purple; Incongruent task: black). Colors in this figure are for illustrative purposes.

In Exp. 1B, each participant completed Congruent and Incongruent tasks (order counterbalanced). In the Congruent task, response keys were 1 (near-left) and 9 (far-right). Hence, left-to-right orientation and the number-distance mapping were congruent (e.g., faster responses to smaller numbers with the near-left key and larger numbers with the far-right key were consistent with both mappings). In the Incongruent task, response keys were 3 (near-right) and 7 (far-left). Hence, the two mappings were incongruent (e.g., faster responses to smaller numbers with the near-right key and larger numbers with the far-left key were consistent with the number-distance mapping, but not left-to-right orientation). All other procedural aspects were identical to Exp. 1A.

Results and Discussion

After excluding trials in which participants responded incorrectly (Exp. 1A: 3.1% of trials; Exp. 1B: 4.6%) and in which reaction times (RTs) were greater than 2.5 SD from individual means (Exp. 1A: 2.7%; Exp. 1B: 2.9%), mean RTs for each participant were computed for left, right, near, and far responses (Exp. 1A) and for near-left, far-right, far-left, and near-right responses (Exp. 1B) separately for each digit pair (0-1, 2-3, 4-5, 6-7, and 8-9). In Exp.1A, left responses were subtracted from right responses (Horizontal task) and near responses from far responses (Near-Far task) for a measure of RT differences (dRT), with negative dRT indicating faster right and faster far responses, respectively, for the two tasks. In Exp. 1B, near-left responses were subtracted from far-right responses (Congruent task) and far-left responses from near-right responses (Incongruent task); negative dRT indicated faster far-right and faster near-right responses, respectively, for the two tasks.

dRT values were regressed on digit magnitude to produce the unstandardized slope coefficient of the best-fitting linear regression (Fias & Fischer, 2005). The slope data were analyzed in separate 2 (task; within-subjects) × 2 (order of tasks; between-subjects) ANOVAs for Exp. 1A and 1B. The main effect of task was significant in Exp. 1B, $F(1,18) = 12.56$, $p = .002$, but not in Exp. 1A, $F(1,20) = .22$, $p = .65$.

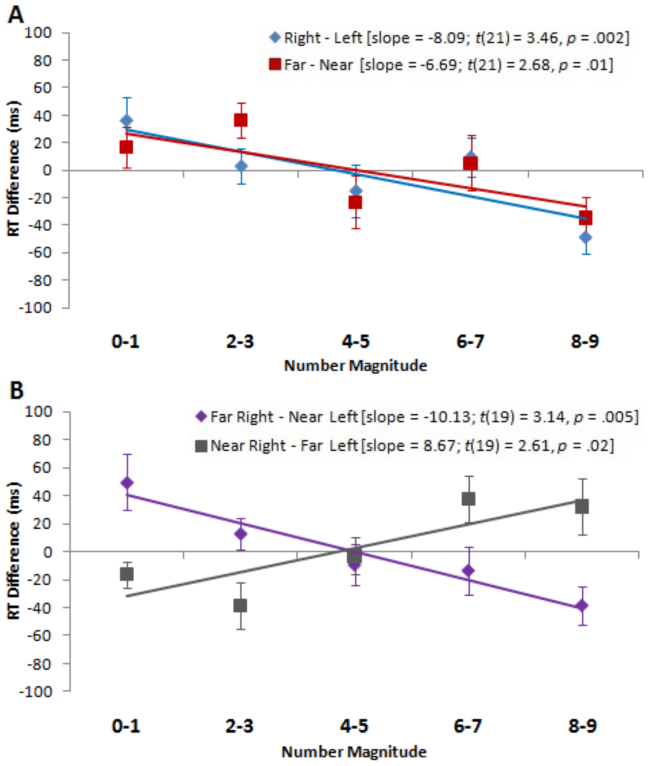

Figure 2: Mean dRT for number pairs in *(A)* Exp. 1A (Left-Right task: blue diamonds; Near-Far task: red squares) and *(B)* Exp. 1B (Congruent task: purple diamonds; Incongruent task: gray squares).

In Exp. 1A, negative slopes were observed in both the Horizontal and Near-Far tasks. As expected, both slopes differed significantly from zero (see Fig. 2A), indicating reliable left-to-right orientation and near-far mapping when tested separately. In Exp. 1B, the Congruent task yielded a significant negative slope (see Fig. 2B), consistent with both left-to-right orientation and near-far mapping. However, the Incongruent task yielded a significant positive slope, consistent with near-far mapping, but not left-to-right orientation (i.e., far responses became faster with increasing distance, despite also being on the left). No other main effects or interactions were significant (*p*s > .07).

The results of Exp. 1 replicate previous findings of left-to-right orientation and the generalized magnitude mapping of number to near-far distance. While Exp. 1A suggests that horizontal orientation and generalized magnitude mappings may both be recruited, Exp. 1B shows that when the two are at odds, the near-far mapping trumps left-to-right orientation. Why might this be? As suggested above, generalized magnitude mappings may be stronger than organization of number along spatial *axes*. Because near-far distance reflects differences in spatial *extent*, analogous differences in numerical magnitude can be readily mapped to this dimension, producing a direct, "magnitude-on-magnitude" mapping (similar to congruity between number and other spatial properties such as physical size; Henik & Tzelgov, 1982). Because previous research has mistakenly assumed that near-far distance is interchangeable with the vertical axis, the results of Exp. 1 leave open the question of whether number is in fact represented vertically, and, if so, whether vertical orientation is as strong as horizontal orientation. Exp. 2 was designed to address these questions.

Experiment 2: Horizontal vs. Vertical

Method

Participants. Fifty-two Emory University undergraduates **(**20 in Exp. 2A; 32 in Exp. 2B) participated for course credit.

Materials. Arabic numerals 0-9 were presented on a touch screen (Keytec Magic Touch, 4096 × 4096 resolution, USB-XD) attached to a 15-in. computer monitor.

Procedure. In Exp. 2A participants completed Horizontal and Vertical tasks (order counterbalanced). On each trial, a number (Calibri font, 3.3° × 2.4°) was presented centrally and surrounded by two boxes (each 11.8° × 11.0°), separated by 20°. Participants made parity judgments by pressing one of the two boxes. All other aspects of the procedure were identical to Exp. 1A.

In Exp. 2B, each participant completed Congruent and Incongruent tasks (order counterbalanced). In the Congruent task, response boxes were located at the bottom-left and top-right of the screen. Hence, horizontal (left-to-right) and vertical (in this case, bottom-to-top) orientations were congruent (e.g., faster bottom-left responses to smaller numbers and faster top-right responses to larger numbers were consistent with both orientations). In the Incongruent task, response boxes were located at the top-left and bottom-right of the screen. Hence, the two orientations were incongruent (e.g., faster bottom-right responses to smaller numbers and faster top-left responses to larger numbers were consistent with bottom-to-top, but not left-to-right, orientation). [Note: Although the labels for the two tasks in Exp. 2B assume bottom-to-top orientation, top-to-bottom orientation can also be assessed. From the perspective of top-to-bottom orientation, the Congruent task is incongruent; for example, faster bottom-left responses to smaller numbers and faster top-right responses to larger numbers were consistent with left-to-right, but not top-to-bottom, orientation).] In both tasks, the response boxes were separated by 130 mm (20° × 20°) diagonally. All other procedural aspects were identical to Exp. 2A.

Results and Discussion

Using Exp. 1 criteria, data were trimmed (Exp. 2A: 8.3% of trials excluded, with 5.2% incorrect; Exp. 2B: 7.1% excluded, 4.1% incorrect). dRT was calculated for each participant (Horizontal task: right minus left; Vertical task: top minus bottom; Congruent task: top-right minus bottom-left; Incongruent task: bottom-right minus top-left) and regressed on digit magnitude to produce slope coefficients.

As in Exp. 1, the slope data were analyzed in separate 2 (task) × 2 (order of tasks) ANOVAs for Exp. 2A and 2B. In Exp. 2A, there was a significant main effect of task, *F*(1,18) = 20.49, *p* = .0003. Slope differed significantly from zero in the Horizontal task, but not in the Vertical task (see Fig. 3A),

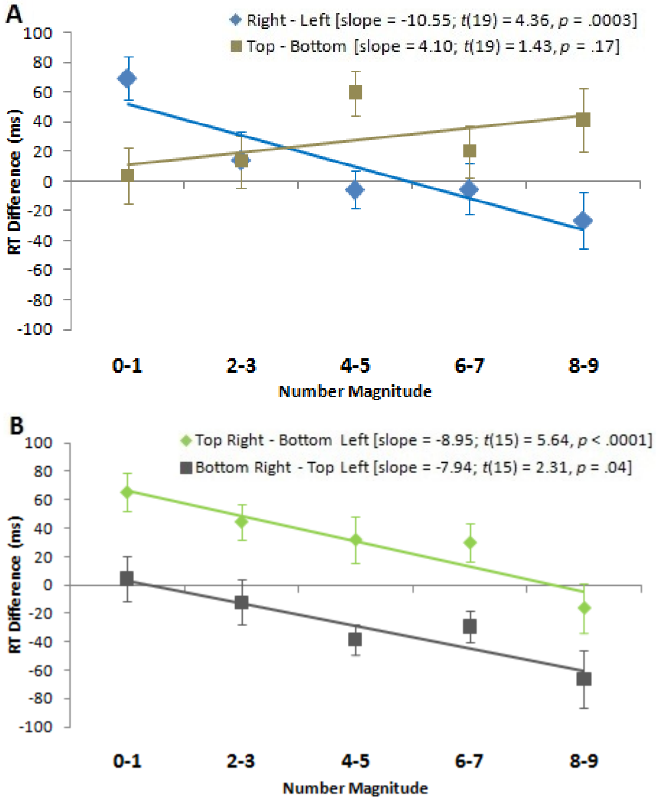

Figure 3: Mean dRT for number pairs in *(A)* Exp. 2A (Horizontal task: blue diamonds; Vertical task: yellow squares), and *(B)* Exp. 2B (first task completed only; Congruent task: green diamonds; Incongruent task: gray squares).

indicating reliable horizontal (left-to-right) orientation but no reliable vertical (bottom-to-top or top-to-bottom) orientation when tested separately. Neither the main effect of order, nor the interaction between task and order, was statistically significant (*ps* > .5).

In Exp. 2B, there were significant main effects of task, $F(1,30) = 13.29$, $p = .001$, and order, $F(1,30) = 6.48$, $p = .02$, and a significant interaction between the two, $F(1,30) = 4.67$, $p = .04$. When completed first, the Congruent task yielded a significant negative slope (see Fig. 3B), consistent with both left-to-right and bottom-to-top orientations. The Incongruent task also yielded a significant negative slope when completed first, suggesting that left-to-right orientation trumps bottom-to-top when the two are in opposition. As there was no significant difference between slopes in the two tasks, $t(30) = .26$, $p = .80$, the effect in the Congruent task was likely driven primarily, if not exclusively, by left-to-right orientation. [When each task was completed second, slope in the Congruent task was significantly negative, but slope in the Incongruent task was non-significantly positive.]

The results of Exp. 2A replicate previous research and Exp. 1A in showing reliable left-to-right orientation, but no reliable vertical orientation. The results of Exp. 2B suggest stronger horizontal than vertical orientation by showing that when the two are in opposition, horizontal trumps vertical. Why might number be only weakly represented along the vertical axis, if at all? One possibility is that conflicting depictions of number on cultural tools, perhaps reflecting dissociable magnitude and non-magnitude properties, pull vertical orientation in opposing directions, effectively canceling each other out. If so, priming a particular vertical depiction might induce its corresponding orientation (top-to-bottom or bottom-to-top), suggesting that number can, at least to some extent, be represented vertically. Although most top-to-bottom depictions of number convey ordinal position exclusively, some also convey magnitude (e.g., the numerical markers denoting levels of depth in a swimming pool). In Exp. 3, we primed different orientations with and without magnitude, comparing subsequent vertical orientation across the various priming conditions.

Experiment 3: Priming Vertical Orientations

Method

Participants. Seventy-four Emory University undergraduates participated for course credit.

Materials and Procedure. Each participant completed the Horizontal and Vertical tasks of Exp. 2A (order counterbalanced), making parity judgments to numbers on a touch screen. Participants were assigned to one of three priming conditions (Shopping, *N* = 16; Building, *N* = 16; Swimming, *N* = 42), differing only in how number was described in the instructions. In the Shopping condition, numbers were described as items on a shopping list (e.g., 1st item on the list, 2nd item, etc.), priming top-to-bottom (ordinal) orientation. In the Building condition, numbers were described as floors in a building (e.g., 1st floor, 2nd floor, etc.), priming bottom-to-top (magnitude; i.e., upward elevation) orientation. In the Swimming condition, numbers were described as levels of depth in a swimming pool (e.g., 1 ft. from the surface of the water, 2 ft. from surface, etc.), priming top-to-bottom (magnitude; i.e., downward elevation) orientation. The instructions included no vertical terms or any explicit description of the spatial layout of the numbers.

Unlike in the previous experiments, each task included only numbers 1 through 8 (because 0 is not meaningful in all conditions). The two blocks of each task consisted of 8 practice trials and 80 test trials each, with each number presented 10 times (random order). All other aspects of the procedure were identical to Exp. 2A.

Results and Discussion

Using Exp. 1 criteria, data were trimmed (8.5% of trials excluded, with 4.7% incorrect). dRT was calculated for each participant (right minus left in Horizontal task; top minus bottom in Vertical task) and regressed on digit magnitude to produce slope coefficients.

The slope data were analyzed in separate 2 (task) × 2 (order of tasks) ANOVAs for each condition. Fig. 4 displays results in the Vertical task across conditions. In the Shopping condition, there was a marginal main effect of task, $F(1,14) = 3.33$, $p = .09$, and no significant main effect of order or interaction (*ps* > .2). In the Horizontal task, slope differed significantly from zero (M = -9.54), $t(15) = 2.02$, $p = .03$ (one-tailed), but in the Vertical task, there was no hint of a difference, suggesting left-to-right orientation but no reliable vertical orientation when top-to-bottom (ordinal) orientation was primed. In the Building condition, there were no significant effects of task or order ($ps > .4$). In both Horizontal (M = -11.61), $t(15) = 2.44$, $p = .03$, and Vertical tasks, slope differed significantly from zero, indicating both left-to-right and bottom-to-top orientations when bottom-to-top (magnitude) orientation was primed. In the Swimming condition, there was a significant main effect of order, $F(1,40) = 6.28$, p = .02, but no significant main effect of task or interaction ($ps > .1$). When each task was completed first, slope differed significantly from zero in the Vertical task, but not in the Horizontal task (M = -4.52), $t(20) = 1.03$, $p = .32$, indicating reliable bottom-to-top orientation but no reliable horizontal orientation when top-to-bottom (magnitude) orientation was primed. [When each task was completed second, slope in the Vertical task was non-significantly positive, but slope in the Horizontal task was significantly negative.]

Despite the non-significant horizontal slope in the Swimming condition (when the Horizontal task was completed first), pairwise comparisons of slope in the Horizontal task across the three conditions yielded no significant differences ($ps > .2$). In contrast, pairwise comparisons of slope in the Vertical task showed that the Shopping condition differed significantly from the Building condition, $t(30) = 2.47$, $p = .02$, and marginally from the Swimming condition, $t(35) = 1.84$, $p = .07$, but no significant difference between Building and Swimming conditions, $t(35) = .13$, $p = .9$.

The results of Exp. 3 suggest that number can be represented vertically, but only when explicitly primed and only when priming invokes numerical magnitude (Building and Swimming conditions). Particularly remarkable is that magnitude priming induced bottom-to-top orientation even when a top-to-bottom instantiation of magnitude was invoked (Swimming condition). No vertical orientation was evident when priming suggested ordinality alone (Shopping condition). These findings suggest that numerical magnitude recruits bottom-to-top orientation, but that it is less robust than left-to-right orientation (at least in Western cultures).

General Discussion

An implicit assumption in research on the spatial organization of numerical magnitude has been that representations of number primarily, if not exclusively, recruit the horizontal axis. While recent evidence has pointed to spatial organization along the vertical axis, such effects may instead be examples of generalized magnitude mappings between number and other magnitude dimensions, such as near-far distance or effort. The present research demonstrates that near-far distance should not be mistaken for the true vertical axis (Exp. 1A and 1B), and that when the latter is examined without the confound of effort, horizontal orientation is stronger than vertical (Exp. 2A and 2B). Indeed, we observed reliable vertical (bottom-to-top) orientation only after explicit priming of numerical magnitude (Exp. 3). The results suggest that horizontal orientation may be psychologically privileged, as it is robustly evident without priming and sometimes even after priming designed to induce vertical orientation. Our findings indicate that the oft-invoked metaphor of the mental number line, implying a single linear representation rather than multiple potentially conflicting ones, is essentially apt, with the caveat that different ways of mentally organizing number are certainly possible despite not holding equal sway.

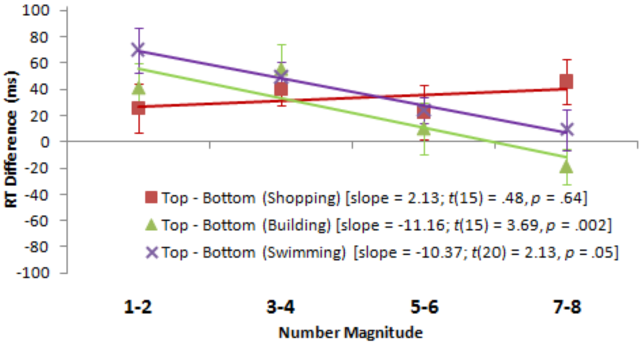

Figure 4: Mean dRT for number pairs on Vertical task in Exp. 3 across conditions (Swimming: first task completed only).

Indeed, although horizontal orientation may trump vertical, the finding that vertical (bottom-to-top) orientation can be primed suggests some propensity to represent number vertically. Evidence that hemispatial neglect patients can show selective impairments in horizontal, but not vertical, number bisection (Cappelletti, Freeman, & Cipolotti, 2007) suggests that horizontal and vertical representations of number may be functionally independent. Interestingly, orientation was manipulated in these patients via a priming technique similar to that of Exp. 3, perhaps accounting for some of the vertical effects.

The findings of Exp. 3 offer clues as to why vertical orientation may be relatively weak. Priming magnitude relations among numbers induced bottom-to-top orientation, but priming only ordinal position, though not enough to fully reverse this orientation, may have attenuated the bottom-to-top effect by pulling it in the other direction (i.e., top-to-bottom). As mentioned previously, these opposing effects may reflect competition between different properties of number (magnitude vs. non-magnitude) and the corresponding orientations in which they are commonly depicted on cultural tools and in the environment more generally (e.g., elevator buttons vs. call numbers on library shelves). Another possibility, suggested by the lack of a significant effect when ordinality alone was primed, is that no reliable top-to-bottom orientation exists, but that there may be other top-to-bottom influences such as reading direction. Although reading direction in Western cultures is predominantly left-to-right, there is also a top-to-bottom component (i.e., shifting to the next row of text). As horizontal reading direction has been shown to influence spatial organization of number (Shaki & Fischer, 2008), it is possible that vertical reading direction may have a similar effect, serving to undermine bottom-to-top orientation of numerical magnitude (while left-to-right reading direction in turn bolsters left-to-right orientation). Yet another possibility is that left-to-right depictions of number are simply more prevalent than bottom-to-top depictions in everyday experience. Such possibilities are not mutually exclusive, however, and, indeed, may even work in combination to render the horizontal axis more dominant.

Interestingly, despite the consistency with which numbers are depicted from left to right in Western cultures, the horizontal axis may in fact show greater flexibility than the vertical. Bächtold, Baumüller, and Brugger (1998) found that left-to-right orientation reversed in participants who were primed with an image of a clock-face (i.e., smaller numbers on the right, larger numbers on the left). In the present study, priming a top-to-bottom depiction of numerical magnitude (i.e., levels of depth in a swimming pool) induced bottom-to-top orientation of comparable strength to that induced by priming of bottom-to-top magnitude, suggesting striking inflexibility. These differences in flexibility may arise from the inherent perceptual asymmetry of the vertical axis, with gravitational forces perhaps establishing the ground as a natural zero point (Clark, 1973), and from exposure to metaphors in language that reinforce mappings of greater magnitude to higher space (e.g., prices “climb” and stocks “fall”; Lakoff & Johnson, 1980).

Importantly, number is but one of countless dimensions of magnitude, all of which may potentially be represented spatially (i.e., a mental *magnitude* line; Holmes & Lourenco, 2011). Which axes and orientations are recruited is likely to differ, however, across dimensions. On the one hand, our findings might not be expected to extend to other magnitude dimensions (e.g., spatial extent) for which the horizontal axis is more agnostic than the vertical with respect to the direction of increasing magnitude (e.g., trees and buildings extend upward rather than downward, but snakes and trains can extend leftward or rightward). On the other hand, there is evidence that other dimensions (e.g., emotional expression; Holmes & Lourenco, 2011) may co-opt left-to-right orientation of number, showing a clear resemblance in their spatial organization. Comparisons of the relative strength of horizontal and vertical orientation across multiple dimensions and points in development will be particularly informative for unpacking the relative contributions of cultural tools, perceptual factors, reading direction, and co-opting of structure to the spatial organization of different forms of magnitude.

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