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How Numbers Bias Preschoolers' Spatial Search

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Abstract

Numbers often bias adults' spatial performance. Because the direction of this bias (left-to-right versus right-to-left) is culture-specific, it has been assumed that spatial-numeric associations develop with reading practice or schooling. The authors tested this assumption by examining spatial-numeric associations in pre-reading preschoolers. Preschoolers were shown two boxes (sample and matching boxes) subdivided into seven verbally numbered "rooms" (e.g., "the four room"). A "winner" card was revealed in the sample box, and children searched for the "winner" in the matching box (located in the same-numbered room). Preschoolers were faster and more accurate when rooms increased numerically from left-to-right versus right-to-left. This advantage was apparently caused by numbers influencing preschoolers' encoding of spatial locations: Ordering of numbers in the sample box affected preschoolers' search greatly, whereas ordering of numbers in the matching box did not. The authors conclude that numeric effects on spatial encoding develop far too early to be caused by reading practice or schooling.

Keywords

spatial numeric associations; number cognition; spatial biases

Spatial associations with abstract concepts appear to permeate our mental life, often in ways that seem to reflect our reading practices. When matching pictures to semantically identical sentences (e.g., "The girl kissed the boy" versus "The boy was kissed by the girl"), for example, English- and Italian-speaking adults—who practice reading from left-to-right—choose pictures where the thematic subject is depicted on the left and the thematic object on the right (Chatterjee, Southwood, & Basilico, 1999; Maas & Russo, 2003), whereas Arabic-speaking adults—who practice reading from right-to-left—do the reverse (Maas & Russo, 2003). When thinking about time, English-speaking adults—who practice reading horizontally—conceptualize future events as occurring in a forward direction and past events in a backward direction (Boroditsky, 2000), whereas Mandarin-speaking adults—who practice reading vertically—conceptualize future events as occurring upward and past events as occurring downward (Boroditsky, 2001; but see Chen, 2007, and January & Kako, 2007). Furthermore, when confronted with Arabic numerals,

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English-speaking adults conceptualize numbers as increasing (logarithmically) from left-to-right (Dehaene, 2007; Hubbard, Piazza, Pinel, & Dehaene, 2005; Longo & Lourenco, 2007; Opfer & Siegler, 2007; Siegler & Opfer, 2003), whereas Arabic-speaking adults' "mental number line" runs from right-to-left (Shaki, Fischer, & Petrusic, 2009).

Finding effects of reading direction on spatial associations (such as the mental number line) is important theoretically because it offers a specific mechanism by which culture could influence thinking and because it also seems to disconfirm two alternative ideas about the relations among language, culture, and cognition. On the one hand, the findings challenge the nativist theory that spatial associations with abstract concepts originate in the innate design characteristics of the human brain, such as the left hemisphere deploying spatial attention to objects in events and sets with a vector from left-to-right (see, for example, Chatterjee, Maher, & Heilman, 1995; Geminiani, Bisiach, Berti, & Rusconi, 1995; Landau, 1996). On the other hand, the findings challenge the perceptual learning theory that directional biases originate in the affordances presented by the non-orthographic environment, such as the frequency of spatial relations and other environmental cues (see, for example, Li & Gleitman, 2002; Loewenstein & Gentner, 2005; Opfer, Thompson, & Furlong, 2010). Finally, if true, the theory that directionality in reading practices changes the way humans encode agency, time, and number would constitute a challenge to most theories of learning and cognitive development, which typically depict far transfer of learning—for example, from one situation (like reading) to another situation (like counting)—as relatively unlikely (Barnett & Ceci, 2002; Opfer & Thompson, 2008; Siegler, 2006; Singley & Anderson, 1989).

In this article, we addressed two broad questions with respect to the "mental number line": When do spatial-numeric associations develop, and what (if any) cultural experience gives rise to them? Regarding the origins of spatial-numeric associations, we wished to test three possibilities about spatial-numeric associations: (1) They emerge only after years of reading practice, a hypothesis suggested by the widespread correlations between writing direction and spatial biases (Boroditsky, 2001; Maas & Russo, 2003; Shaki et al., 2009); (2) they emerge as soon as children learn numeric symbols, a hypothesis consistent with findings of early and persisting parietal activations by numeric symbols and visual search (Ansari, Nicolas, Lucas, Hamon, & Dhital, 2005; Dehaene, Piazza, Pinel, & Cohen, 2003; Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Pinel, Dehaene, Riviere, & LeBihan, 2001; Pinel, Piazza, LeBihan, & Dehaene, 2004; Zorzi, Priftis, & Umilta, 2002); and (3) they emerge before any formal reading instruction, originating in preschoolers' visuo-motor experiences of exact quantification (e.g., counting, adding, and subtracting), a hypothesis suggested by evidence that visuo-motor training improves neglect patients' numerical bisection (Rosetti et al., 2004).

To test these hypotheses, we examined directional biases in how pre-reading preschoolers use numeric information on spatial tasks and whether individual differences in counting and arithmetic performance moderated these directional biases. In the next three sections, we briefly review the types of evidence indicating robust spatial-numeric associations in adults, the scant evidence for such associations in young children, and how we examined the early development of spatial-numeric associations.

Spatial-Numeric Associations in Adults

Behavioral evidence for adults' spatial-numeric associations comes from three types of evidence. The first type is provided by the effect the of numeric magnitude on participants' judgments of whether a number is odd or even (Berch, Foley, Hill, & Ryan, 1999; Dehaene, Bossini, & Giraux, 1993). Although knowledge of numeric magnitude is unnecessary to solve the task, if knowledge of parity is stored in semantic memory with the mental number line, Dehaene et al.

(1993) reasoned, representation of numerals on a mental number line might intrude on task performance. Specifically, they found that when participants were asked whether large numbers (e.g., 8 or 9) were even, they responded most quickly with their right hand, whereas when they were asked about small numbers (e.g., 1 or 2), they responded most quickly with their left hand. Interestingly, the direction of this effect—the "Spatial-Numerical Association of Response Codes (SNARC) effect"—was not affected by handedness or hemispheric dominance but rather by the direction of writing in the culture of the participants. Specifically, when Iranian participants—who write right- to-left—were tested, the direction of the association was reversed (Dehaene et al., 1993), supporting the idea that the semantic representation of number is associated with a mental number line oriented left-to-right in societies that write left-to-right.

A second type of evidence for spatial-numeric association is provided by the effect of numerical magnitude on line bisection tasks. Although adults are approximately accurate when locating the middle of a string of x's, their estimates are systematically biased to the left when finding the middle of a small magnitude string (i.e., deuxdeuxdeux) and to the right when finding the middle of a large magnitude string (i.e., neufneufneuf) (Callabria & Rossetti, 2005; Fischer, 2001). Furthermore, adults' speed at detecting a target is influenced by the magnitude of an irrelevant Arabic number preceding it (Fischer, Castel, Dodd, & Pratt, 2003). When the target was preceded by a small number (e.g., 1 or 2), participants were quicker to detect it in the left visual field than the right visual field; in contrast, when the target was preceded by a large number (e.g., 8 or 9), participants were quicker to detect it in the right visual field than the left visual field. The importance of this finding is underscored by the fact that the numerical digit was completely non-informative about the actual location of the target.

Neurological evidence also supports the idea that the mental machinery of spatial representation aids adults' representation of semantic number. Specifically, neural circuitry crucial for numerical representations lies in regions substantially overlapping neural circuitry serving spatial representations (Fias et al., 2003; Pinel et al., 2001; Pinel et al., 2004; Zorzi et al., 2002). For example, the posterior superior parietal lobule (PSPL) is activated by both spatial tasks, such as pointing and visuo-spatial attention, and numeric tasks, such as approximate addition and subtraction and magnitude estimation (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Lee, 2000; Piazza, Mechelli, Butterworth, & Price, 2002; Simon, Cohen, Mangin, Bihan, & Dehaene, 2002). Moreover, repetitive transcranial magnetic stimulation resulting in a "virtual lesion" at a site in the left angular gyrus compromises both visual search and speed of numeric comparisons (e.g., judge 5 as being greater than 1), suggesting that the representation of numerical magnitudes depends on circuitry for spatial coding (Göbel, Walsh, & Rushworth, 2001).

Development of Spatial-Numeric Associations

Although evidence for spatial-numeric associations in adults has been drawn from a wide array of phenomena (the SNARC effect, the line bisection effect, and the attention bias effect), it is unclear when these effects emerge ontogenetically and when they show a conventional directionality (e.g., associating large numbers with right versus the left).

One possibility is that spatial-numeric associations are automatic but "progressively shaped by cultural conventions, such as the orientation of writing or the conventional orientation of mathematical graph axes" (Hubbard et al., 2005, p. 437). In support of this view, the SNARC effect is reversed in adult Iranian and Palestinian participants who read from right-to-left (Dehaene et al., 1993; Shaki et al., 2009) and has not been observed in preschool children, failing to emerge until age nine (Berch et al., 1999). Furthermore, adult spatial-numeric neural networks may not exist to the same extent in young children, as developmental changes may result in children and adults processing the same information in different brain regions (Ansari & Dhital, 2006; Ansari et al., 2005; Cantlon, Brannon, Carter, & Pelphrey, 2006; Johnson, 2005; Karmiloff-Smith, 1998).

Against this hypothesis, preliminary evidence suggests that even preschool children, who have not yet begun learning to read, may have already developed spatial numeric associations (Opfer et al., 2010). Specifically, children were shown two boxes (the sample box and the matching box) with seven compartments ("rooms") verbally labeled with numbers increasing either from left-to-right (i.e., 1, 2, 3, 4, 5, 6, 7) or from right-to-left (i.e., 7, 6, 5, 4, 3, 2, 1). The experimenter showed the child where a hidden object could be found in the sample box (i.e., the Number 3 room) and asked the child to search for the object in the same numeric location in the matching box (i.e., the Number 3 room). When numeric values increased from left-to-right, children were faster and more accurate at finding the hidden object than when numeric values increased from right-to-left.

What remains to be seen, however, is *how* numbers affected children's searches in the spatial search task. Namely, did numbers affect children's search by biasing their *encoding* of the spatial location (i.e., the left-to-right vs. right-to-left ordering of the sample box) or during *performance* (i.e., the left-to-right vs. right-to-left ordering of the matching box)? We will explore these questions in the present studies.

The Present Studies

To examine early development of spatial-numeric associations, we first attempted to replicate Opfer et al. (2010) to address both whether preschoolers associate numbers with spatial locations and, if so, whether directionality (left-to-right vs. right-to-left ordering of spatial locations) affects this ability. Next, we explored *how* directionality affected search strategies by examining whether these spatial biases arose as a result of spatial biases in *encoding* (i.e., children expected the sample box to increase from left-to-right) or whether they result from spatial biases in *performance* (i.e., children automatically count from left-to-right in the matching box).

Method

Participants

Participants included 84 English-speaking 4-year-olds (LR/LR condition: $n = 21$, 11 females, ages 4.01 to 4.99, mean age = 4.54; LR/RL condition: $n = 21$, 7 females, ages 4.03 to 4.86, mean age = 4.46; RL/LR condition: $n = 21$, 11 females, ages 4.02 to 4.98, mean age = 4.50; RL/RL condition: $n = 21$, 8 females, ages 4.01 to 4.99, mean age = 4.45). All participated in a drawing task to assess handedness; 89% of children were right-handed and 11% were left-handed. Handedness had no effect on performance.

Tasks and Stimuli

Children participated in two tasks: a spatial search task and a quantification task. In the *spatial search task*, children were shown two boxes (63.5 × 11.4 × 19.1 cm) with seven compartments each (8.9 × 11.4 × 19.1 cm). These compartments each contained cards with pictures of familiar objects (balloons, keys, ball, shoe, flower, bike, ice cream) with the constraint that the order of pictures did not follow the order in which the rooms were numbered. To familiarize children with the task, the experimenter pointed to and verbally labeled (i.e., "this is the Number 1 room," "this is the Number 2 room," etc.) each compartment in an increasing order, either from left-to-right or right-to-left (Figure 1). Children then pointed to and numerically labeled the

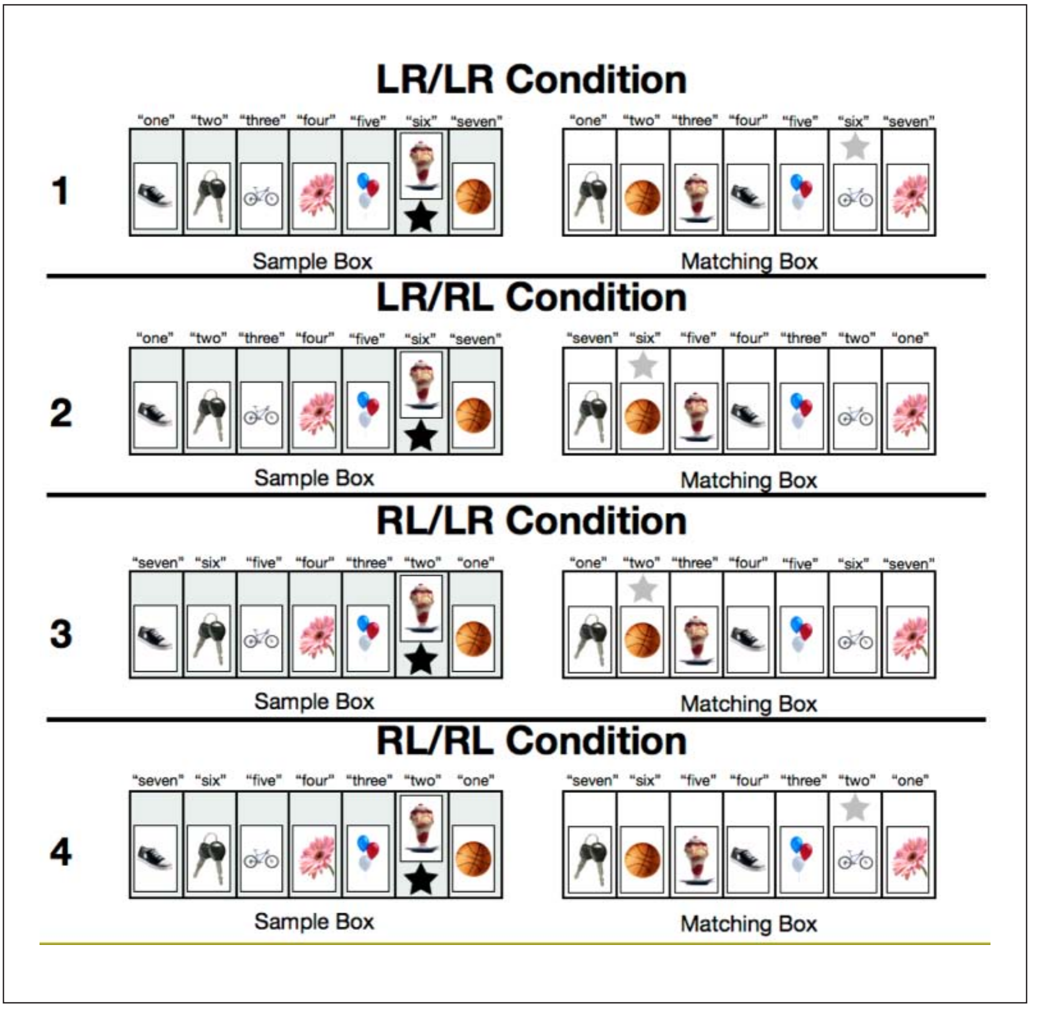

Figure 1. An Illustration of the Spatial Search Task
Note: In the LR/LR condition, compartments in the sample and matching boxes were verbally labeled in an increasing order from left-to-right. In the LR/RL condition, numeric labels of compartments in the sample box increased from left-to-right, but in the matching box, they increased from right-to-left. Similarly, in the RL/LR condition numeric labels of compartments in the sample box increased from right-to-left, while in the matching box they increased from left-to-right. In the RL/RL condition, numeric labels of compartments in both the sample and matching boxes increased from right-to-left.

compartments until they did so in the same order as the experimenter. (Of the 84 participants, 78 children successfully ordered compartments on their first attempt; the remaining 6 children required a second attempt. These 6 children were distributed among all four conditions, and therefore, any errors in initially encoding directionality in sample and matching boxes could not account for condition differences in search strategies.)

The experimenter then showed the child an object (a star) hidden under a picture in one of the compartments of the sample box and asked the child to find another object in the same numbered room in the matching box. Children were first given an example: "If the winner [hidden object] was in the Number 1 room [with a picture of balloons] in the hiding box [sample box], it will be in the Number 1 room [with a picture of a bike] in the finding box [matching box]." The experimenter checked to ensure the child understood by asking, "If the winner was in the Number 2 room [with a picture of keys] in the hiding box [sample box], what room do you think it will be in the finding box [matching box]?" Testing began when children understood instructions (i.e., selected the Number 2 room with a picture of a flower), and a post-task comprehension check confirmed that children's understanding of the task remained strong over the course of the experiment. Each child participated in the searching task seven times, resulting in the object being found in each location exactly once. After completing all seven trials, the experimenter asked the child to re-label the numbers of the rooms in both the sample and matching boxes as a memory check.

In the *quantification task*, we tested whether children spontaneously counted, added, and subtracted in a left-to-right direction. Adults' addition and subtraction errors are often consistent with spatial movement on a mental number line (Knops, Viarouge, & Dehaene, 2009; McCrink, Dehaene, & Dehaene-Lambertz, 2007), and we hypothesized that this bias would affect the physical, spatial characteristics of adding and subtracting (i.e., adding left-to-right, subtracting right-to-left). To test this, children were first presented with three poker chips centered on the table in front of them, given one poker chip to his/her right hand, and asked to add a poker chip to create four. Next, children were asked to remove one of the poker chips to create three. Finally, they were presented with the cards used in the spatial search task and asked to identify the pictures and count them.

Design and Procedure

Children were tested individually in a single 15-minute session. Half completed the spatial search task followed by the quantification task, and half received the reverse order.

For the spatial search task, preschoolers were randomly assigned to one of four conditions: (1) *LR/LR*: numbers in the sample box were ordered left-to-right, and numbers in the matching box were ordered from left-to-right; (2) *LR/RL*: numbers in the sample box were ordered left-to-right, and numbers in the matching box were ordered from right-to-left; (3) *RL/LR*: numbers in the sample box were ordered right-to-left, and numbers in the matching box were ordered from left-to-right; or (4) *RL/RL*: numbers in the sample box were ordered right-to-left, and numbers in the matching box were ordered from right-to-left. This design allowed us to test the accuracy of spatial search given a left-to-right numbering scheme when presented in the sample box (1 and 2), the matching box (1 and 3), both (1), and neither (4).

The pictures hiding the "winner" appeared in the same order for all children, both in the sample box (balloons, keys, ball, shoe, flower, bike, ice cream) and the matching box (bike, flower, balloon, ice cream, keys, ball, shoe), with the constraint that the order of pictures did not follow the order in which the rooms were numbered. The order of presentation was also counterbalanced such that, on each trial, the object was equally likely to be hidden in each compartment. Solutions were timed from when the location of the hidden object was revealed in the sample box until the corresponding object was found in the matching box.

Results and Discussion

We observed that preschoolers used three main strategies (accounting for performance on 74% of all trials) to find the "winner": (1) *numeric matches*, in which children successfully made an accurate numeric match between the sample and matching box on their first trial (e.g., the "winner" was hidden in the Number 2 room of the sample box, and the child immediately searched in the Number 2 room of the matching box); (2) *perceptual matches*, in which children ignored the numeric match and simply searched for a perceptual match (e.g., the "winner" was hidden

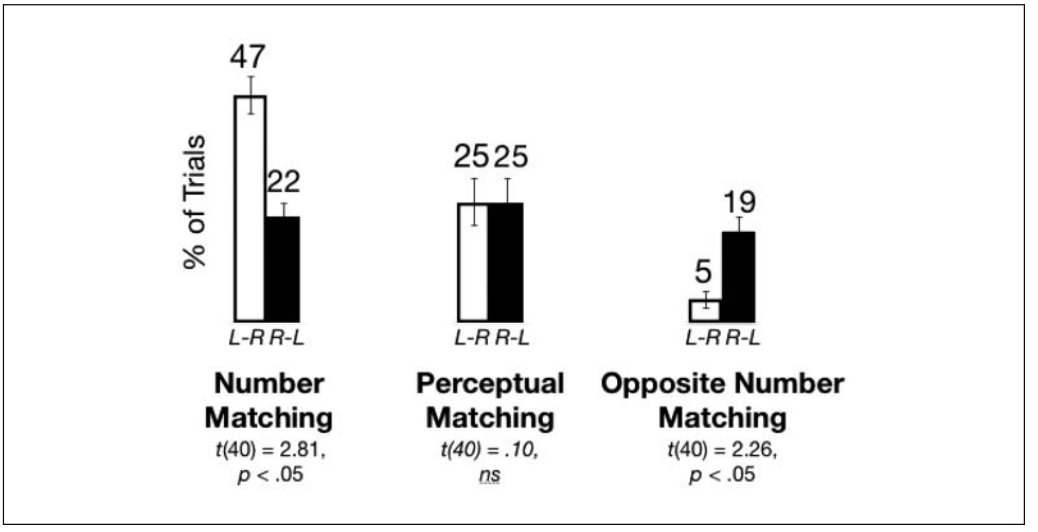

Figure 2. Children in the LR/LR Condition Were More Accurate (Number Matching) Than Children in the RL/RL Condition

Note: Furthermore, children in the RL/RL condition were more likely to make an opposite end error than children in the LR/LR condition. However, no condition differences were observed for perceptual matches.

in room with a picture of keys, and the child's first search in the sample box was the room with a picture of keys); and (3) *opposite end matches*, in which children searched for the hidden object in the opposite end of the correct location (e.g., the hidden object was in the Number 1, Number 2, or Number 3 room in the sample box, and the child searched in the Number 7, Number 6, or Number 5 room in the matching box, respectively).

Did Numbering Bias Preschoolers' Spatial Search?

We first examined accuracy of searches by exploring whether children matched the room number in the sample box to the room number in the matching box as the first (correct) guess about location of the hidden object. Searches in the LR/LR condition were more accurate than searches in the RL/RL condition (LR/LR: $M = 47\%$ of trials, $SD = 2.27$; RL/RL: $M = 22\%$ of trials, $SD = 1.62$), $t(40) = 2.81$, $p < 0.05$. Similarly, children in the LR/LR condition tended to solve the task more quickly ($M = 11.95$ seconds, $SD = 6.03$) than children in the RL/RL condition ($M = 16.12$ seconds, $SD = 4.42$), $t(40) = 1.47$, $p < .10$, one-tailed (Figure 2).

Errors were also highly revealing: searches at the opposite end occurred more often in the RL/RL condition (19% of trials) than in the LR/LR condition (5% of trials), $t(40) = 2.26$, $p < .05$, indicating that children in the RL/RL condition attempted to impose a left-to-right numeric ordering even where none existed. Moreover, use of other erroneous strategies indicated that the right-to-left condition was not simply more difficult; there was no difference between conditions in searching at perceptual matches, $t(40) = 0.10$, *ns*, despite perceptual matching being the preferred initial strategy on Trial 1 in both conditions (40% perceptual matches vs. 21% number matches), $t(40) = 1.90$, $p < .05$.

Although children in this and other studies (DeLoache, 1987; Loewenstein & Gentner, 2005) were otherwise likely to ignore the equivalent spatial relation in their spatial search, we found that numeric information helped children code these spatial relations. In this, numbers served a function for young children very similar to that of spatial language: By matching rooms based on a shared number (e.g., "the two room") or a shared spatial term ("above" or "below"), children were able to ignore the salient visual distractors (matching pictures) and encode space using a cue with higher predictive accuracy. Critically, however, we found that this help came only if the numbers conformed to the conventional left-to-right ordering dominant in their culture (as in Opfer et al., 2010).

How might the left-to-right numbering convention influence children's cognition? Unfortunately, nothing in Opfer et al. (2010) provided any guidance on this issue. Hypothetically, the difference in performance across the LR/LR and RL/RL could be traced to two causes: (1) *encoding biases*, in which the expectation that numbers increase from left-to-right interfered with the encoding of the numeric labels provided (i.e., by the experimenter in the sample box), or (2) *production biases*, in which children's habit of producing numeric labels from left-to-right (i.e., when counting in the matching box) interfered with their finding the room with the target number. Thus, if directional biases in encoding affected children's strategies, they should expect the sample box to increase from left-to-right, and therefore, performance in the LR/RL condition should be similar to performance in the LR/LR condition and performance in the RL/LR condition should be similar to performance in the RL/RL condition. However, if directional biases in production affected children's strategies, they should expect the matching box to increase from left-to-right, and therefore, performance in the RL/LR condition should be similar to that in the LR/LR condition and performance in the LR/RL condition should be similar to performance in the RL/RL condition.

To examine the effect of order in the sample box (and thereby test the encoding hypothesis), we combined the conditions in which the sample box increased left-to-right (i.e., LR/LR and LR/RL) and compared strategies to the conditions in which the matching box increased from right-to-left (i.e., RL/LR and RL/RL). Consistent with the encoding hypothesis, searches in the left-to-right conditions (LR/__) were more accurate (52%) than searches in the right-to-left conditions (RL/__, 32%), $t(82) = 2.95$, $p < .05$. Furthermore, searches at the opposite end occurred more in the RL/__ conditions (13%) than in the LR/__ conditions (4%), $t(82) = 2.77$, $p < .05$. Additionally, no differences in perceptual matching emerged (LR/__: 21%, RL/__, 26%), $t(82) = 1.23$, *ns*. Thus, the order of the sample box strongly affected children's performance in the spatial search task, thereby supporting the encoding hypothesis.

To examine the effect of order in the matching box (and thereby test the production hypothesis), we combined the conditions in which the matching box increased left-to-right (i.e., LR/LR and RL/LR) and compared strategies to the conditions in which the sample box increased from right-to-left (i.e., LR/RL and RL/RL) (Table 1). Contrary to the production hypothesis, searches in the left-to-right conditions (__/LR; 45%) were no more accurate than searches in the right-to-left conditions (__/RL; 40%), $t(82) = 0.81$, *ns*. Furthermore, there were no differences in opposite end searches in the __/LR conditions (6%) than in the __/RL conditions (11%), $t(82) = 1.23$, *ns*, nor were there any differences in perceptual matches between conditions (__/LR: 26%; __/RL: 20%), $t(82) = 1.07$, *ns*. Thus, the order of the matching box did not affect children's performance in the spatial search task, thereby failing to support the production hypothesis.

The effect of order in the sample box (but not the matching box) suggests that the conventional left-to-right order of numbers has a powerful effect on how children use numbers to code space. This conclusion, however, depends on the assumption that that superior performance in the LR/__ conditions did not come from preexisting group differences in numeric competence. To test this assumption, we examined the comprehension check question, where all children were asked to count the rooms. Here, the two groups did not differ reliably in counting accuracy: 93% of children in the LR/__ conditions counted flawlessly versus 81% of children in the RL/__ conditions, $\chi^2(1) = 1.64$, *ns.* Thus, we conclude that the left-to-right convention for numbering items influences how children encode numerically tagged items.

Individual Differences in How Numbers Bias Search

At the group level, 4-year-olds appeared to have robust expectations about verbal numbers increasing in a left-to-right order. *Which* children or *how many* had these spatial-numeric associations, however, was impossible to determine given the nature of the searching task. To address this issue, we next examined directional biases on the quantification task, where no spatial biases were needed to solve the three simple problems presented: counting objects, adding objects to a set, and subtracting objects from a set. We were specifically interested in three types of directional biases: counting from left-to-right, adding from left-to-right, and subtracting from right-to-left. This test of spatial-numeric associations is thus a strong one because it is quite conservative: The chance probability of consistently associating "more" with "right" on these three problems was at least 0.00002 (probability of counting left-to-right over seven cards was 1/7!, probability of adding to the right was no more than 0.5, and the probability of subtracting from the right was also no more than 0.5).

Of the 84 preschoolers tested, 76% counted left-to-right, 77% added to the right, 56% subtracted from the right, and 38% displayed the same *more-to-right/less-to-left* associations across all three quantification tasks. By way of comparison, Opfer et al. (2010) found 50% of 6-year-olds and 64% of 22-year-olds showed *more-to-right/less-to-left* associations across all three quantification tasks. Assuming these percentages generalize to the whole population, it would appear that roughly 60% of adult levels of spatial-numeric associations develop before children start kindergarten and even learn to identify letters and simple letter-phoneme associations.

For children showing directional biases across all three quantification tasks (the SNA group: $n = 31$, mean age = 4.5, 61% boys), condition differences in the direction of numbering (LR/__ vs. RL/__) had a large impact on spatial search strategies, whereas for other children (the No SNA group: $n = 53$, mean age = 4.5, 53% boys) condition differences in direction of numbering had no such effect. As indicated in Table 2, the SNA group used the number matching strategy in the LR/__ conditions ($M = 65\%$) more often than in the RL/__ conditions ($M = 20\%$), $t(29) = 4.27$, $p < .001$, whereas the No SNA group tended to number match equally often in the LR/__ ($M = 43\%$) and RL/__ conditions ($M = 38\%$), $t(51) = 0.67$, *ns*. Furthermore, SNA children were less likely to use the incorrect perceptual matching strategy in the LR/__ conditions (9%) than in the RL/__ conditions (20%), $t(29) = 1.81$, $p < .05$, whereas the No SNA group showed no difference in perceptual matching in the two conditions (LR/__ 29%, RL/__ 29%), $t(51) = 0$, *ns*. Finally, the SNA group often incorrectly searched the opposite end in the RL/__ conditions ($M = 22\%$) but rarely searched the opposite end in the LR/__ conditions ($M = 4\%$), $t(29) = 2.78$, $p < .05$, whereas the No SNA group rarely searched the opposite end in either the LR/__ conditions ($M = 4\%$) or in the RL/__ conditions ($M = 8\%$), $t(51) = 1.38$, *ns*. Thus, children who had developed left-to-right biases in quantification also showed left-to-right biases in using numbers to code space, whereas children who had not yet developed left-to-right biases in quantification showed no biases in using numbers to code space.

General Conclusion

The goal of our studies was to examine alternative hypotheses regarding the relations between language, culture, and cognition. Specifically, we sought to test whether the spatial-numeric associations widely reported in adults developed (1) with reading experience, (2) with the acquisition of numeric symbols, or (3) with counting experience. To address this issue, we examined directional biases in how pre-reading preschoolers used numeric information in spatial search, how they spontaneously used a spatial strategy to perform basic quantification, and whether spatial biases in quantification moderated the effect of numbers on spatial search.

Table 1. Effect of Left-to-Right Versus Right-to-Left Ordering in the Sample Box (Encoding Hypothesis) and in the Matching Box (Production Hypothesis) on Strategy Use in the Spatial Search Task

	Sample Box Order		Matching Box Order	
Spatial Search Strategy	Left-to-Right (n = 42)	Right-to-Left (n = 42)	Left-to-Right (n = 42)	Right-to-Left (n = 42)
Numeric matching (accurate)	52%	32%	45%	40%
Perceptual matching	21%	26%	26%	21%
Opposite end	4%	13%	6%	10%

Although previous work had indicated that spatial-numeric associations originated in reading practices (Dehaene et al., 1993; Hubbard et al., 2005), our results indicated that spatial-numeric associations develop long before children begin formal reading instruction. First, we found that while preschoolers easily and accurately encoded the location of hidden objects when numbered from left-to-right, they experienced tremendous difficulty when the same objects were numbered right-to-left. Suggesting that the source of this spatial-numeric association came from an experience other than reading, almost all preschoolers spontaneously counted left-to-right, with many spontaneously generalizing this bias to the way they added and subtracted objects to or from a set.

Our results are not compatible with the idea that spatial-numeric associations develop either as early as the typical acquisition of numeric symbols or as late as reading education. Against the idea that spatial-numeric associations develop as early as the acquisition of numeric symbols, we found the SNA and No SNA groups performing equally well when counting. Thus, it appears that children can know and use numeric symbols sufficiently well to spontaneously match sets and to produce verbal numbers for a set of objects yet still show no effect of this ability on their spatial-numeric associations. Against the idea that spatial-numeric associations develop as late as the development of reading skills, results found directional biases in counting, adding, and subtracting long before children were to have any formal training in reading. Taken together, these results suggest that spatial-numeric associations have some source other than knowledge of numeric symbols or reading.

Possibly some of the interesting links widely observed between numeric and spatial coding (Berch et al., 1999; Callabria & Rossetti, 2005; Dehaene et al., 1993; de Hevia, Girelli, & Vallar, 2006; Fias et al., 2003; Fischer, 2001; Fischer et al., 2003; Göbel et al., 2001; Pinel et al., 2001; Pinel et al., 2004; Shaki et al., 2009; Zorzi et al., 2002) are laid down in early childhood as children repeatedly engage in the physical action of counting. Our finding that directional biases in counting moderate the effect of directionality in spatial search is consistent with this idea. Moreover, if true, it suggests that (1) there may also be yet uncovered cultural differences in counting direction that could explain cultural differences in the widely reported SNARC effect, and (2) children who grow up in cultures with fewer number words (e.g., Munducuru; Dehaene, Izard, Spelke, & Pica, 2008) may not have any consistent directional biases when using numbers to code spatial locations.

Our proposal—that early practice in counting leads to development of spatial-numeric associations—is based only on correlational behavioral data, and further evidence is clearly needed to rule out alternative developmental paths. One such alternative is that counting and spatial-numeric associations have a common origin in a culture-specific habit that extends well beyond numbers (e.g., a yet-undiscovered directional bias in ostension or eye gaze). Hypothetically, such a practice might enhance preschoolers' encoding whenever any ordinal information (numeric or

Table 2. Strategy Use on Spatial Search Task by Condition (Left-to-Right Numbering, Right-to-Left Numbering) and by Performance on Quantification Task (SNA Group, With Spatial Biases; No SNA Group, Without Spatial Biases)

	SNA Group		No SNA Group	
Spatial Search Strategy	Left-to-Right ($n = 17$)	Right-to-Left ($n = 14$)	Left-to-Right ($n = 25$)	Right-to-Left ($n = 28$)
Numeric matching (accurate)	65%	20%	43%	38%
Perceptual matching	9%	20%	29%	29%
Opposite end	4%	22%	4%	8%

non-numeric) is presented in a left-to-right orientation. A quite different alternative—suggested by preschoolers' performance on line bisection tasks—is that directional biases in spatial-numeric associations may be initially limited only to numeric symbols and not non-symbolic numbers (de Hevia & Spelke, 2009). Like our account, both alternatives posit no necessary relation between reading practice and spatial-numeric associations; the accounts differ, however, in the proposed scope of directional biases (i.e., broader than numbers vs. limited to symbolic number).

Converging evidence for our proposal, however, comes from observed correlations between spatial enumeration (the ability to point out each member of a set once and only once) and counting ability (Potter & Levy, 1968), finger tapping and numeracy, finger gnosia and numeracy, and finger gnosia and numerical estimation (Penner-Wilger et al., 2007, 2008). If directional biases in encoding were initially broader than spatial-numeric associations, spatial enumeration would be trivial for children who do not yet know the order of number words—yet children as young as 2 can easily recite number words in the correct order, while struggling with spatial enumeration until after years of counting practice (Potter & Levy, 1968). Moreover, if spatial-numeric associations were initially limited to symbolic numbers, one would not find evidence of directional biases in non-symbolic adding and subtracting, as we found in our quantification tasks and others have found using a much wider range of numbers (e.g., Knops et al., 2009; McCrink et al., 2007). An intriguing hypothesis raised by this pattern of evidence is that the counting routine improves both symbolic and non-symbolic numerical knowledge, as well as spatial enumeration, finger tapping, and finger knowledge. Moreover, if our account is correct, the study of counting behavior could be important for understanding the plasticity and development of an important neural substrate for the systems examined.

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