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PAPER

Early development of spatial-numeric associations: evidence from spatial and quantitative performance of preschoolers

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Abstract

Numeric magnitudes often bias adults' spatial performance. Partly because the direction of this bias (left-to-right versus right-to-left) is culture-specific, it has been assumed that the orientation of spatial-numeric associations is a late development, tied to reading practice or schooling. Challenging this assumption, we found that preschoolers expected numbers to be ordered from left-to-right when they searched for objects in numbered containers, when they counted, and (to a lesser extent) when they added and subtracted. Further, preschoolers who lacked these biases demonstrated more immature, logarithmic representations of numeric value than preschoolers who exhibited the directional bias, suggesting that spatial-numeric associations aid magnitude representations for symbols denoting increasingly large numbers.

Introduction

Spatial associations with abstract concepts appear to permeate our mental life, often in surprising ways. When matching pictures to semantically identical sentences (e.g. 'The girl kissed the boy' versus 'The boy was kissed by the girl'), English-speaking adults 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). When thinking about time, subjects conceptualize future events as occurring in a forward direction and past events in a backward direction (Boroditsky, 2000). Further, when confronted with numerical magnitudes, people conceptualize numbers as increasing (logarithmically) from left-to-right, as if they possessed a mental number line (Hubbard, Piazza, Pinel & Dehaene, 2005; Longo & Lourenco, 2007). Indeed, the seeming universality of spatial associations has suggested that they could derive from 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 (Chatterjee, Maher & Heilman, 1995; Geminiani, Bisiach, Berti & Rusconi, 1995; Landau, 1996).

In this paper, we addressed two questions with respect to the 'mental number line': Where do these associations come from, and what (if any) representational function might they serve? Regarding the origins of spatial-numeric associations, we wished to test three possibilities about spatial-numeric associations: (1) they emerge as soon as children learn numeric symbols, an 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); (2) they emerge only after years of reading practice, an hypothesis suggested by evidence from the SNARC effect (see below); and (3) they emerge from the visuo-motor experience of the counting routine itself (i.e. serially tagging items in a left-to-right manner while reciting the integer list), an hypothesis suggested by evidence that visuo-motor training improves neglect patients' numerical bisection (Rossetti, Jacquin-Courtois, Rode, Ota, Michel & Boisson, 2004). The last hypothesis is particularly interesting because it suggests that spatial-numeric associations could serve an early representational function: providing numeric symbols with a neural code that possesses three essential properties of the number system (ordinality, cardinality, and approximate value).

To test these hypotheses, we examined directional biases in how pre-reading preschoolers use numeric information on spatial tasks (Study 1), how they use spatial information on numeric tasks (Study 2), and whether these spatial-numeric associations are associated with mature representations of numeric value (Study 3). In the next three sections, we briefly review the types of evidence indicating robust spatial-numeric associations

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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 of numeric magnitude on subjects' 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 and colleagues (1993) reasoned, representation of numerals on a mental number line might intrude on task performance. Specifically, they found that when subjects 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 by the direction of writing in the culture of the subjects. Specifically, when Iranian subjects – 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). Further, 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 (Pinel *et al.*, 2001; Pinel *et al.*, 2004; Fias *et al.*, 2003; 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 & Shukman, 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 participants who read from right-to-left (Dehaene *et al.*, 1993) and has not been observed in preschool children, failing to emerge until age 9 (Berch *et al.*, 1999). Further, 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).

Alternatively, the development of spatial-numeric associations may stem from children's visuo-motor activity, suggesting that the source of conventional spatial-numeric associations might be found in cultural practices not specifically tied to orthography or schooling. Indeed, the counting routine – in which English-speaking children serially tag items from left-to-right while reciting the integer list – seems a plausible candidate. Moreover, this hypothesis implies that the development of spatial-numeric associations could appear as children gain practice counting, certainly earlier than the age at which children show the SNARC effect in parity judgments. Further, counting experience provides a plausible candidate for forging the links between the numeric symbols and parietal areas that Ansari and others (2005) observed to be activated as preschoolers made numeric comparisons.

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The present studies

To examine early development of spatial-numeric associations, we first examined whether spatial-numeric associations affected preschoolers' ability to use numbers to code spatial location, and whether this ability was correlated with directional biases in counting and adding (Study 1). Next, we examined the development of directional biases across three numerical tasks: a counting task, in which children were asked to serially tag the items in a linear array; an adding task, in which children were asked to add an object to a linear array; and a subtracting task, in which children were asked to subtract an object from a linear array (Study 2). If preschoolers represent increasing magnitudes as following a left-to-right (or right-to-left) orientation, a consistent directional bias should be evident across all tasks in Studies 1 and 2. In Study 3, we tested whether spatial-numeric associations help children represent the meanings of numeric symbols by examining whether directional biases are associated with better performance in matching physical magnitudes to numeric symbols.

Study 1: Directional biases in using numbers to code space

To test whether preschoolers expected a left-to-right ordering of numbers, we randomly assigned 4-year-olds to one of two conditions in a relational match-to-sample task (based on DeLoache, 1987; see also Loewenstein & Gentner, 2005) designed to place strong demands on spatial-numeric mappings. In the left-to-right condition of our task (see Figure 1), a hidden object was revealed in one of seven sample locations verbally numbered from left-to-right, and subjects had to find a similar object in a new location receiving the same verbal number; in the right-to-left condition, the same task was presented but number labels increased from right-to-left. If preschoolers expect numbers to increase from left-to-right, those in the left-to-right condition should find the hidden object more quickly and accurately than preschoolers in the right-to-left condition, where their expectancies would be violated.

Method

Participants

Participants included 56 English-speaking 4-year-olds (left-to-right condition: n = 28, ages 4.01 to 4.99, mean age = 4.49; right-to-left condition: n = 28, ages 4.0 to 4.95, mean age = 4.54). There were an equal number of males and females in each condition. All participated in a drawing task to assess handedness; 86% of children were right-handed, 12% left-handed, and one child was ambidextrous. 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 were verbally labeled in an increasing order, either from left-to-right or right-to-left (Figure 1), and participants repeated the numerical

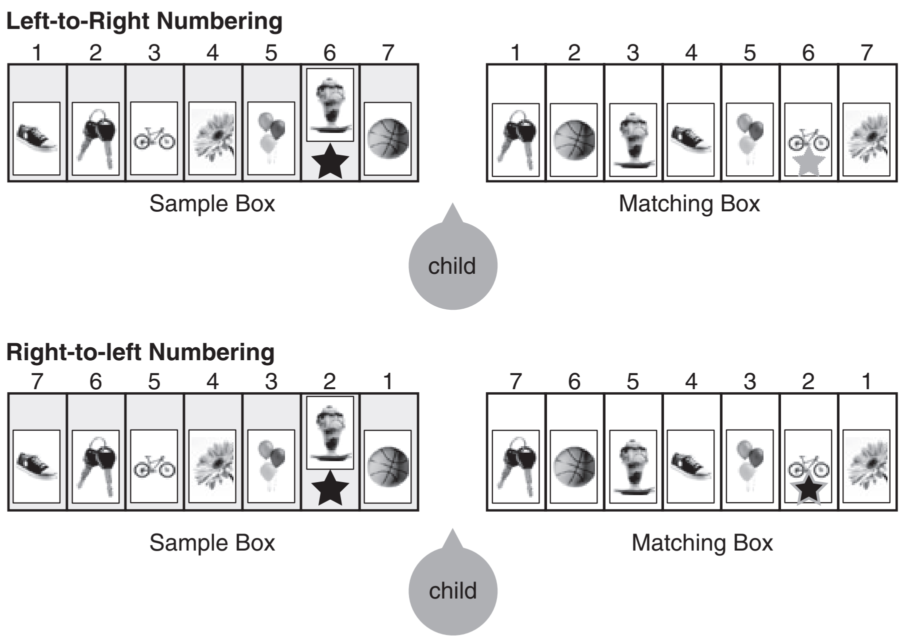

Figure 1 *Study 1: An illustration of the spatial search task. In the left-to-right condition, compartments in the sample and matching boxes were labeled in an increasing order from left to right. In the right-to-left condition, the order was reversed.*

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labels of the compartments until successful. 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 given an example: 'If the winner [hidden object] was in the number one room in the hiding box [sample box], it will be in the number one room in the finding box [matching box].' The experimenter checked to ensure the child understood by asking: 'If the winner was in the number two room in the hiding box, what room do you think it will be in the finding box?' Testing began when children understood instructions, 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 and added in a left-to-right direction. Children were first presented with three poker chips centered on the table in front of them, given one poker chip to their right hand, and asked to add a poker chip to create four. Next, children were presented with the cards used in the spatial search task and asked to count the pictures.

Design and procedure

Children were tested individually. Half completed the spatial search task followed by the quantification task, and half received the reverse order. In the spatial search task, preschoolers were randomly assigned to one of two conditions: the left-to-right condition or the right-to-left condition. The pictures 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 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. As illustrated in Figure 2, searches in the left-to-right condition were more accurate than searches in the right-to-left condition (left-to-right: M = 44% of trials, SD = 34.33; right-to-left: M = 26% of trials, SD = 26.43; $t[54] = 2.23$, p <.05). Similarly, children in the left-to-right condition tended to solve the task more quickly (M = 11.35 seconds, SD = 6.64) than children in the right-to-left condition (M = 14.17 seconds, SD = 5.64; $t[54] = 1.72$, $p < .10$).

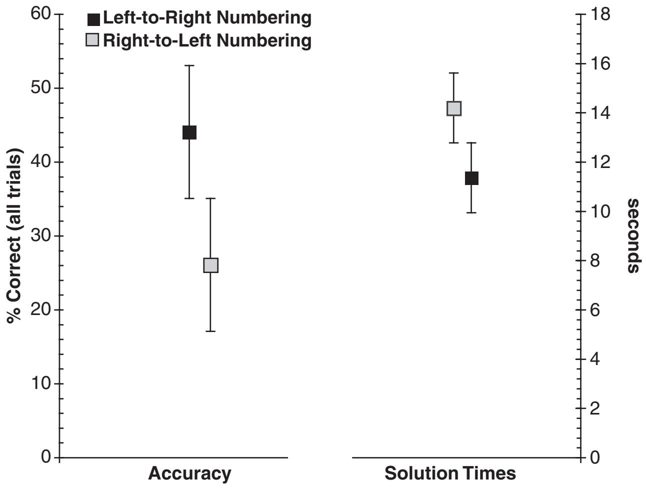

Figure 2 *Study 1: Searches in the left-to-right condition were faster and more accurate than searches in the right-to-left condition.*

To further examine differences in accuracy, we explored search strategies from trial to trial. Three main strategies were used to find the hidden object (accounting for performance on 70% of all trials): (1) making an accurate numeric match between the sample box and the matching box (e.g. the object was hidden in the number 2 room in the sample box and the child immediately searched in the number 2 room in the matching box); (2) ignoring the numeric match and simply searching by a perceptual match (e.g. the object was hidden in the room with the keys and the child's first search was in the room with the keys in the matching box); and (3) searching for the hidden object at 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).

To examine adaptation of search strategies to numbering condition, we conducted a 2 (condition: left-to-right, right-to-left) × 7 (trial: 1, 2, 3, 4, 5, 6, 7) repeated-measures ANOVA on numeric matches. As indicated in Figure 3, searches in the left-to-right condition improved over trials, with the optimal search strategy of making numeric matches used increasingly often in later trials, $F(6, 312) = 2.98$, $p < .05$. In contrast, searches in the right-to-left condition did not show improvement. Errors were also highly revealing: a one-way ANOVA revealed that searches at the opposite end occurred more often in the right-to-left condition (24% of trials) than in the left-to-right condition (10% of trials), $F(1, 52) = 10.36$, $p < .01$. Thus, for children in the right-to-left condition, it appeared that the expectation

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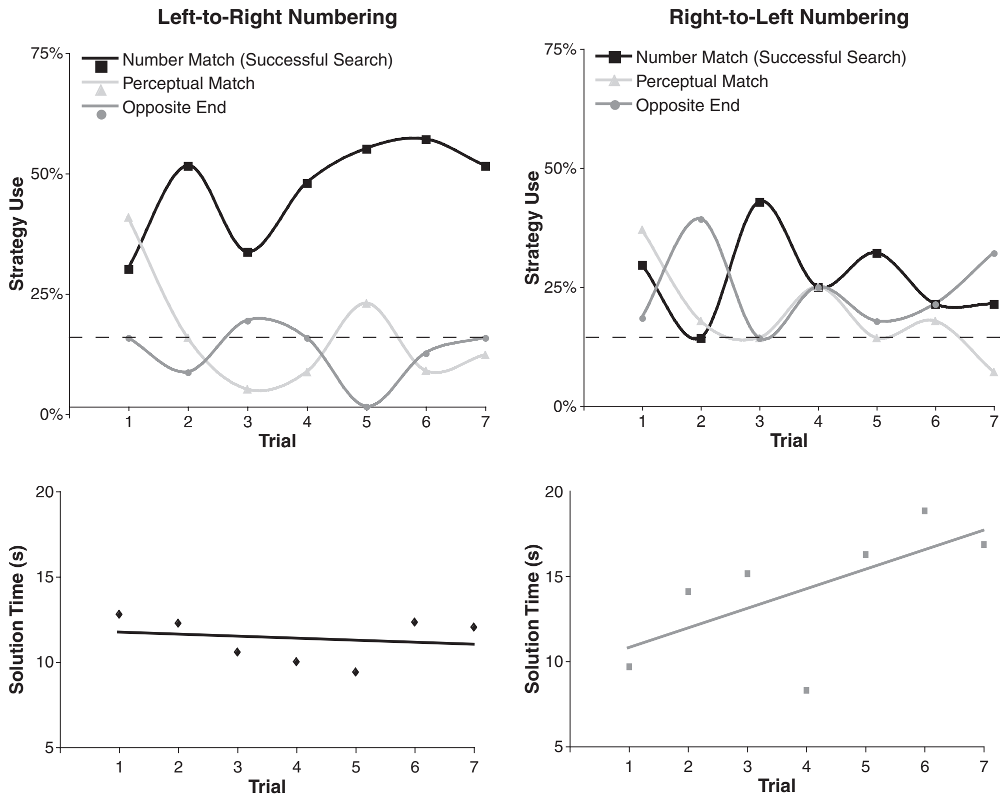

Figure 3 *Study 1: Children in the left-to-right condition increased their use of the optimal strategy (number matching) over trials, whereas children in the right-to-left condition did not improve. Solution times for children in the left-to-right condition remained fast across trials, but actually increased in the right-to-left condition.*

that numbers increase from left-to-right interfered with the encoding of the numeric labels provided. 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, $F(1, 52) = 0.95$, *ns*, despite perceptual matching being the preferred initial strategy (see also DeLoache, 1987).

The expectation of left-to-right ordering of numbers was also reflected in solution times. Because searching for the object continued after initially unsuccessful attempts, solution times provided a useful indicator of strategy efficiency, and trial-to-trial solution time differences were an equally useful indicator of learning. We conducted a 2 (condition: left-to-right, right-to-left) × 7 (trial: 1, 2, 3, 4, 5, 6, 7) repeated-measures ANOVA on solution times, and found a strong interaction between condition and trial, $F(6, 312) = 2.60$, $p < .05$. Overall, solution times for children in the left-to-right condition did not change over trials ($F[6] = 1.12$, *ns*); in the right-to-left condition, however, solution times *increased* across trials, $F(6) = 4.5$, $p < .001$, which is consistent with the highly variable search strategies in the right-to-left condition.

Finally, to check our assumption that superior performance in the left-to-right condition did not come from pre-existing group differences in numeric competence, 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: 71% of children in the left-to-right group counted flawlessly versus 89% of children in the right-to-left group, χ^2 (1) = 1.81, *ns*, with the nominal difference in accuracy actually favoring children in the right-to-left group rather than the left-to-right group.

Thus, 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 two simple problems presented: counting objects and adding objects to a set. We were specifically interested in two types of directional biases: counting from left-to-right and adding from left-to-right. 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 two problems was at least 0.00004 (probability of counting left-to-right over seven cards was 1/7! and probability of adding to the right was no more than .5).

Some pre-reading preschoolers ($n = 11$) displayed directional biases that were clearly more frequent than expected by chance (binomial test, $p < .001$). Moreover, our quite conservative index of spatial-numeric associations (SNA) was also associated with accuracy on the

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spatial searching task, χ^2 (3) = 12.86, $p < .005$. Specifically, SNA 4-year-olds (i.e. those who counted left-to-right and added left-to-right) were often immediately accurate in the left-to-right condition (M = 73%), but were less accurate in the right-to-left condition (M = 46%). In contrast, children without spatial numeric associations tended to be equally accurate in the left-to-right (M = 48%) and right-to-left condition (M = 39%). Consistent with this overall pattern, there was also an association between SNA status and opposite-end searching, χ^2 (3) = 18.57, $p < .001$. Children with spatial-numeric associations rarely searched the opposite end in the left-to-right condition (M = 6%), but they often searched the opposite end in the right-to-left condition (M = 29%). In contrast, children without spatial numeric associations were equally likely to search the opposite end in both the left-to-right condition (M = 12%) and in the right-to-left condition (M = 23%). Thus, it appeared that directional biases on our quantification test provided a good, albeit conservative, predictor of spatial-numeric associations more broadly.

Study 2: Development of spatial-numeric associations

In Study 1, we found that pre-reading preschoolers strongly expected numbers to be ordered from left-to-right when engaging in a spatial search task. Moreover, this directional bias was associated with a bias to count from left-to-right and to add objects to a set in a left-to-right order. To examine the development of this directional bias more directly, Study 2 presented the quantification task used in Study 1 to children ranging in age from 2.5 to 8.4 years old and to adult university students. Additionally, we added a subtraction task to our battery, where consistent directional biases in increasing magnitudes would lead one to subtract in a right-to-left rather than left-to-right manner.

Method

Participants

Participants included 95 English-speaking children drawn from nine age groups: 2.5- to 2.99-year-olds (n = 11; M = 2.85; five males, six females), 3- to 3.49-year-olds (n = 15, M = 3.38; seven males, eight females), 3.5- to 3.99-year-olds (n = 16, M = 3.76; five males, 11 females), 4- to 4.49-year-olds (n = 10, M = 4.29; five males, five females), 4.5- to 4.99-year-olds (n = 15, M = 4.74; 10 males, five females), 5- to 5.49-year-olds (n = 4, M = 5.42; two males, two females), 5.5- to 5.99-year-olds (n = 9, M = 5.74, six males, three females), 6.0- to 6.6-year-olds (n = 6, M = 6.38; two males, four females), and 7.7- to 8.4-year-olds (n = 9, M = 7.99; six males, three females). Additionally, 22 young adults drawn from two age groups served as comparison groups: 17.9- to 18.98-year-olds (n = 11, M = 18.58; four males, seven females) and 18.99- to 28-year-olds (n = 11, M = 21.35; six males, five females).

Stimuli and procedure

Participants were presented with three tasks – counting, adding, and subtracting. In the counting task, participants were shown a linear array of nine poker chips, centered on their midline, and were asked to count the number of poker chips in the set aloud and to touch each object that they counted. In the adding task, participants were presented with a linear array of three objects, also centered on their midline, and were asked to add one poker chip to the set 'to make it 4'. In the subtracting task, participants were presented with a linear array of four poker chips, similarly centered, and asked to take one object away from the set 'to make it 3 again'.

Results and discussion

On our counting task, 76% of all children and 100% of adults counted from left-to-right. Additionally, consistent with previous findings that most 3- to 5-year-olds prefer left-to-right counting (Briars & Siegler, 1984), we found that 73% of preschoolers also counted from left-to-right.

To examine the breadth of this bias, we next examined how children added and subtracted elements to and from a set (e.g. by placing the new element above the set, below the set, to/from the right of the set, or to/from the left of the set). We were particularly interested in identifying participants who both added in a left-to-right manner and subtracted in a right-to-left manner ('SNA group' henceforth), thereby indicating the same spatial-numeric associations seen in Study 1. As indicated in Figure 4, the

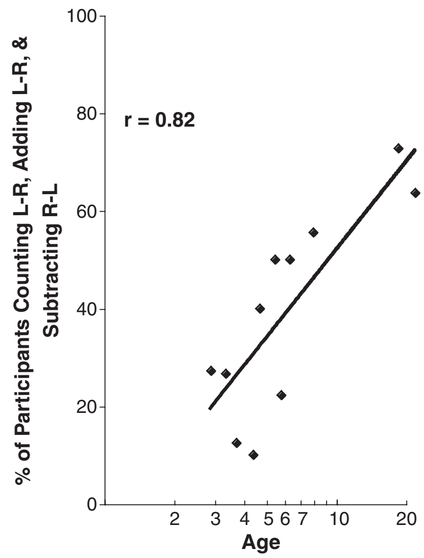

Figure 4 *Study 2: Proportion of subjects who counted left-to-right, created a set of objects by adding left-to-right, and created a set of objects by subtracting from right-to-left.*

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number of participants falling into this group increased substantially with age. The average age of all participants in the SNA group (M = 10.53) was greater than that in the No SNA group (M = 5.91), $t(113)$ = 4. 1, p < .0001, and age accounted for 76% of the variance in SNA status, $F(1, 10)$ = 12.57, p < . 01. When adults were excluded from the analysis, there was still a statistically significant difference in mean ages between the SNA (M = 5.21) and No SNA group (M = 4.45), $t(91)$ = 2.27, p < .05, with the majority of change occurring in preschool, before children had formal reading instruction. Finally, we performed a logistic regression to examine the relation between age and SNA status, and found that with each additional year after 2.5 years, the likelihood of SNA status was 1.13 times as likely, $\hat{\beta}$ = .12, z = 3.48, Wald (1, N = 117) = 12.734, p < .001. Thus, by age 5, the frequency of children meeting the strictest criterion of spatial-numeric associations was already at 80% of adult levels, strongly suggesting that reading practice could not be the dominant source of children's developing spatial-numeric associations.

Study 3: How are spatial-numeric associations related to numeric competence?

If directional biases in adding and subtracting were a feature of PSPL processing, a region that also processes symbolic number comparisons in adults (Pesenti, Thioux, Seron & De Volder, 2000; Pinel *et al.*, 2001), we would expect children with these biases to have a better representation of the relation between numeric symbols and linearly increasing physical quantities than age-matched controls. To test this hypothesis, we presented children with four tasks in which they had to translate between numeric symbols and physical quantities. The main prediction concerned performance on a task in which children were asked to provide a physical quantity of number in response to a verbal request for number (NC). Specifically, children in the SNA group were expected to provide linearly increasing physical quantities in response to requests more often than age-matched children in the No SNA group, who were expected to rely on a logarithmic representation of number widely observed in young children, non-human animals, and – under some circumstances – even adults (Furlong & Opfer, 2009; Jordan & Brannon, 2006; Opfer & Siegler, 2007; Opfer & Thompson, 2008; Roberts, 2005; Siegler & Booth, 2004; Siegler & Opfer, 2003; Siegler, Thompson & Opfer, 2009; Thompson & Opfer, 2008; Thompson & Opfer, in press; Ward & Smuts, 2007).

Method

Participants

Participants in Study 3 were 67 age-matched preschoolers from the SNA (n = 16; M age = 3.8, SD = .58) and No SNA (n = 51, M age = 3.8, SD = .41) groups in Study 2. Age matching was critical to estimate the effects of spatial-numeric associations without confounding age-related improvements in other sources of numeric competence.

Stimuli and procedure

All groups were given four tasks: two integer matching tasks – number words to number words (NN) and number words to chips (NC), and two object-set matching tasks – chips to number words (CN), and chips to chips (CC). In each case they were asked to match one format of numeric magnitude (verbal, visual) with either the same format or another. For each task, children were asked to match to all numerosities 1–9. The four tasks and the presentation of numerosities within each task were randomized.

On the integer matching tasks, children were asked, 'How many is N?' and children were to give the experimenter N poker chips from their pile of 25 poker chips (NC) or simply to repeat the number (NN). On the object-set matching tasks, children were asked, 'How many is this (e.g. experimenter showed the child four poker chips)?' and the child was asked to say the number given (CN) or simply to match the experimenter's N chips (CC) from their pile of 25. This matching paradigm has been used successfully in prior studies to identify children's representations of integers and object sets (i.e. the counting and 'give-a-number tasks' used by Wynn, 1990, and the 'matching task' used by Huttenlocher, Jordan & Levine, 1994).

Results and discussion

We first examined performance on the NN and CC tasks to ensure that the SNA and No SNA groups were equally capable of attending to and encoding the number words and set sizes presented in the NC and CN tasks. To do so, we regressed children's answers against the actual number provided. As expected, both groups did very well. On the NN task, the R^2 of the linear function was nearly 1.0 for numerosities 1–4 and 5–9 (SNA: 1–4, R^2 = 1, 5–9, R^2 = .98; No SNA: 1–4, R^2 = .98, 5–9, R^2 = .99). On the CC task, the R^2 of the linear function was also nearly 1.0 for numerosities 1–4 and 5–9 (SNA: 1–4, R^2 = .97, 5–9, R^2 = .98; No SNA: 1–4, R^2 = .99, 5–9, R^2 = .96). Thus, children had no difficulty matching by verbal or visual numeric magnitude alone.

We next examined performance on the NC and CN tasks, which required children to map a symbolic to a non-symbolic numerosity or vice versa. On the CN task, where children could simply recite the integer list while tagging each chip and provide the last number as the value of the set, both the SNA and No SNA groups did equally well. The R^2 of the linear function was again nearly 1.0 for numerosities 1–4 and 5–9 (SNA: 1–4, R^2 = 1.0, 5–9, R^2 = .97; No SNA: 1–4, R^2 = 1.0, 5–9, R^2 = .97). This performance suggests either that children in both groups understood the numbers they provided to

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denote the cardinal value of the set or that the children simply used a 'last word rule' (Fuson, 1988), but did not actually represent the cardinal value of the numbers.

To test this, we examined performance on the more telling NC task, where children were given a number word and asked to provide that number of objects. If children used numbers to represent cardinal value (as implied by a mental number line), performance on the NC task would be as accurate as performance on the CN task for the SNA group but not the No SNA group. As hypothesized, the SNA and No SNA groups differed dramatically (see Figure 5). For the SNA group, the R^2 of the linear function was again nearly 1.0 for numerosities 1–4 and 5–9 (1–4, $R^2 = .96$, 5–9, $R^2 = .78$). In contrast, for the No SNA group, the linear R^2 value for numerosities 1–4 was .996, whereas for larger numerosities (5–9), linear $R^2 = .11$.

This finding that small numbers are better represented than large numbers is consistent with previous claims that children possess at least two different systems for representing numerical quantity – an 'object file' system that provides young children with a direct, linear mapping between small numbers (1–4) and small set sizes, and another 'analog magnitude' system that provides older children with an analog mapping between larger numbers and larger set sizes (Feigenson, Dehaene & Spelke, 2004; Revkin, Izard, Cohen & Dehaene, 2008).

Subsequent analyses, however, tended to militate against the hypothesis that children initially use two different systems for representing the meaning of small versus large numbers. Rather than observing a break in the response patterns for 1–4 versus 5–9 (as in Revkin *et al.*, 2008), we found that children's accuracy and responses were better and more parsimoniously described as a mapping of all numbers to the analog magnitude system (see also Wagner & Johnson, under review). Specifically, two hallmarks of this system were evident – scalar variability and logarithmic compression. That is, variability of responses (as measured by the *SD* in the number of chips given) increased with the number of chips requested (No SNA: $r[9] = .74$, $p < .05$; SNA: $r[9] = .87$, $p < .01$). This scalar variability is consistent with prominent models of analog magnitude representations, with either (1) the quantities represented by children increasing *linearly* with numeric value but becoming more variable (Gallistel & Gelman, 2000) or (2) the quantities represented increasing *logarithmically* with numeric value but with constant (Dehaene & Changeux, 1993) or increasing variability (Dehaene, 2007). As indicated in Figure 5, we found evidence of both logarithmic and linear response patterns. That is, when we regressed the median number of chips provided against the number verbally requested, the logarithmic function provided a better fit than the linear function (log $R^2 = .91$ vs. lin $R^2 = .85$) for the No SNA group, as suggested by the Dehaene (2007) model. In contrast, for the SNA group, the linear function provided a better fit than the logarithmic (lin $R^2 = .95$ vs. log $R^2 = .92$), as suggested by the Gallistel and Gelman (2000) model.

In sum, we found that individual differences in spatial-numeric associations mirrored prior findings of age differences in numeric representation (e.g. Wynn, 1990; Siegler & Opfer, 2003). First, paralleling the developmental finding in Wynn (1990), children in the SNA group provided more accurate estimates of large numbers than did children in the No SNA group. Second, subsequent analyses indicated that much of the inaccuracy in the estimates of children in the No SNA group came from their use of a logarithmic representation of number, whereas children's errors in the SNA group came from random noise distributed around an accurate midpoint. These findings of a logarithmic to linear shift in the representation of the numbers 1–9 in 3- to 4-year-olds also parallel previous developmental findings: A similar shift has been observed for estimates of the values 0–10,000 for 9- to 12-year-olds (Thompson & Opfer, in

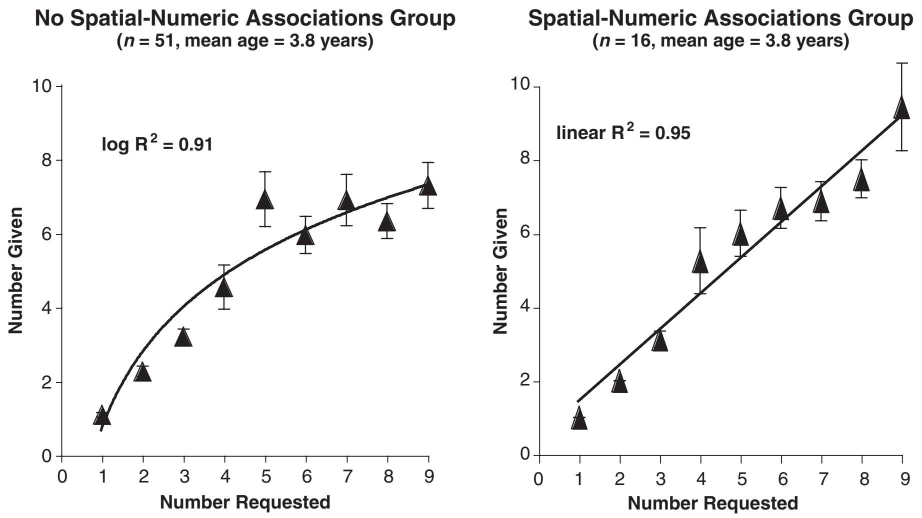

Figure 5 *Study 3: Children who showed spatial-numeric associations in Study 2 showed an earlier logarithmic to linear shift in representing numeric value than age-matched controls.*

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press), 0–1000 for 7- to 9-year-olds (Opfer & DeVries, 2008; Opfer & Siegler, 2007; Opfer & Thompson, 2008; Siegler & Opfer, 2003; Thompson & Opfer, 2008) and 0–100 for 5- to 7-year-olds (Siegler & Booth, 2004).

General discussion

The goal of our studies was to test whether spatial-numeric associations developed (1) with the acquisition of numeric symbols, (2) with reading experience, or (3) with counting experience. To address this issue, we examined directional biases in how preschoolers used numeric information on spatial tasks before formal reading instruction, how they used spatial information on numeric tasks, whether these spatial-numeric associations were associated with mature representations of numeric value, and whether spatial-numeric associations were tied to early biases in counting direction.

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 in Study 1 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, 73% of all preschoolers in Study 2 spontaneously counted left-to-right (ranging from 45% of 2.5-year-olds to 80% of 4.5-year-olds), with nearly 40% spontaneously generalizing this bias to the way they added and subtracted objects to or from a set (compared to 68% of adults who generalized the left-to-right bias).

Preschoolers' spatial-numeric associations appeared to have an important representational function: preschoolers showing spatial-numeric associations in Study 2 displayed more mature, linear representations of symbolic value in Study 3 than age-matched preschoolers lacking spatial-numeric associations and displaying less mature, logarithmic representations of numerical value. This role of spatial-numeric associations in representations of numeric value was most evident in Study 3, where children with robust spatial-numeric associations performed best on the quantitative tasks that required accessing representations of numerical value (the number-to-chip task) rather than just reciting the integer list (the chip-to-number task).

These 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, Study 3 found the SNA and No SNA groups performing equally well on the chips-to-chips matching task and the chips-to-number task. 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, the results of all three studies found directional biases in counting, adding and subtracting long before children have formal training in reading. Moreover, our pilot studies on knowledge of reading direction also showed no effect of this knowledge on spatial-numeric associations. 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, Fischer & Petrusic, 2009; Zorzi *et al*., 2002) are laid down in early childhood as children repeatedly engage in the physical action of counting. In the current case, of course, our proposal is based only on correlational behavioral data, and further evidence is needed to test the direction of causation. However, converging evidence for the idea 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, Fast, Lefevre, Smith-Chant, Skwarchuk, Kamawar & Bisanz, 2007; Penner-Wilger, Fast, Lefevre, Smith-Chant, Skwarchuk, Kamawar, Bisanz & Deslauriers, 2008). One intriguing hypothesis raised by these connections is that the counting routine improves 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.

One cortical region that appears central in providing for these behavioral links is the posterior superior parietal lobule (PSPL). Several lines of research suggest PSPL as a candidate. First, directional counting involves integration of several types of information that are processed by PSPL, including visuo-spatial information required for successful pointing and visual search as well as information about magnitudes of symbolic numbers (Corbetta *et al*., 2000; Simon *et al*., 2002; Pesenti *et al*., 2000; Pinel *et al*., 2001). Second, PSPL processing of approximate addition and subtraction information has also been observed (Dehaene *et al*., 1999; Lee, 2000), two tasks that also elicited substantial directional biases here. Finally, representation of magnitudes of symbolic numbers – which we found affected by spatial-numeric associations – also depends on PSPL regions (Pesenti *et al*., 2000; Pinel *et al*., 2001). Indeed, over development,

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numeric processing involves increasing engagement of these parietal regions and decreasing engagement of frontal regions (Ansari *et al*., 2005). Thus, PSPL provides a plausible neural mechanism for our observed behavioral associations among directional biases in spatial search, counting, adding, subtracting, and numeric representation.

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References

Ansari, D., & Dhital, B. (2006). Age-related changes in the activation of the intraparietal sulcus during nonsymbolic magnitude processing: an event-related functional magnetic resonance imaging study. *Journal of Cognitive Neuroscience*, **18**, 1820–1828.

Ansari, D., Nicolas, G., Lucas, E., Hamon, K., & Dhital, B. (2005). Neural correlates of symbolic number processing in children and adults. *Brain Imaging*, **16**, 1769–1773.

Berch, D.B., Foley, E.J., Hill, R.J., & Ryan, P.M. (1999). Extracting parity and magnitude from Arabic numerals: developmental changes in number processing and mental representation. *Journal of Experimental Child Psychology*, **74**, 286–308.

Boroditsky, L. (2000). Metaphoric structuring: understanding time through spatial metaphors. *Cognition*, **75**, 1–28.

Briars, D., & Siegler, R.S. (1984). A featural analysis of preschoolers' counting knowledge. *Developmental Psychology*, **20**, 607–618.

Callabria, M., & Rossetti, Y. (2005). Interference between number processing and line bisection: a methodology. *Neuropsychologia*, **43**, 779–783.

Cantlon, J.F., Brannon, E.M., Carter, E.J., & Pelphrey, K.A. (2006). Functional imaging of numerical processing in adults and 4-y-old children. *PLoS Biology*, **4**, 844–854.

Chatterjee, A., Maher, L.M., & Heilman, K.M. (1995). Spatial characteristics of thematic role representation. *Neuropsychologia*, **33**, 643–648.

Chatterjee, A., Southwood, M.H., & Basilico, D. (1999). Verbs, events and spatial representations. *Neuropsychologia*, **37**, 395–402.

Corbetta, M., Kincade, J., Ollinger, J., McAvoy, M., & Shulman, G. (2000). Volutary orienting is dissociated from target detection in human posterior parietal cortex. *Nature Neuroscience*, **3**, 292–297.

Dehaene, S. (2007). Symbols and quantities in parietal cortex: elements of a mathematical theory of number representation and manipulation. In P. Haggard, Y. Rossetti, & M. Kawato (Eds.), *Sensorimotor foundations of higher cognition: Attention and performance*, *Vol. XXII* (pp. 527–574). Cambridge, MA: Harvard University Press.

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

Dehaene, S., & Changeux, J.P. (1993). Development of elementary numerical abilities: a neuronal model. *Journal of Cognitive Neuroscience*, **5**, 390–407.

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology*, **20**, 487–506.

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of mathematical thinking: behavioral and brain-imaging evidence. *Science*, **284**, 970–974.

de Hevia, M.D., Girelli, L., & Vallar, G. (2006). Numbers and space: a cognitive illusion. *Experimental Brain Research*, **168**, 254–264.

DeLoache, J.S. (1987). Rapid change in the symbolic functioning of very young children. *Science*, **238**, 1556–1557.

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences*, **8** (7), 307–314.

Fias, W., Lammertyn, J., Reynvoet, B., Dupont, P., & Orban, G.A. (2003). Parietal representation of symbolic and nonsymbolic magnitude. *Journal of Cognitive Neuroscience*, **15**, 47–56.

Fischer, M.H. (2001). Number processing induces spatial performance biases. *Neurology*, **57**, 822–826.

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

Furlong, E.E., & Opfer, J.E. (2009). Cognitive constraints on how economic rewards affect cooperation. *Psychological Science*, **20**, 11–16.

Fuson, K.C. (1988). *Children's counting and conceptions of number*. New York: Springer-Verlang.

Gallistel, R., & Gelman, R. (2000). Non-verbal numerical cognition: from reals to integers. *Trends in Cognitive Sciences*, **4** (2), 59–65.

Geminiani, G., Bisiach, E., Berti, A., & Rusconi, M.L. (1995). Analogical representation and language structure. *Neuropsychologia*, **33**, 1565–1574.

Göbel, S., Walsh, V., & Rushworth, M.F.S. (2001). The mental number line and the human angular gyrus. *NeuroImage*, **14** (6), 1278–1289.

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

Huttenlocher, J., Jordan, N.C., & Levine, S.C. (1994). A mental model for early arithmetic. *Journal of Experimental Psychology: General*, **123**, 284–296.

Johnson, M.H. (2005). Subcortical face processing. *Nature Reviews Neuroscience*, **6**, 766–774.

Jordan, K.E., & Brannon, E.M. (2006). A common representational system governed by Weber's law: nonverbal numerical similarity judgments in 6-year-olds and rhesus macaques. *Journal of Experimental Child Psychology*, **95**, 215–229.

Karmiloff-Smith, A. (1998). Development itself is the key to understanding developmental disorders. *Trends in Cognitive Sciences*, **2**, 389–398.

Landau, B. (1996). Multiple geometric representations of objects in languages and language learners. In P. Bloom, M.A. Peterson, L. Nadel, & M.F. Garrett (Eds.), *Language and space* (pp. 317–363). Cambridge, MA: MIT Press.

© 2009 Blackwell Publishing Ltd.

Lee, K. (2000). Cortical areas differentially involved in multiplication and subtraction: a functional magnetic resonance imaging study and correlation with a case of selective acalculia. *Annals of Neurology*, **48**, 657–661.

Loewenstein, J., & Gentner, D. (2005). Relational language and the development of relational mapping. *Cognitive Psychology*, **50**, 315–353.

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

Maas, A., & Russo, A. (2003). Directional bias in the mental representation of spatial events: nature or culture? *Psychological Science*, **14**, 296–301.

Opfer, J.E., & DeVries, J.M. (2008). Representational change and magnitude estimation: why young children can make more accurate salary comparisons than adults. *Cognition*, **108**, 843–849.

Opfer, J.E., & Siegler, R.S. (2007). Representational change and children's numerical estimation. *Cognitive Psychology*, **55**, 169–195.

Opfer, J.E., & Thompson, C.A. (2008). The trouble with transfer: insights from microgenetic changes in the representation of numerical magnitude. *Child Development*, **79**, 788–804.

Penner-Wilger, M., Fast, L., Lefevre, J.A., Smith-Chant, B.L., Skwarchuk, S.L., Kamawar, D., & Bisanz, J. (2007). The foundations of numeracy: subitizing, finger gnosia, and fine motor ability. In D.S. McNamara & J.G. Trafton (Eds.), *Proceedings of the 29th Annual Conference of the Cognitive Science Society*. Austin, TX: Cognitive Science Society.

Penner-Wilger, M., Fast, L., Lefevre, J.A., Smith-Chant, B.L., Skwarchuk, S.L., Kamawar, D., Bisanz, J., & Deslauriers, W.A. (2008). Investigating the building blocks of numerical representations: subitizing and finger gnosis. In B.C. Love, K. McRae, & V.M. Sloutsky (Eds.), *Proceedings of the 30th Annual Conference of the Cognitive Science Society*. Austin, TX: Cognitive Science Society.

Pesenti, M., Thioux, M., Seron, X., & De Volder, A. (2000). Neuroanatomical substrates of Arabic number processing, numerical comparisons, and simple addition: a PET study. *Journal of Cognitive Neuroscience*, **12**, 461–476.

Piazza, M., Mechelli, A., Butterworth, B., & Price, C. (2002). Are subitizing and counting implemented as separate or functionally overlapping processes? *NeuroImage*, **15**, 435–446.

Pinel, P., Dehaene, S., Riviere, D., & LeBihan, D. (2001). Modulation of parietal activation by semantic distance in a number comparison task. *NeuroImage*, **14**, 1013–1026.

Pinel, P., Piazza, M., LeBihan, D., & Dehaene, S. (2004). Distributed and overlapping cerebral representations of number, size, and luminance during comparative judgments. *Neuron*, **41**, 983–993.

Potter, M.C., & Levy, E.I. (1968). Spatial enumeration without counting. *Child Development*, **39**, 54–98.

Revkin, S.K., Izard, M.P., Cohen, L., & Dehaene, S. (2008). Does subitizing reflect numerical estimation? *Psychological Science*, **19**, 607–614.

Roberts, W.A. (2005). How do pigeons represent numbers? Studies of number scale bisection *Behavioral Processes*, **69**, 33–43.

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

Shaki, S., Fischer, M.H., & Petrusic, W.M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin & Review*, **16**, 328–331.

Siegler, R.S., & Booth, J.L. (2004). Development of numerical estimation in young children. *Child Development*, **75**, 428–444.

Siegler, R.S., & Opfer, J.E. (2003). The development of numerical estimation: evidence for multiple representations of numerical quantity. *Psychological Science*, **14**, 237–243.

Siegler, R.S., Thompson, C.A., & Opfer, J.E. (2009). The logarithmic-to-linear shift: one learning sequence, many tasks, many time scales. *Mind, Brain, & Education*, **3**, 143–150.

Simon, O., Cohen, L., Mangin, J., Bihan, D., & Dehaene, S. (2002). Topographical layout of hand, eye, calculation and language related areas in the human parietal lobe. *Neuron*, **33**, 475–487.

Thompson, C.A., & Opfer, J.E. (2008). Costs and benefits of representational change: effects of context on age and sex differences in symbolic magnitude estimation. *Journal of Experimental Child Psychology*, **101**, 20–51.

Thompson, C.A., & Opfer, J.E. (in press). How 15 hundred is like 15 cherries: effect of progressive alignment on representational changes in numerical cognition. *Child Development*.

Wagner, J., & Johnson, S.C. (under review). A relationship between understanding cardinality and analog magnitude representations in preschoolers. *Cognition*.

Ward, C., & Smuts, B.B. (2007). Quantity-based judgments in domestic dogs (*Canis lupus familiaris*). *Animal Cognition*, **10**, 71–80.

Wynn, K. (1990). Children's understanding of counting. *Cognition*, **36**, 155–193.

Zorzi, M., Priftis, K., & Umilta, C. (2002). Brain damage: neglect disrupts the mental number line. *Nature*, **417** (6885), 138–139.

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