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Brief article

Mental movements without magnitude? A study of spatial biases in symbolic arithmetic

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ABSTRACT

McCrink (McCrink, Dehaene, & Dehaene-Lambertz (2007). Moving along the number line: Operational momentum in nonsymbolic arithmetic. Perception and Psychophysics, 69(8), 1324-1333) documented an "Operational Momentum" (OM) effect – overestimation of addition and underestimation of subtraction outcomes in non-symbolic (dot pattern) arithmetic. We investigated whether OM also occurs with Arabic number symbols. Participants pointed to number locations (1–9) on a visually given number line after computing them from addition or subtraction problems. Pointing was biased leftward after subtracting and rightward after adding, especially when the second operand was zero. The findings generalize OM to the spatial domain and to symbolic number processing. Alternative interpretations of our results are discussed.

1. Introduction

The mental representation of numbers is under intense investigation. This is partly a result of the discovery that small numbers tend to be associated with left space, and larger numbers with right space. This Spatial-Numerical Association of Response Codes (SNARC) effect influences response selection, attention allocation, manual pointing and movement endpoints (Fischer, 2001, 2003; Song & Nakayama, 2008; for reviews, see Fias & Fischer, 2005; Hubbard, Piazza, Pinel, & Dehaene, 2005). The effect is interpreted as indicating a spatially oriented "mental number line" (MNL, e.g., Dehaene, Bossini, & Giraux, 1993). Importantly, SNARC effects have so far only been documented for single numbers, but the involvement of spatial and attentional areas in the parietal lobes during mental calculation predicts spatial biases also during more complex numerical cognition, such as mental arithmetic (Hubbard et al., 2005). McCrink, Dehaene, and Dehaene-Lambertz (2007) reported a novel bias in mental arithmetic. They showed adults addition and subtraction problems as moving dot patterns and found an "operational momentum" (OM) effect: a bias toward larger presented outcome values for addition and smaller values for subtraction problems.

The combined evidence from SNARC and OM effects suggests that mental arithmetic should be spatially biased: Addition yields larger numbers, which are further right, while subtraction yields smaller numbers, which are further left on the MNL. We tested this prediction by presenting symbolic arithmetic problems (e.g., $2+4$, $8-2$) and measuring how participants pointed to the locations of results on a visually presented line that represented the numerical interval from 0 to 10 (cf. Siegler & Opfer, 2003). OM should induce systematic response shifts to the left and right for subtraction and addition, respectively, and also faster pointing to small and large results following subtraction and addition, respectively.

Note that any OM effect could reflect the magnitude of the first or second operand, or the result, or a bias induced by the plus or minus sign. To reduce ambiguity about the

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origin of OM, we included zero problems (e.g., 2 + 0, 2 − 0) which are considered rule-based problems (Butterworth, Zorzi, Girelli, & Jonckheere, 2001; Campbell & Metcalfe, 2007; Wellman & Miller, 1986). Together with the fact that zero is not usually represented on the MNL (e.g., Brysbaert, 1995; Tzelgov, Ganor-Stern, & Maymon-Schreiber, in press), this should minimize OM from the second operand.

Single digit localization was measured before and after the calculation task to establish baseline performance and assess its stability. Pre-school children show logarithmic compression in their spatial mapping of numbers, whereas school children and adults show a linear metric (Siegler & Opfer, 2003) in this task.

2. Method

2.1. Participants

Fourteen native English-speaking students (mean age 21 years; 1 male; two left-handers) participated in the experiment for credit or £4. All had normal or corrected vision.

2.2. Apparatus and stimuli

Stimuli appeared on an ELO 20" touch-screen with 1024×768 pixel resolution, controlled via E-Prime (Schneider, Eschman, & Zuccolotto, 2002). A display sequence (Fig. 1) began with a green start box (40×40 pixels, 10×10 mm) at the bottom center of the grey screen. All other stimuli were black. A horizontal line (20×400 pixels, 5×100 mm) flanked by digits 0 and 10 (Courier New 30 point font) appeared at fixed height on the screen (y coordinate = 350 pixels, 87.5 mm above the start box) but its left edge varied pseudo-randomly between center (312 pixels), left (232 pixels) and right (392 pixels) positions. Stimuli consisted of single digits 1–9 (except 5[1]) or arithmetic problems derived from digits 1–9. Digits were presented in Courier New 40 point font and appeared inside a rectangle (75×75 pixels, 19×19 mm). Problems appeared inside a wider rectangle (166×75 pixels, 42×19 mm) with an operation sign (+ or − sign, 5 pixels wide, 20 pixels long; 1.25×5 mm) between the two operands.

2.3. Materials and design

For the localization task, each digit appeared randomly nine times, resulting in 72 trials. This task was presented both before and after the calculation task to assess the stability of spatial associations for these digits. For the calculation task, 18 addition and 18 subtraction problems were generated on the basis of several considerations. For example, for outcomes close to the edges of the interval used there was an asymmetry between addition and subtraction problems. Consequently, problems starting with 0, 1, or 9 were excluded because the operation was predictable from the magnitude of the first operand. We tested OM with outcomes 4 and 6 because these were equally often the result of addition or subtraction, and because they had comparable second operands (0, 1, and 2). We included a total of 12 problems (6 for each operation) with zero as the second operand to assess "pure" OM without contamination by a second magnitude. Table A1 (Appendix A) lists all 36 problems used. Each problem appeared nine times, resulting in 324 trials. Calculation problems were randomly presented in 6 successive blocks (54 trials per block).

2.4. Procedure

Participants sat on a height-adjustable chair about 50 cm from the touch-screen. They touched the start box with the right index finger to trigger the display of either a digit or a problem and the line with flankers. The digit or problem disappeared after 200 ms. Participants were instructed to accurately point to where the digit or result would be located on the line. Pointing time (PT) was the interval between contacting the start box and the next touch-down and reflected the sum of reaction time (an indicator of movement planning) and movement time (the time of movement execution). All touch coordinates (in pixels, relative to the start of a line) and PTs (in ms) were recorded. An error beep was played whenever PT exceeded 800 ms to induce fast responding.

3. Results

We successively eliminated trials with PTs outside 200–800 ms, PTs outside 2.5 standard deviations from each individual's mean, and lift-off coordinates outwith the start box or where the target line was clearly missed, leaving 95% of data for statistical analysis.

3.1. Localization task

Average landing coordinates for numbers 1, 2, 3, 4, 6, 7, 8, and 9 were 36, 70, 104, 137, 231, 269, 299 and 332 pixels, respectively. A 2 (pre-test, post-test) × 8 (number magnitude) analysis of variance (ANOVA) found an effect of magnitude, $F(7,91) = 1331.88$, $p < 0.01$. Post hoc comparisons revealed a positive linear trend[2] $F(1,13) = 2645.19$, $p < 0.01$. There was also a reliable interaction, $F(7,91) = 3.24$, $p < 0.01$: post hoc contrasts showed that larger magnitudes (6–9) were localized 10 pixels further right [$F(1,13) = 8.34$, $p < 0.05$], and smaller magnitudes (1–4) were localized 5 pixels further left in the post-test compared to the pre-test [$F(1,13) = 5.03$, $p < 0.05$].

Next, we computed differences between adjacent means to assess whether distances decreased with increasing magnitude, reflecting a logarithmic MNL, or whether all distances would be equal, reflecting a linear structure (Dehaene, 2001). The average distance between target locations was 33.6 pixels. In the 2 (pre-test, post-test) × 6

[1] We excluded 0, 5, and 10 because the edges or midpoint of the line were much easier to attain in pilot tests than other target locations.

[2] In cases of unequal spacing between independent variable levels, compatible linear trend coefficients were computed according to Robson (1959).

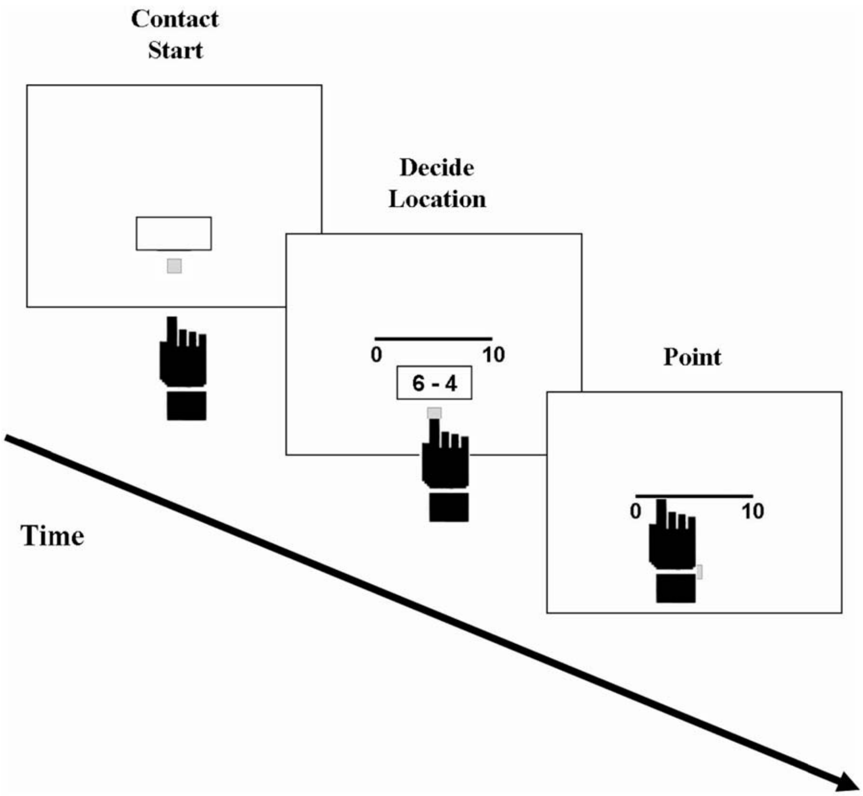

Fig. 1. Illustration of the experimental procedure with the calculation task, not drawn to scale.

(distances) ANOVA there were no reliable effects, all $p > 0.13$. The linear MNL hypothesis also predicts increasing variability with magnitude (scalar property) whereas the logarithmic hypothesis predicts no change in variability. The standard deviations for ascending numbers were 17, 20, 26, 26, 29, 29, 25, and 34 pixels, respectively, $F(7,91) = 6.23$, $p < 0.01$, indicating increasing variability for larger magnitudes. This was confirmed by a significant linear trend, $F(1,13) = 11.39$, $p < 0.01$. There were no other reliable effects, $F < 1$.

Finally, average PT was 587 ms. An effect of magnitude, $F(7,91) = 6.31$, $p < 0.01$, indicated faster pointing as magnitude increased, $F(1,13) = 23.19$, $p < 0.01$. There were no other effects, $F < 1$. Together, these localization results show that participants understood the task, relied on a linear mapping of numbers to space, and made more complete use of the number line in the post- compared to the pre-test.

3.2. Calculation task

We determined the presence of OM by comparing horizontal landing coordinates on the visually presented line for "4" and "6" which each were the result of eight different addition and subtraction operations. Separate ANOVAs evaluated effects of result size (four, six), operation (addition, subtraction) and second operand size (zero, one, two) on horizontal landing coordinates and on PTs. Participants pointed further to the right to indicate "6" (209 pixels) compared to "4" (136 pixels), $F(1,13) = 407.79$, $p < 0.01$. Importantly, participants pointed further right following addition (193 pixels) compared to subtraction (164 pixels), $F(1,13) = 10.52$, $p < 0.01$, indicating an OM effect. The main effect of second operand size, $F(2,26) = 7.50$, $p < 0.01$, reflected pointing further right when the second operand was smaller (181 pixels for "0" and 186 pixels for "1", no reliable difference), than when it was larger (172 pixels for "2", which differed significantly from the former pair, $p < 0.01$). There was also a significant triple interaction, $F(2,26) = 3.34$, $p = 0.05$, depicted in Fig. 2. For "6", post hoc tests confirmed that the OM bias was present with each second operand size, all p-values < 0.05, whereas for "4", the OM effect was only reliable when the second operand size was "0".

We further checked for OM relative to baseline performance by comparing horizontal landing coordinates of results "4" and "6" for each operation in the calculation task with those of "4" and "6" in the localization task (averaged across pre- and post-test). A target (four, six) × task (localization, calculation-addition, calculation-subtraction) ANOVA found a reliable main effect of target, $F(1,13) = 503.2$, $p < 0.01$, due to locating "6" (223 pixels) further rightward than "4" (141 pixels). The main effect of task, $F(2,26) = 9.25$, $p < 0.01$, reflected pointing further to the left in subtraction (176 pixels) compared to baseline (187 pixels), $F(1,13) = 13.37$, $p < 0.01$; there was no significant rightward bias for addition (185 pixels) compared to baseline, $F < 1$. There was also a reliable interaction,

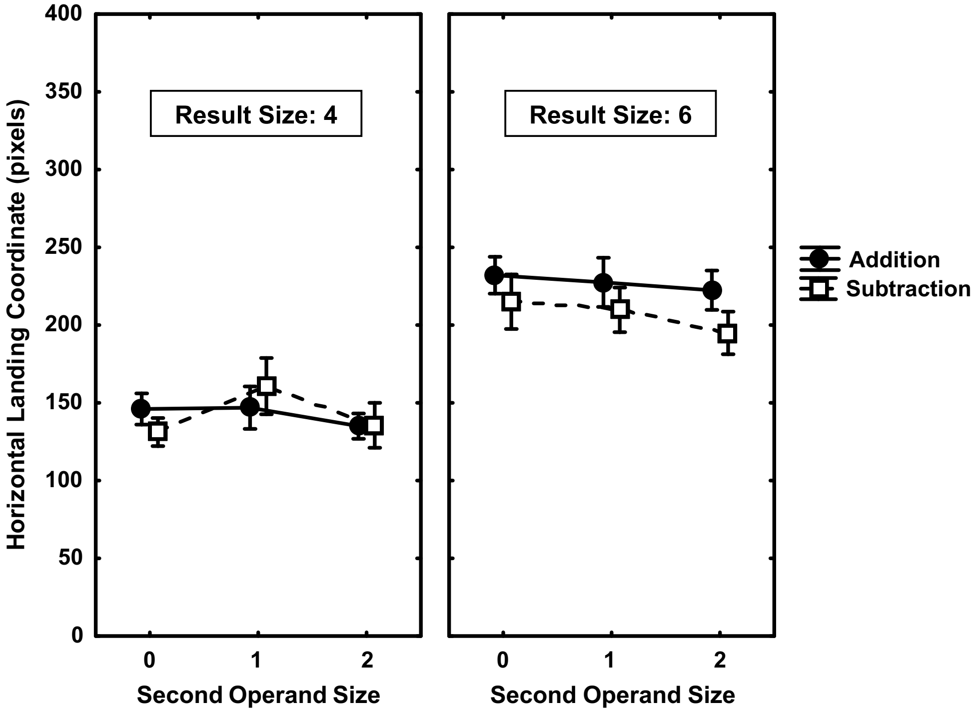

Fig. 2. Mean horizontal landing coordinates (pixels) as a function of result size, operation and second operand size. Vertical bars denote 95% confidence intervals.

$F(2,26) = 25.02$, $p < 0.01$. This was due to significant rightward bias with target "4" for addition compared to baseline (141 vs. 137 pixels), $F(1,13) = 4.88$, $p < 0.05$, but no leftward bias for subtraction (142 pixels), $F(1,13) = 1.36$, *ns*. With target "6" (baseline 231 pixels) we found reliable *leftward* bias for addition (222 pixels), $F(1,13) = 6.93$, $p < 0.05$, but much more so for subtraction (201 pixels), $F(1,13) = 42.72$, $p < 0.01$.

In the PT analysis, a reliable main effect of operation, $F(1,13) = 56.23$, $p < 0.01$, showed that participants responded faster to addition (659 ms) than to subtraction (688 ms). The main effect of second operand size, $F(2,26) = 13.8$, $p < 0.01$, reflected faster pointing for "0" (656 ms) compared to "1" or "2" (680 and 683 ms, respectively). Fig. 3 shows that operation interacted significantly with second operand size [$F(2,26) = 8.47$, $p < 0.01$] because the addition advantage was significant for "1" [$F(1,13) = 35.99$, $p < 0.01$] and "2" [$F(1,13) = 25.26$, $p < 0.01$], but not for "0" [$F(1,13) = 1.6$, *ns*]. All other effects were not reliable, all $p > 0.22$.

We analyzed "pure" OM by looking at zero problems without activation of second operand magnitudes. Separate ANOVAs evaluated effects of operation (addition, subtraction) and result size (2, 3, 4, 6, 7, 8) on horizontal landing coordinates and on PTs. For landing coordinates (Fig. 4), the main effect of operation, $F(1,13) = 20.48$, $p < 0.01$, showed that participants pointed significantly further leftward when subtracting (177 pixels) compared to adding (188 pixels). The main effect of result size, $F(5,65) = 517.51$, $p < 0.01$, reflected the ordered target locations, and a significant linear trend, $F(1,13) = 839$, $p < 0.01$, confirmed task compliance. Average landing coordinates for results 2, 3, 4, 6, 7, and 8 were 77, 106, 138, 223, 263 and 287 pixels, respectively. Although there was no reliable interaction, $F(5,65) = 1.4$, *ns*, post hoc comparisons checked each result for OM. OM was significant for results "2" [$F(1,13) = 5.53$, $p < 0.05$], "4" [$F(1,13) = 14.71$, $p < 0.01$], "6" [$F(1,13) = 6.3$, $p < 0.05$], and "7" [$F(1,13) = 4.93$, $p < 0.05$], but not for "3" ($F < 1$) and "8" [$F(1,13) = 1.92$, *ns*]. Further paired contrasts showed that almost all zero problems had significantly more OM [for addition: 6 + 0 vs. (2 + 4, 4 + 2, 5 + 1); 7 + 0 vs. (3 + 4, 2 + 5); 8 + 0 vs. 3 + 5, but not 4 + 0 vs. 3 + 1; for subtraction: 2–0 vs. (6–4, 7–5); 3–0 vs. (7–4, 8–5); 4–0 vs. (5–1, 6–2, 7–3, 8–4), but not 6–0 vs. (7–1, 8–2)], and significantly smaller variability of landing coordinates in all subtraction problems, with similar trends in all addition problems (see Table A1 in Appendix A). We also noticed smaller variability of pointing coordinates for two out of the three tie problems (problems number 13 and 22, see Table A1 in Appendix A) compared to non-tie problems with the same result.

Comparing OM in zero problems to (averaged) baseline performance with a target (2, 3, 4, 6, 7, 8) × task (localization, calculation-addition, calculation-subtraction) ANOVA revealed a main effect of target, $F(5,65) = 700$, $p < 0.01$, reflecting left-to-right-ordered targets [$F(1,13) = 1116.85$, $p < 0.01$]. The main effect of task, $F(2,26) = 12.3$, $p < 0.01$, reflected pointing further left in subtraction (177 pixels) compared to baseline (185 pixels), $F(1,13) = 10.96$, $p < 0.01$, and further right in addition (188 pixels) compared to baseline, though this comparison failed to reach

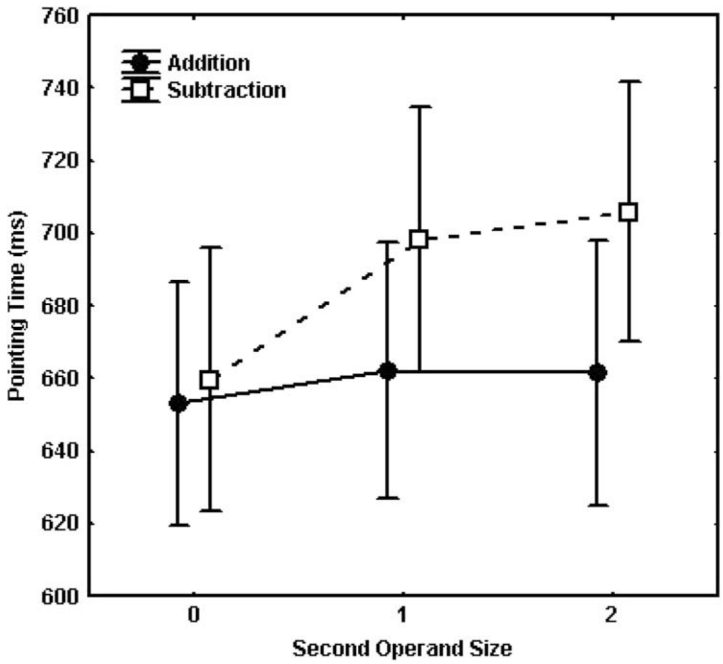

Fig. 3. Mean PTs as a function of operation and second operand size. Vertical bars denote 95% confidence intervals.

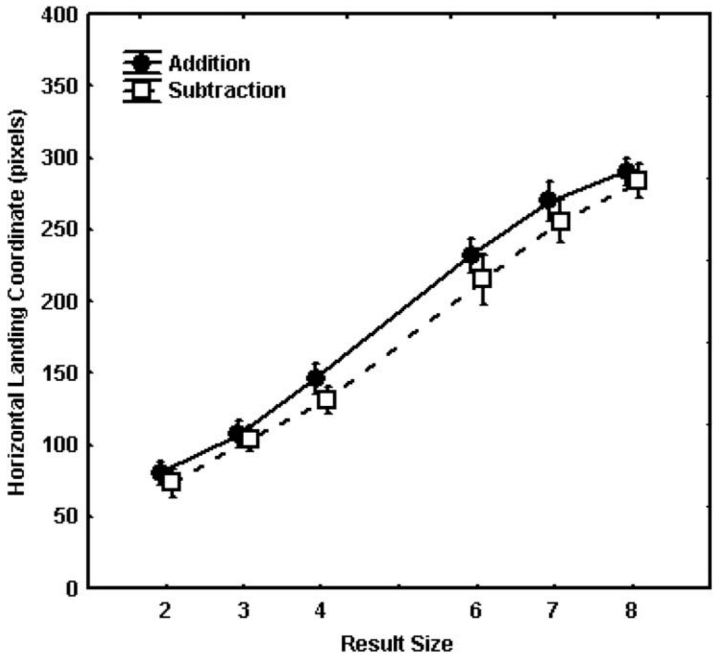

Fig. 4. Mean horizontal landing coordinates (pixels) as a function of result size and operation for zero-problems. Vertical bars denote 95% confidence intervals.

significance, $F(1,13) = 1.83$, *ns*. There was also a reliable interaction, $F(10,130) = 3.37$, $p < 0.01$. Post hoc contrasts showed rightward shift for addition in all targets but "8", although this bias was significant only in targets "2" and "4"; for subtraction, significant leftward shift was found for all targets but "2" and "3" (see Table A2 in Appendix A).

The analysis of PTs in zero problems revealed a reliable interaction of operation and result size [$F(5,65) = 4.13$, $p < 0.01$]. Fig. 5 shows that for small results (2–4) responses were faster for subtractions than additions [$F(1,13) = 4.3$, $p = 0.05$] while for large results (6–8) responses were faster for additions than subtractions

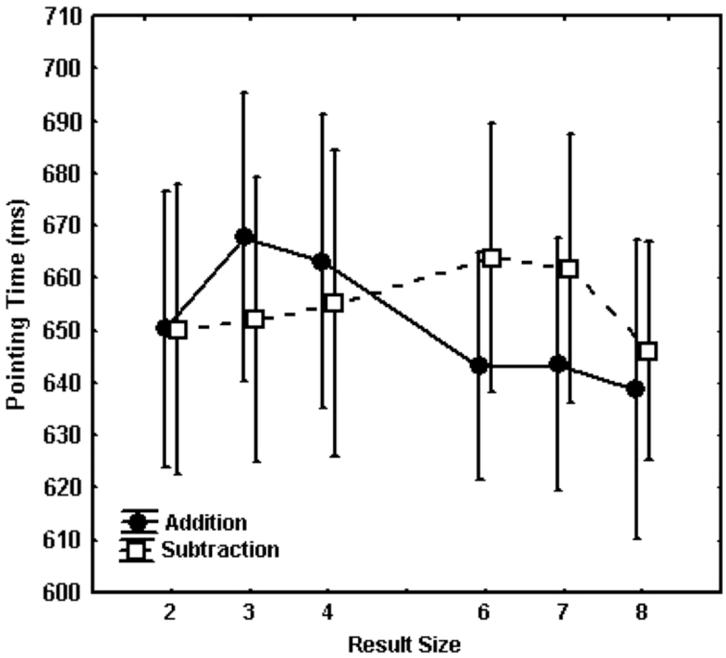

Fig. 5. Mean PTs as a function of result size and operation for zero-problems. Vertical bars denote 95% confidence intervals.

[$F(1,13) = 13.2$, $p < 0.01$]. Further analyses showed reliably faster PTs for all zero-problems compared to non-zero problems with the same result, except for 4 + 0 vs. 3 + 1 (see Table A1 in Appendix A).

4. Discussion

Our study of speeded pointing to arithmetic results extends previous research on spatial-numerical associations from single-digit tasks to more complex mental arithmetic. It is, however, unclear whether SNARC and OM effects indicate the same underlying activation of a spatially oriented MNL. The original OM effect (McCrink et al., 2007) reflected accepting the wrong results but the spatial OM effect in the present study is too small to imply systematically distorted calculation outcomes. Instead, while responding accurately, our participants mapped the same number onto different segments of a spatial interval, depending on whether they activated the number concept through addition or subtraction. This is reminiscent of the flexibility of SNARC with number range (Dehaene et al., 1993, Experiment 3) or task instructions (Bächtold, Baumüller, & Brugger, 1998).

Our results document OM with symbolic numbers, thus extending the work of McCrink et al. (2007) with dot patterns into the domain of everyday numerical cognition and showing that performance with precise quantities is prone to similar biases. The authors offered two accounts of OM: One hypothesis was that adding and subtracting are equivalent to covert movements to the right and left along the MNL, respectively. This is supported by congruency effects in overt movement times (Fig. 5; see also Fischer, 2003), and similar OM across operands (Fig. 4). Their alternative account of OM as reflecting a logarithmically compressed MNL can be rejected: Our baseline data reveal a linear mapping of numbers (Siegler & Opfer, 2003) and even suggest further expansion during testing. However, this latter observation needs to be replicated in future studies, ideally intermixing localization and calculation tasks.

We briefly discuss a third possible origin of OM. Assume a left-to-right oriented MNL where each operand induces spatially localized activation that competes for responses. Such activation is always to the left of target for addition, thus explaining our smaller OM for addition compared to subtraction. Subtraction problems have the target either between operands (e.g., 6–2) or to their left (e.g., 6–4), with the latter case diluting OM the most. Inspection of Appendix A supports this competition hypothesis: If landing positions in zero problems reflect the unbiased response range for a given result (e.g., “2” ranges from 74 to 81 pixels), then four of the six subtraction problems with both operands to the right of the target show reduced OM from attraction towards the second operand (problems number 5, 6, 9, and 10). For zero problems, in contrast, there is no competing second operand, either because zero is not usually represented on the MNL (Brysbaert, 1995; Tzelgov et al., 2008) or because these problems are solved on the basis of rules instead of arithmetic operations (Butterworth et al., 2001; Campbell & Metcalfe, 2007; Wellman & Miller, 1986). The result is less diffuse activation and a clearer, operation-based spatial bias in zero problems, just as we find. Smaller variability of landing distributions and faster PTs for zero compared to non-zero problems, and smaller variability for most tie problems compared to other problems with the same result, are all consistent with the idea of reduced spatial competition during movement planning and/or execution with fewer activated operands. We therefore suggest that OM reflects the combined bias of spatial activation from operands, operator, and result size. Further research with this novel paradigm can test these possibilities, also by studying movement kinematics (Song & Nakayama, 2008). Our spatial competition hypothesis predicts least competition in zero problems, more for tie problems, and most competition for problems where the result differs from both operands.

Speeded pointing is a new tool for the study of on-line activation of number representations and its behavioral consequences. Although others have looked at how numbers are mapped onto a visually presented line (e.g., Siegler & Opfer, 2003) this is the first application to mental arithmetic. Future studies could look at effects of first operand size and larger number ranges, to see whether spatial bias increases with magnitude (McCrink et al., 2007), or at different arithmetic operations. Effects of expertise, gender and handedness would also be of interest to establish the validity of this task. The relation between numerical expertise and spatial-numerical associations is understudied (see Fischer, 2006, for discussion), and our combination of spatial behaviour (male dominance) and numerical performance (female dominance, Kimura, 1999) does not allow clear predictions. Similarly, while the bilateral representation of numbers in the brain predicts that left- and right-handers should perform equivalently on this task, reliance on different brain structures for different arithmetic operations might favor one over the other response side.

The pointing arithmetic task provides excellent control over spatial and temporal aspects of stimulation and performance and is likely to contribute to our understanding of the link between numerical and spatial representations. It might also point the way towards remedial techniques for numerically impaired populations (Wood & Fischer, 2008) and have implications for the use of gestures in mathematics teaching (e.g., Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001).

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Appendix A

Appendix Table A1
Appendix Table A2

Table A1
Materials used in the study and associated performance. PT (ms) = pointing time in milliseconds.

Problem number	Operand 1	Operation	Operand 2	Result	Horizontal landing coordinate (pixels)		PT (ms)
					Average	Standard deviation	
1	5	–	4	1	127	103	735
2	6	–	5	1	85	59	734
3	2	+	0	2	81	24	650
4	2	–	0	2	73	25	650
5	6	–	4	2	102	49	719
6	7	–	5	2	112	53	730
7	3	+	0	3	108	29	668
8	3	–	0	3	104	29	652
9	7	–	4	3	132	51	718
10	8	–	5	3	128	57	735
11	4	+	0	4	146	32	664
12	3	+	1	4	147	40	657
13	2	+	2	4	135	32	655
14	4	–	0	4	131	32	655
15	5	–	1	4	159	55	693
16	6	–	2	4	136	43	704
17	7	–	3	4	135	47	719
18	8	–	4	4	139	48	724
19	6	+	0	6	232	39	642
20	5	+	1	6	227	36	666
21	4	+	2	6	222	47	668
22	3	+	3	6	220	39	658
23	2	+	4	6	219	46	677
24	6	–	0	6	214	50	664
25	7	–	1	6	211	55	705
26	8	–	2	6	194	68	705
27	7	+	0	7	270	39	643
28	3	+	4	7	258	39	682
29	2	+	5	7	249	40	682
30	7	–	0	7	255	51	660
31	8	+	0	8	290	33	638
32	4	+	4	8	267	43	659
33	3	+	5	8	275	35	672
34	8	–	0	8	284	31	645
35	5	+	4	9	319	34	665
36	4	+	5	9	320	36	663

Table A2
Spatial performance (in pixels) for localization (separately for pre-test and post-test) and for calculation (based on zero problems only)

Target	Localization – pre-test		Localization – post-test		Calculation – addition		Calculation – subtraction	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
2	73	19	66	21	81	24	73	25
3	108	26	99	25	108	29	104	29
4	138	29	136	23	146	32	131	32
6	226	29	236	29	232	39	214	50
7	265	29	273	28	270	39	255	51
8	294	28	304	22	290	33	284	31

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