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Document type : *Article de périodique (Journal article)*

Référence bibliographique

Masson, Nicolas ; Pesenti, Mauro. *Attentional bias induced by solving simple and complex addition and subtraction problems.* In: *The Quarterly Journal of Experimental Psychology*, Vol. 67, no. 8, p. 1514-1526 (2014)

DOI : 10.1080/17470218.2014.903985

Attentional bias induced by solving simple and complex addition and subtraction problems

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Chapter 2: Attentional bias induced by solving simple and complex addition and subtraction problems

Published in Quarterly Journal of Experimental Psychology in 2014

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Abstract

The processing of numbers has been shown to induce shifts of spatial attention in simple probe detection tasks, with small numbers orienting attention to the left and large numbers to the right side of space. Recently, the investigation of this spatial-numerical association has been extended to mental arithmetic with the hypothesis that solving addition or subtraction problems may induce attentional displacements (to the right and to the left respectively) along a mental number line (MNL) onto which the magnitude of the numbers would range from left to right, from small to large numbers. Here we investigated such attentional shifts using a target detection task primed by arithmetic problems in healthy participants. The constituents of the addition and subtraction problems (first operand; operator; second operand) were flashed sequentially in the centre of a screen, then followed by a target on the left or the right side of the screen which the participants had to detect. This paradigm was employed with arithmetic facts (Experiment 1) and with more complex arithmetic problems (Experiment 2) in order to assess the effects of the operation, the magnitude of the operands, the magnitude of the results, and the presence or absence of a requirement for the participants to carry or borrow numbers. The results showed that arithmetic operations induce some spatial shifts of attention, possibly through a semantic link between the operation and space.

2.1Introduction

Numerous behavioural, neuroimaging and neuropsychological findings support the assumption that a functional link exists between numbers and space (for reviews, see Hubbard, Piazza, Pinel, & Dehaene, 2005; Walsh, 2003). This association has been conceptualized by the idea of the mental number line (MNL), a cognitive representation of the magnitude of numbers where small numbers are represented spatially on the left and large numbers on the right (Dehaene, 1992). This idea is a useful metaphor for interpreting the observation of shifts of visuospatial attention following the mere presentation of numerical information. Indeed, visual targets are detected faster in the left hemifield after the presentation of a small digit cue and in the right hemifield when they are preceded by larger digits (Fischer, Castel, Dodd, & Pratt, 2003). However, this effect was not always observed (Bonato, Priftis, Marenzi, & Zorzi, 2009), and when participants were asked to imagine a right to left number line, a reverse effect was found (Galfano, Rusconi, & Umiltà, 2006; Ristic, Wright, & Kingstone, 2006). Moreover, the position of numbers in memorized series of four digits could overcome the effect of numerical magnitude upon attention (van Dijck, Abrahamse, Majerus, & Fias, 2013). Interestingly, a recent study showed that, in cancellation tasks, the distribution of participants’ hits was shifted to the left for small and to the right for large numbers (Di Luca, Pesenti, Vallar, & Girelli, 2013). However, this effect was maximized when the numerical cues were irrelevant to the task i.e., when used as distractors rather than targets. Conversely, in a temporal order judgement paradigm, when targets appeared at the same time, the mere presentation of digits did not bias participants’ decisions unless they were asked to report the digit cue after performing the task (Casarotti, Michielin, Zorzi, & Umiltà, 2007). This suggests that the type and depth of numerical processing required by the tasks modulate the way spatial attention biases occur.

Unsurprisingly given the salience of the numbers' magnitude in this type of task, solving arithmetic problems was also shown to cause spatial attentional shifts. An overestimation bias was observed when participants were asked to solve addition problems and an underestimation bias was observed when participants were asked to solve subtraction problems. This effect was termed *operational momentum* (OM; McCrink, Dehaene, & Dehaene-Lambertz, 2007). It occurs with both symbolic and non-symbolic material (Knops, Viarouge, & Dehaene, 2009a; McCrink & Wynn, 2009), and was observed with different response modalities such as multiple choice paradigms (Knops et al., 2009a; Knops, Zitzmann, & McCrink, 2013; McCrink & Wynn, 2009), and pointing to the estimated response on a line flanked line by numbers (Pinhas & Fisher, 2008). However, no OM effect was observed with problems involving carrying, perhaps because they would rely more on verbal mechanisms than on attentional processes (Lindemann & Tira, 2011). The most popular interpretation of this bias is that mental calculation is processed via "motion" or a "walk" along the MNL in the direction related to the operation (i.e., to the left for subtraction and to the right for addition) where the participant goes "too far", which leads to underestimation or overestimation for subtraction or addition problems respectively (e.g., McCrink et al., 2007). Indeed, the OM effect could result from the combination of compressed number-space mapping (i.e., the MNL) and an uncompressed computation on this mapping. This hypothesis is supported by a recent computational model showing that performing arithmetic problems relies upon basic spatial functions such as shifting attention on a spatial continuum (Chen &

Verguts, 2012). Nevertheless, this model does not explain the absence of an OM effect for problems that involve carrying (Lindemann & Tira, 2011).

At the neurofunctional level, it has been shown that the brain activations elicited by the resolution of large addition problems (e.g., 50 ± 26) resemble activations induced by rightward saccades (Knops, Thirion, Hubbard, Michel, & Dehaene, 2009b). Indeed, a classifier was built to predict whether participants were solving addition problems or subtractions based upon the activation of the superior parietal cortex when their eyes shifted to the right or to the left. The classifier could accurately distinguish addition trials but no such precision could be obtained for subtractions. It has also been shown that participants who calculate the approximate outcomes of addition or subtraction problems and are afterwards required to select the number closest to their estimation from seven proposed results presented to them in the form of a circle, prefer to select the proposals located on the upper right of the circle in the case of addition problems and on the upper left of the circle in the case of subtraction problems (Knops et al., 2009a). Altogether, these observations suggest that spatial-attentional processing is employed in solving arithmetic problems.

Nevertheless, the idea that solving arithmetic problems leads to spatial shifts of attention due to movements along a spatial-numerical continuum related to adding or subtracting operands is still a matter of debate. Indeed, problems where zero is the second operand (hereinafter "zero problems") have been shown to induce spatial biases to the right or to the left in the case of addition or subtraction problems, respectively (Pinhas & Fischer, 2008), although no “movement” on the MNL is required in this case. The spatial biases in arithmetic could therefore simply result from a competition between localized activation of the operands, the result, and a semantic link between the type of operation and space (i.e., right-addition; left-subtraction; Pinhas & Fischer, 2008). Moreover, no previous studies examining spatial bias in arithmetic have used basic and complex arithmetic problems that simultaneously controlled some variables such as the magnitude of the operands and the outcomes or the type of problems (i.e., carry *vs.* non-carry problems) with symbolic material. Indeed, in Lindemann and Tira 's study (2011), the answers required a production in a non-symbolic notation (i.e., with dot collections). For problems involving carrying, the second operands of addition problems were significantly larger than for subtraction problems (addition: 38±12, subtraction: 21±9; $t(11)=3.575$, $p<.005$), and the problems not involving carrying had both the smallest and the largest outcomes among the set of problems presented. Finally, the results of the addition problems used by Knops et al. (2009b) in their neuroimaging study were also significantly larger than the results of the subtraction problems. Given that larger magnitudes can induce attentional shifts to the right and smaller magnitudes to the left *per se* (e.g., Fischer et al., 2003), it is critical to control for the magnitude of the results of addition and subtraction problems. Indeed, using larger results for addition than for subtraction problems makes it difficult to isolate the effect of the type of operation and the effect of the magnitude of the numbers that are being manipulated.

To assess whether solving addition and subtraction problems in symbolic notation induces shifts of spatial attention, we adapted the target detection task initially used by Fischer and his colleagues (2003), replacing the digit shown before the target with an arithmetic problem. Participants thus completed a target-detection task after solving arithmetic problems. If solving addition and subtraction problems gives rise to shifts of visuospatial attention, it is expected that addition problems would facilitate the detection of right-sided targets and/or impair the detection of targets in the left hemifield and that subtraction problems would facilitate the detection of targets located on the left visual field and/or impair detection in the right hemifield. Moreover, if solving arithmetic problems is akin to a progression along the MNL, the larger the second operand, the larger the attentional bias should be for both operations. Finally, as the OM effect has so far only been observed in problems that do not involve carrying (Lindemann & Tira, 2011), an interaction between the side of the target and the operation solved would appear only in these problems if the OM effect is related to spatial attention shifts. Two experiments were performed; the first used arithmetic facts (Experiment 1), and the second used more complex arithmetic problems (Experiment 2), in order to assess the effect of the magnitude of the operands and of the results, and of the presence or absence of carrying or borrowing in the problem.

Experiment 1: Arithmetic Facts

Method

Participants

Twenty-four French-speaking university students (mean age = 20.7 ± 1.9 years; 19 females; 22 right-handed) participated in this experiment to receive course credits. They were not aware of the hypotheses tested. The experiment was non-invasive and was performed in accordance with the ethical standards established by the Declaration of Helsinki.

Task and stimuli

Participants were asked to perform two tasks successively in each trial: (i) to answer aloud to visual arithmetic problems presented at the centre of the screen, then (ii) as quickly as possible to detect a target appearing on the left or right side of the screen by pressing with their left or right hand the left or right response key separated by 17 cm (i.e., keys “q” and “m” on the AZERTY keyboard).

The arithmetic problems were presented in Courier New 40 point font. We used the 18 addition problems and 18 subtraction problems from Pinhas and Fischer (2008) with operands from 0 to 8 and responses ranging from 1 to 9 (see Supplemental Material Table 1). This list excluded problems starting with 0, 1, or 9 because the solution was predictable from the magnitude of the first operand, and contained a total of 12 problems with zero as second operand (i.e., 6 for each operation). All the problems were presented in 4 successive blocks of 72 pseudorandomly ordered trials, each problem being presented twice in each block, once before a target on the right and once before a target on the left, for a total of 288 trials. The target for detection was the shape of a star (size: 3.5° of visual angle) appearing at about 14° of visual angle on the left or right side from the centre of the screen. We also added a control task wherein the participants had to detect the same targets but without first solving a problem, so as to establish a baseline for each participant for the detection of targets in both hemifields in a non-calculation situation. There were 40 trials comprising 3 symbols (i.e., a triangle, a square and a clover) flashed successively in the centre of the screen at the same pace as the operands of the problems in the arithmetic condition before the target appeared on one side or the other.

Procedure

The participants were seated at 50 cm from a 15-inch computer screen such that the midline of their face was aligned with the centre of the screen, with their head positioned in a chin-rest to limit inopportune movements as much as possible.

Stimulus presentation and data collection were programmed using E-Prime 1 (Schneider, Eschman, & Zuccolotto, 2002). The latencies of the verbal responses to problems were recorded with an interfaced microphone while accuracy was assessed on-line by the experimenter.

For the calculation task, the sequence of events was as follows. A fixation dot was presented for 1000 ms and was replaced sequentially by the first operand (O1), the operator (+ or -), and then the second operand (O2). Each of these elements was presented for 400 ms (Figure 1). A sequential mode was used to prevent participants from performing a visual scan from left to right while reading the problem, and to ensure that they were fixing the centre of the screen during calculation. The verbal answer prompted a target to appear to the left or the right of the screen with equal probability after a 450 ms delay. This delay was used as it falls within the time interval in which attentional cues produce their maximal gain in classical phasic alertness paradigms, and it was one of the delays which produced the most marked attentional bias in the Fischer *et al.* study (2003). The participants were asked to respond with their left hand if the target appeared at the left side of the screen and with their right hand if the target was appeared at the right side. For the baseline task, the participants had to say aloud the French word “Top” when the clover appeared on the screen to prompt the appearance of the target. Then they had to detect a target by pressing the right response-key if the target was on the right and on the left response-key if the target was on the left.

The session always started with the baseline condition; the whole experiment lasted about 35 minutes.

Insert Figure 1 about here

Results

Arithmetic problem solving: Response latencies (RLs) and accuracy

Trials where the answer to the arithmetic problem was incorrect (1.3%) were excluded from the analyses on RLs; trials where the microphone failed to trigger (3.7%) were excluded from all analyses.

The participants performed equally well in both operations (Addition: 98.6±1.8 %; Subtraction: 98.8±2.2 %; $t(23)=.21$, *ns*). Moreover, they answered addition and subtraction problems equally quickly (Addition: 938±213 ms; Subtraction: 933±199 ms; $t(23)=.51$, *ns*).

Target detection

Trials where the answer to the arithmetic problem was incorrect, where the microphone failed to trigger, and where participants failed to detect the targets (0.74%) were excluded from the following analyses.

First, a repeated-measures analysis of variance (ANOVA) was carried out on the median RLs using CONDITION (Control; Addition; Subtraction) and SIDE (Left; Right) as factors. CONDITION had a significant main effect ($F(2,46)= 21.255$, $p<.001$, $\eta^2=.48$) indicating that participants were slower to detect a target after solving an addition problem (320±32ms; $t(23)=4.944$, $p<.001$) or a subtraction (315±28ms; $t(23)=4.338$, $p<.001$) problem than in the control condition (293±22 ms). They also took longer to detect the target after solving an addition than a subtraction problem ($t(23)=3.024$, $p<.01$). Crucially, there was no main effect of SIDE showing that the participants were not generally faster at detecting a target on one side or the other (Left: 310±27 ms; Right: 309±24 ms; $F<1$). Moreover, there was a significant interaction between CONDITION and SIDE ($F(2,46)=4.902$, $p<.02$, $\eta^2=.176$; Figure 2A).

Paired-sample *t*-tests revealed a significant difference between the two operations for left-sided targets ($t(23)=4.179$, $p<.001$, one-tailed *t*-test) indicating that the participants were faster at detecting targets in the left hemifield after solving a subtraction (312±29 ms) than after solving an addition (322±35 ms). No such difference between the two arithmetic conditions was observed for targets on the right side (Right Addition: 318±30 ms; Right Subtraction: 318±28 ms; $t(23)=.036$, *ns*). There was also a significant difference in the detection of targets on the right side compared to targets on the left side when solving a subtraction problem ($t(23)=1.877$, $p<.04$, one-tailed *t*-test) but no difference between the two sides of the screen after an addition problem ($t(23)=1.142$, *ns*). Finally, participants detected targets on the left side and on the right side equally quickly in the control task (Left: 296 ± 26 ms; Right: 291±24 ms; $t(23)=1.103$, *ns*).

Insert Figure 2 about here

Zero problems

As it was demonstrated that zero problems could induce spatial bias (Pinhas & Fischer, 2008), we conducted an ANOVA focusing on zero problems from our list with OPERATION and SIDE. This analysis did not show a main effect of OPERATION ($F<1$) or of SIDE ($F<1$), but it revealed a significant interaction between OPERATION and SIDE ($F(1,23)=6.001$, $p<.03$, $\eta^2=.207$). Paired sample *t*-tests showed that the detection of targets was faster on the left (318±31 ms) than on the right (325±33 ms) side after solving a subtraction problem ($t(23)=1.766$, $p<.05$, one-tailed *t*-test), while the reverse difference was not observed after solving an addition problem (Left: 325±30 ms; Right: 320±30 ms; $t(23)=1.249$, *ns*). Moreover, detecting targets on the right side was faster after addition than after subtraction problems ($t(23)=2.447$, $p<.02$, one-tailed *t*-

test); on the left side, participants were slower after an addition problem than after a subtraction problem (*t*(23)=1.721, *p*<.05, one-tailed *t*-test).

Experiment 2: Complex Arithmetic Problems with or without Carrying or Borrowing

Experiment 1 showed an interaction between the operation and the time taken to detect targets. In the context of a global slowing down in the detection of the target in the arithmetic conditions, solving subtraction problems decreases the detection time for targets in the left hemifield more than addition problems; the reverse effect is not observed in the right hemifield. The fact that the effect is restricted to the left hemifield following subtraction problems may be the result of only using small numbers. As all the operands in this experiment ranged from 1 to 9, a more general association between small magnitudes and left space could overwhelm any potential bias induced by solving addition problems. Moreover, the processes involved in the resolution of these simple addition problems may vary among participants. Some may indeed rely more on direct retrieval of the answer from long-term memory (Campbell & Xue, 2001; Dehaene & Cohen, 1995, but see Fayol & Thevenot, 2012), which may have elicited fewer strategies recruiting visuo-spatial processes. Experiment 2 was conducted to test whether an attentional bias would occur while solving problems of a larger range that require participants to rely more heavily on actual calculation. Given that OM occurred only for problems which did not involve carrying (Lindemann & Tira, 2011), we created a set of problems that controlled the presence of carrying and borrowing operations.

Method

Participants

Twenty-eight French-speaking students (mean age=20.6±2.1 years; 20 females; 25 right-handed) participated in this experiment to receive course credits. They had not participated in Experiment 1 and were not aware of the objectives of the study. The experiment was non-invasive and was performed in accordance with the ethical standards established by the Declaration of Helsinki.

Tasks, stimuli and procedure

Experiment 2 was identical to Experiment 1 except for the arithmetic problems used as primes. A list of multi-digit problems was generated on the basis of the following considerations (see Supplemental Material Table 2). The magnitude of the first operand ranged from 22 to 89. The amount of carry and non-carry problems for additions and subtractions was equalized (i.e., 50 %) as the OM effect has been shown to arise only in non-carry problems (Lindemann & Tira, 2011). We also selected 3 ranges for the second operand (O2): small (i.e., 2 or 3), medium (i.e., 4, 5 or 6) and large (i.e., 7 or 8), which resulted in a total of 144 different problems, with 12 problems per condition (e.g., Addition/Carry/Small O2). A mean of the results for each combination of the 3 factors was taken and equilibrated (range: 23-89; mean for addition problems 58±16; subtraction problems: 57±18) such that, when conducting an ANOVA on the magnitude of the results with OPERATION (Addition; Subtraction), O2 RANGE (Large; Medium; Small), and TYPE (Carry; Non-Carry), no main effect nor interaction reached significance (all *p*-values>.1), thus excluding any shifts of spatial attention that would be due to bias of the magnitude of the results. The whole set of problems was repeated only twice (i.e., once associated with a left and once associated with a right target) to ensure that participants would not memorize the results. The experiment lasted about 45 minutes.

Results

Trials where the answer to the arithmetic problem was incorrect (15.3 %) were excluded from the analyses on RLs and those where the microphone failed to trigger (1.7%) from all the analyses on problem solving. Moreover, trials where the participants failed to detect the target correctly (0.68%) were also removed from the analyses on target detection.

<u>Arithmetic problem solving:</u>

<u>** RLs:*</u>

We conducted a repeated-measures ANOVA on the median RLs of correctly solved problems with OPERATION (Addition; Subtraction), O2 RANGE (Large; Medium; Small) and TYPE (Carry; Non-Carry). There was a main effect of OPERATION ($F(1, 27)=33.484$, $p<.001$, $\eta^2=.554$) showing that the participants were slower at subtraction problems (1421±251 ms) than at addition problems (1311±259 ms). A main effect of TYPE ($F(1, 27)=171.602$, $p<.001$, $\eta^2=.864$) showed that participants took longer to respond to carry problems (1699±367 ms) than to non-carry problems (1034±163 ms). The main effect of O2 RANGE was also significant ($F(2, 54)=76.834$, $p<.001$, $\eta^2=.74$): participants responded more quickly to problems with small O2 (1187±204 ms) than to problems with a medium O2 (1353±255 ms; $t(27)=8.942$, $p<.001$). In turn, participants responded more quickly to problems with a medium O2 than those with a large O2 (1559±326 ms; $t(27)=7.446$, $p<.001$). There was also a significant OPERATION by TYPE interaction ($F(1, 27)=12.389$, $p<.001$, $\eta^2=.315$). Paired-sample *t*-tests revealed a difference between the two operations for carry (Addition: 1612±388 ms; Subtraction: 1785±370 ms; $t(27)=4.821$, $p<.001$) and non-carry (Addition: 1010±167 ms; Subtraction: 1057±161 ms; $t(27)=5.529$, $p<.001$) problems, and a difference between the TYPE of problems within the addition ($t(27)=10.749$,

$p<.001$) and subtraction ($t(27)=14.144$, $p<.001$) problems; there was a larger difference between operations for carry problems than for non-carry problems ($t(27)=3.52$, $p<.005$). A significant interaction between TYPE and O2 RANGE ($F(2, 54)=75.113$, $p<.001$, $\eta^2=.736$) revealed that carry problems with a large O2 (2092±543 ms) were solved more slowly than medium O2 problems (1652±365 ms; $t(27)=7.422$, $p<.001$), and that medium O2 problems were solved more slowly than small O2 problems (1353±271 ms; $t(27)=10.137$, $p<.001$). For non-carry problems, participants responded more slowly to medium O2 problems (1053±171 ms) than both large (1027±166 ms; $t(27)=2.132$, $p<.05$) and small (1021±164 ms; $t(27)=2.255$, $p<.05$) O2 problems.

** Accuracy:*

A similar ANOVA on the mean error rates revealed a main effect for each variable. The main effect of OPERATION revealed that addition problems (13.52±8.82 %) were solved more accurately than subtraction problems (17.06±9.95 %; $F(1, 27)=13.335$, $p<.005$, $\eta^2=.331$). The main effect of TYPE showed that error rates were higher for carry (22.37±13.72 %) than for non-carry (8.28±5.7 %; $F(1, 27)=49.089$, $p<.001$, $\eta^2=.645$) problems. As regards O2 RANGE ($F(2, 54)=46.356$, $p<.001$, $\eta^2=.632$), paired-sample *t*-tests showed that the error rates were higher for problems with a large O2 (20.35±11.73 %) than for problems with a medium-sized O2 (15.81±9.03 %; $t(27)=4.606$, $p<.001$), which, in turn, showed higher error rates than problems with a small O2 (9.71±7.8 %; $t(27)=6.578$, $p<.001$). There was also a significant interaction between OPERATION and TYPE ($F(1, 27)=16.179$, $p<.001$, $\eta^2=.375$): addition problems (18.9±13.4 %) were solved more accurately than subtraction problems (25.84±15.17 %) where carrying was involved ($t(27)=4.451$, $p<0.001$) but not problems where carrying was not involved (Addition: 8.13±5.96 %;

Subtraction: 8.28±6.77 %; $t(27)=.159$, *ns*). There were significant interactions between TYPE and RANGE ($F(1, 27)=36.052$, $p<.001$, $\eta^2=.572$), and between OPERATION and O2 RANGE ($F(2, 54)=6.569$, $p<.005$, $\eta^2=.196$), that were qualified by the triple interaction between OPERATION, TYPE and O2 RANGE ($F(2, 54)=5.787$, $p<.005$, $\eta^2=.177$). In order to decompose the latter, we conducted separate ANOVAs for each OPERATION, with TYPE and O2 RANGE. Both ANOVAs revealed the main effects of TYPE and O2 RANGE, and a significant interaction. Paired-sample *t*-tests showed that subtraction problems involving carrying were solved less accurately than problems which did not involve carrying, whatever the RANGE of the O2 (all *p*-values<.05) whereas for addition, problems involving carrying were solved less accurately than problems which did not involve carrying where there were large O2 ($t(27)=5.912$, $p<.001$) and medium O2 ($t(27)=6.055$, $p<.001$) but not where there was a small O2 ($t(27)=1.805$, $p>.05$).

Target detection: RLs

As the structural variables of arithmetic problems could not be used to classify items in the control task, we first globally compared the control condition to the arithmetic condition. To do so, the RLs of target detection after additions and subtractions were averaged and entered into an ANOVA with TASK (Control; Arithmetic) and SIDE (Left; Right) as factors. This revealed that TASK had the following significant main effect: participants were generally slower at detecting a target after solving an arithmetic problem (332±37 ms) than they were in the neutral condition (289±25 ms; $F(1, 27)=58.731$, $p<.001$, $\eta^2=.686$). There was no significant main effect of SIDE (Left: 312±27 ms; Right: 308±31 ms; $F(1, 27)=2.156$, $p=.154$) and no interaction between TASK and SIDE ($F<1$). We also compared the RLs to detect targets on the right and left in the control task; this comparison showed that participants detected targets equally quickly on both sides (Left: 291±26 ms; Right: 287±27 ms; $t(27)=1.093$, *ns*).

A repeated-measures ANOVA was then conducted on the median RLs in the arithmetic task with OPERATION (Addition; Subtraction), SIDE (Left; Right), O2 RANGE (Large; Medium; Small) and TYPE (Carry; Non-Carry) as factors. None of the main effects was significant (all *p*-values at least >.1). The interaction between OPERATION and TYPE was significant ($F(1, 27)=8.038$, $p<.01$, $\eta^2=.229$), and paired-sample *t*-tests revealed that the participants took longer to detect a target after performing a subtraction problem with carrying than after performing an addition with carrying (respectively: 336±42ms and 330±39ms; $t(27)=2.091$, $p<.05$), and after a subtraction problem that did not involve carrying (328±34ms; $t(27)=2.274$, $p<.05$). Moreover, the RLs were smaller after non-carry subtraction problems than after non-carry addition problems (333±39ms; $t(27)=2.213$, $p<.05$). There was also a significant interaction between TYPE and O2 RANGE ($F(2, 54)=10.813$, $p<.001$, $\eta^2=.286$). For carry problems, the participants were slower at performing the problems after a large (342±43 ms) than a medium (331±41ms; $t(27)=2.406$, $p<.05$) or a small O2 (326±41 ms; $t(27)=3.364$, $p<.005$). For non-carry problems, the RLs were longer following small O2 problems (336±44 ms) than following medium O2 (327±33ms; $t(27)=2.827$, $p<.01$) or after large O2 (326±36ms; $t(27)=2.029$, $p<.05$) problems. The interaction between TYPE and SIDE ($F(1, 27)=4.615$, $p<.05$, $\eta^2=.146$) indicated that the participants were slower to detect targets in the left hemifield after performing problems involving carrying (337±38ms) than after performing problems which did not involve carrying (331±37ms; $t(27)=2.095$, $p<.05$). No such difference was observed regarding targets in the right hemifield (Carry: 329±44 ms; Non-carry: 330±38 ms; $t(27)=.324$, *ns*). Most importantly, a significant interaction between OPERATION and

SIDE ($F(1, 27)=5.25$, $p<.03$, $\eta^2=.163$; see Figure 2B) indicated that after performing addition problems, participants detected targets faster in the right hemifield (328 ± 39 ms) than in the left hemifield (335 ± 39 ms; $t(27)=1.991$, $p<.03$, one-tailed *t*-test). No such effect was observed in the case of subtraction problems (Left: 333±35 ms; Right: 332±41 ms; $t(27)=.315$, *ns*). Moreover, participants detected targets on the right side of the screen faster after solving addition problems than after solving subtraction problems (332 ± 41 ms; $t(27)=1.959$, $p<.03$, one-tailed *t*-tests) whereas the speed of detecting targets on the left of the screen was not accelerated by subtraction problems (333 ± 35 ms) when compared to addition problems ($t(27)1.179$, *ns*). No other interactions were significant (all *p*-values >.1).

Comparison between Experiment 1 and 2

In order to compare Experiments 1 and 2, we calculated, for both the right and left hemifield targets, the difference between the median RLs for detecting a target after solving an arithmetic problem and the median RLs for detecting a target in the non-arithmetic context (i.e., dRLs = arithmetic RLs – control RLs). Positive dRLs mean that participants were slowed by the arithmetic task in comparison to the control task. A mixed repeated-measures ANOVA was then conducted on the dRLs with EXPERIMENT as a between-subject variable (1; 2) and OPERATION (Addition; Subtraction) and SIDE (Left; Right) as within-subject variables. A significant main effect of EXPERIMENT ($F(1, 50)=6.219$, $p<.02$, $\eta^2=.111$) was observed: the participants' detection of targets was affected more by the arithmetic problems in Experiment 2 (43±30 ms) than in Experiment 1 (24±25 ms). There was also a significant interaction between EXPERIMENT and OPERATION ($F(1, 50)=5.645$, $p<.03$, $\eta^2=.101$) indicating that in Experiment 1 participants were slowed slightly more by addition (26±26 ms) than subtraction problems (23±24 ms; $t(23)=3.024$, $p<.01$) while there was no such difference between operations in Experiment 2 (Addition: 43±30 ms; Subtraction: 44±30 ms; *t*(27)=.321, *ns*). Finally, there was a significant interaction between OPERATION and SIDE ($F(1, 50)=17.546$, $p<.001$, $\eta^2=.26$). This interaction showed that the participants' detection of targets in the left hemifield was slowed significantly less by subtraction problems (30±32 ms) than by addition problems (36±34 ms) ($t(51)=3.495$, $p<.001$). The reverse pattern was not significant for targets in the right hemifield (Addition: 35±30 ms; Subtraction: 37±31 ms; $t(51)=1.546$, $p=.06$). Moreover, after solving subtraction problems, participants' detection of targets in the left hemifield was slowed less than their detection of targets in the right hemifield ($t(51)=2.170$, $p<.02$). However, no such difference was observed after participants solved addition problems ($t(51)=.41$, *ns*). No other main effects or interactions were significant (all *p*-values >.1).

General Discussion

The involvement of spatial attention in numerical processing has been intensively studied, but the degree to which it extends to arithmetical processing has received little attention so far. The observation of an OM effect was the first clue suggesting that attentional resources are employed in solving addition or subtraction problems (McCrink et al., 2007) although the attentional nature of this effect was still a matter of debate (e.g., Knops et al., 2013). Shifts of attention produced by perceiving numbers had already been demonstrated (e.g., Fischer et al., 2003; Casarotti et al., 2007) but whether arithmetic induces such bias was still an open question, as no direct observation of attentional shifts during arithmetic problem solving had been reported. In this study, the relationship between arithmetic problem solving and visuospatial attention orientation was examined in two experiments using a lateralized target detection following different lists of arithmetic problems as primes in order to assess the effect of the magnitude of the operands, the magnitude of the results, and the presence or absence of the need to perform carrying or borrowing. Our results show for the first time that solving basic subtractions and complex additions induces shifts of visuospatial attention that impact upon the speed at which targets located on the left and right side of the screen are detected respectively.

Experiment 1 was intended to determine whether a shift of spatial attention would occur with basic arithmetic problem solving presented in Arabic notation and requiring a verbal answer. We first showed that the participants detected targets faster without first having to solve a problem, irrespective of where they appeared. It is not possible to determine whether this general increased latency in the arithmetical task is due to a non-specific tiredness effect or the cost of task switching; the key point is that there is no difference between detection of the targets in the left and right hemifields in the control condition. We then showed that even for these very simple problems within a range inferior to 10, there was an interaction between the arithmetical operation and side of space on the time taken to detect the targets. Indeed, participants detected targets on the left side of the screen faster after solving a subtraction problem than after solving an addition problem, and also faster than on the right side. This interaction between the arithmetic operation and space is consistent with a previous study that showed a pointing bias to the left part of a ruler when solving the very same subtractions and to the right when solving additions (Pinhas & Fischer, 2008). However, no such acceleration was found here for the right side as regards addition problems, as participants' detection of targets in the left and right hemifields was performed at the same speed. This absence of effect for addition problems in the present study may be explained by retrieval strategies that are more likely to be recruited for simple addition problems in symbolic notations and with verbal answers, and which would rely less on attentional process than when the answer must be produced analogically by pointing on a ruler (as in Pinhas & Fischer, 2008). Another possibility is that manipulating small magnitudes *per se* induces spatial shifts to the left (Fischer et al., 2003). Therefore, in this set of problems of small magnitude, it is possible that no shift to the right occurred when addition problems were solved because all the numbers involved in the problems small. Interestingly, the interaction between OPERATION and SIDE was also significant when the second operand was equal to zero, which suggests that the shifts of spatial attention cannot be fully explained by mental movements along the MNL. Uncontrolled magnitude differences across problem sets can also be excluded as the magnitudes of the operands and results were strictly equivalent in this subset of problems. Together, this suggests that the interaction might reflect some semantic association between operations and space. It has already been reported that problems with zero as second operand could produce a spatial bias in a pointing task (Pinhas & Fischer, 2008). These authors suggested that spatial biases related to arithmetic may be the consequence of different spatially localized activations of operands and of the operator that are competing, which results in a bias towards the left or right sides of space. Our results seem to support this suggestion that needs to be investigated further in order to identify the source of spatial-numerical association in arithmetic.

The aim of Experiment 2 was to assess whether solving arithmetic problems of a higher range would also induce spatial shifts of attention. As regards the arithmetical task itself, the results are in line with the literature: the more difficult the problems, the longer the participants take to solve them and the higher the error rate. This explains the effects of OPERATION (subtraction problems being more difficult than addition problems), of CARRY (problems with carrying or borrowing processes being more difficult), and of O2 range (the larger the O2, the more difficult the problem), as well as the OPERATION by TYPE and TYPE by O2 RANGE interactions that all reflect this difficulty gradient. These findings are important as they show that the participants did actually perform the arithmetic task as expected. In the control detection task, the participants generally detected targets more quickly than after solving an arithmetic problem, and they detected targets in the right and left hemifields equally quickly. Following the solving of an arithmetic problem, there was a significant interaction between OPERATION and SIDE, irrespective of the size of the O2: in the context of a global slowing down to detect the target in the arithmetic condition, solving addition problems accelerated the detection of targets in the right hemifield while solving subtraction problems did not produce such a facilitation effect in the left hemifield. Since the spatial shifts occurred on the right side of space with this set of problems of higher magnitude and since there was no modulation of the effect by the magnitude of the second operand, our data suggest that the crucial element that induces the spatial shift is the operation itself and the magnitude of the set of numbers that are manipulated rather than the second operand alone. This would fit with the reverse effect observed in Experiment 1 for subtractions. This suggestion must however be viewed with caution as the direct statistical comparison of Experiments 1 and 2 showed that the interaction between OPERATION and SIDE was not modulated by the experiment, hence the global magnitude of problem sets. This may be due to the fact that the effect was greater in Experiment 1 than Experiment 2, which has left little room for a crossover effect to appear.

In Experiment 2, we also wanted to assess whether the carrying process modulated attentional shifts observed in the solving of arithmetic problems. Indeed, it has been shown that the OM effect, in non-symbolic arithmetic, only arises in problems which do not involve carrying (Lindemann, & Tira, 2011). Problems involving carrying are supposed to rely more on working memory resources in order to process decomposition of the place-value system (Dehaene, 1992; Imbo, Vandierendonck, & De Rammelaere, 2007) and less on magnitude processing. As there was no main effect of TYPE and as the interaction between OPERATION and SIDE was not moderated by TYPE, our analyses confirmed the presence of a similar attentional bias both in problems involving carrying and problems that do not involve carrying. Thus, even problems that are supposed to rely more on working memory induce spatial shifts. Surprisingly, the size of the effect appeared smaller with the complex problems used in Experiment 2 than with the arithmetical facts used in Experiment 1. This suggests that the need to apply several computation steps might in fact weaken rather than strengthen the impact which the operation has on attention.

Along with the effect observed for zero problems in Experiment 1, the absence of an enhancing effect for large O2s does not support the idea that the solving of arithmetic problems is akin to mentally moving along a spatial-numerical continuum. Indeed, the larger the O2, the larger the movement should be, hence the attentional shift, which was not observed here. However, because we assessed the attentional bias after the answer to the problem was made, we cannot exclude the possibility that our paradigm is not sensitive enough to detect early influence of the magnitude of the operands on spatial shifts. Indeed, operands might induce spatial shifts when they are processed and before any computation is launched. Moreover, it is possible that some attentional effects occur before or after the 450-ms delay we used. Therefore, further research is necessary to investigate the temporal course of the spatial shifts while the participants are calculating or even while they are processing the operands.

It is worth noting that, even if they are small, the size of the effects observed in our experiments is in line with previous investigations of the spatial-numerical association in detection of targets tasks, where effects of an average size of 10 ms (e.g., Fischer et al., 2003; Galfano et al., 2006; Ristic et al., 2006) or of very few pixels in a pointing task (Pinhas & Fischer, 2008) are reported. It is not surprising to find such limited effects given the simplicity and speed of the target detection task which lead to a performance close to ceiling.

Finally, it is still unclear if attentional shifts are necessary, or even useful, in arithmetic processes. Indeed, attentional shifting might be an epiphenomenon that is not crucial for solving problems. Evaluating the impact on calculation abilities of orienting attention to the left or to the right should help in determining the contribution of the attentional process to mental arithmetic. Also, using two effectors to answer to the target detection task leaves open the question whether the observed interaction between space and operation type is a direct consequence of a spatial shift of attention, or an indirect consequence of spatial attention somehow moderating hand motor preparation. Future research will show whether this may constitute an interesting alternative.

Acknowledgements

This study was supported by grant 1.A057.12 from the National Fund for Scientific Research (Belgium). NM is a research fellow and MP is a research associate at the National Fund for Scientific Research (Belgium).

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Figure captions

Figure 1: Sequence of events and temporal attributes for one trial. The operands of the arithmetic problems were presented sequentially in the centre of the screen, followed by a blank screen. After the participant gave the answer verbally, a delay of 450 ms preceded the appearance of a lateralized target.

Figure 2: Mean response latencies (± S.E.) as a function of Condition (Addition *vs.* Subtraction *vs.* Control) and Side (Left *vs.* Right) for Experiment 1 (A) and for Experiment 2 (B).