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Time course of overt attentional shifts in mental arithmetic: Evidence from gaze metrics

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Abstract

Processing numbers induces shifts of spatial attention in probe detection tasks, with small numbers orienting attention to the left and large numbers to the right side of space. This has been interpreted as supporting the concept of a mental number line with number magnitudes ranging from left to right, from small to large numbers. Recently, the investigation of this spatial-numerical link has been extended to mental arithmetic with the hypothesis that solving addition or subtraction problems might induce attentional displacements, rightward or leftward respectively. At the neurofunctional level, the activations elicited by the resolution of additions have been shown to resemble those induced by rightward eye movements. However, the possible behavioural counterpart of these activations has not yet been observed. Here we investigated overt attentional shifts with a target detection task primed by addition and subtraction problems (2-digit ± 1-digit operands) in participants whose gaze orientation was recorded during the presentation of the problems and while calculating. No evidence of early overt attentional shifts was observed while participants were hearing the first operand, the operator or the second operand, but they shifted their gaze towards the right during the solving step of addition. These results show that gaze shifts related to arithmetic problem solving are elicited during the solving procedure, and suggest that their functional role is to access, from the first operand, the representation of the result.

Keywords: mental arithmetic; visuo-spatial attention; attentional shifts, gaze metrics
**Introduction**

The association between number magnitude and space has often been conceptualized by the idea of the mental number line (MNL), a mental representation of numerical magnitude on which numbers are spatially represented in ascending order from left to right (Dehaene, 1992). In line with this idea, processing small-magnitude numbers has been shown to orient attention and/or gaze towards the left part of space and processing large-magnitude numbers towards the right part of space: participants detect more rapidly targets displayed on the left part of a screen after they have processed small-magnitude numbers, and on the right part after they have processed large-magnitude numbers (Fischer, Castel, Dodd, & Pratt, 2003; Fischer, Warlop, Hill, & Fias, 2004; Schwarz & Keus, 2004). Because moving one's eyes allows a specific part of the visual field to be brought into the attentional focus by directing the fovea to it (e.g. Corbetta et al., 1998; Sheliga, Riggio, & Rizzolatti, 1994), and because gaze shifts closely reflect the content and spatial relations of mental images (e.g. Brandt & Stark, 1997; Leang & Teodorescu, 2002), recording eye movements can be useful to investigate ongoing mental processes such as overt attentional shifts in numerical cognition. Indeed, it has been shown that participants' gaze may shift in a direction that depends on the magnitude of the numbers that are presented on screen (Ruiz Fernandez, Rahona, Hervas, Vazquez, & Ulrich, 2011). Moreover, forcing participants to shift their gaze towards the right by means of reflexive eye pursuits of meaningless visual moving stimuli (i.e., optokinetic stimulation) accelerates the processing of large numbers in a numerical comparison task (Ranzini et al., 2015). Interestingly, during random number generation, the direction of eye movements that precede the moment when the numbers are spoken out correlates with their magnitude: rightward and upward saccades are more
frequent when the number produced is larger than the previous one (Loetscher, Bockisch, Nicholls, & Brugger, 2010). Importantly, the spontaneous eye movements observed in this last study were not triggered by any perceptual event since the screen remained blank throughout the experiment. Conversely, observing human models shifting their gaze leftward or downward led participants to produce smaller numbers (Grade, Lefèvre, & Pesenti, 2013), which suggests that perceiving gaze shifts also induces exogenous shifts of attention in the internal spatial representation of numbers, and that the influence between numbers and space is bi-directional.

Recently, a few studies have investigated whether solving mental arithmetic problems would also use cognitive mechanisms akin to those supporting spatial attention (for a review, see Fischer & Shaki, 2014). It has been reported that while solving an addition problem, participants tend to overestimate the result and, while solving a subtraction problem, they tend to underestimate the result (Klein, Huber, Nuerk, & Moeller, 2014; Knops, Dehaene, Berteletti, & Zorzi, 2014; Knops, Viarouge, & Dehaene, 2009; Knops, Zitzmann, & McCrink, 2013; Lindemann & Tira, 2011; McCrink, Dehaene, & Dehaene-Lambertz, 2007; McCrink & Wynn, 2009; Pinhas & Fischer, 2008). This effect, called operational momentum (OM), has generally been interpreted as an attentional movement along the MNL that “goes too far” in the direction related to the operation (Knops, Viarouge et al., 2009; Lindemann & Tira, 2011; McCrink et al., 2007). A functional magnetic resonance imaging (fMRI) study further revealed that circuits located in the posterior part of the superior parietal lobule (PSPL), but not those located in the frontal eye field (FEF) that are activated by rightward eye movements, partially overlap with those related to addition solving with large operands (Knops, Thirion, Hubbard, Michel, & Dehaene, 2009), suggesting that mental arithmetic shares some neural bases with overt attention orientation.
However, the possible behavioural counterpart of these activations has never been reported.

Strong evidence of shifts of spatial attention consequent to arithmetic problem solving in healthy participants was observed with a target detection task (Masson & Pesenti, 2014). Participants were faster to detect targets located on the left or right visual field after solving respectively subtraction or addition problems matched for the magnitude of their results. A leftward or rightward deflection in hand movements has also been shown when participants were asked to indicate by moving a mouse cursor the result of subtractions or additions respectively (Marghetis, Nunez, & Bergen, 2014). Moreover, presenting the second operand of simple additions or subtractions on the right side of the screen facilitated the solving of addition problems while presenting the second operand on the left side of the screen facilitated the solving of subtraction problems (Mathieu, Gourjon, Couderc, Thévenot, & Prado, 2016).

Spatial associations with problems involving zero were also reported when participants were asked to provide their estimated response by pointing on a line flanked by numbers (Pinhas & Fischer, 2008), or to detect lateralized targets (Masson & Pesenti, 2014). Moreover, the operation signs themselves can evoke spatial associations. When participants were asked to classify plus and minus signs by pressing a right or a left response key, response latencies were indeed faster when the plus sign was associated with the right response key and the minus sign with the left response key (Pinhas, Shaki, & Fischer, 2014). This "Operation Sign Spatial Association" effect (OSSA) was very weak for the minus sign and was only observed when preceded by numerical tasks that highlighted the mathematical context to the operation sign. Based on the observation of the OSSA and the
attentional shifts induced by zero problems, it has been suggested that spatial biases related to arithmetic may be the consequence of a competition between the localized activation of the operands, the result, and a semantic link between the type of operator and space (i.e., right-addition; left-subtraction). This hypothesis has recently been supported by the observation of spontaneous eye movements while participants were hearing single digit additions or subtractions and while they were solving them (Hartmann, Mast, & Fischer, 2015). These authors observed that gaze position shifted more upward as soon as the plus sign was auditorily presented and more downward when a minus sign was presented. This occurred before the presentation of the second operand, thus before any calculation could actually start (although the procedure itself might have been activated, as suggested by Mathieu et al., 2016). It is worth noting that this study used single-digit operand problems of very small magnitude; yet, problems with a result of a large magnitude could induce attentional shifts different than those involving single digits (Masson & Pesenti, 2014). Unlike problems of smaller magnitude (i.e., arithmetic facts) that may be solved by memory retrieval, problems of higher magnitude necessitate a greater use of attentional mechanisms (Dormal, Schuller, Nihoul, Pesenti, & Andres, 2014; Masson & Pesenti, 2016). We thus suggest that solving problems that necessitate calculation procedures should induce horizontal eye movements during calculation.

In this study, we analysed spontaneous eye movements on a blank screen while participants solved auditorily presented addition and subtraction problems carefully matched for the mean magnitude of their results. Recording eye movements offers the opportunity to observe directly overt attentional shifts and to measure their amplitude. It also allows the time course of attentional shifts that occur while solving problems to be measured to find out which elements of the problem possibly elicit
spatial biases. If attentional shifts in mental arithmetic are the consequence of a sum of lateralized activation depending on the magnitude of the operands or of the answers and on the semantic link between the operator and space (Pinhas & Fischer, 2008; Pinhas et al., 2014), a series of left and right attentional shifts accompanying the processing of each element should be observed. Conversely, if attentional shifts are caused by the process of accessing the representation of the answer, be it calculation, memory retrieval or a mixture of both, participants’ gaze should shift rightward and/or upward for additions and leftward and/or downward for subtractions when they actually start solving the problem once the second operand has been heard.

**Methods**

**Participants**

Nineteen French-speaking university students with normal or corrected-to-normal vision (mean age: 22±2 years; 12 females; 17 right handed) participated in this experiment in exchange for course credits; they were not aware of the hypotheses being tested. The experiment was non-invasive, was performed in accordance with the ethical standards established by the Declaration of Helsinki, and was approved by the Ethics Committee of the Institut de Recherche en Sciences Psychologiques of the Université catholique de Louvain.

**Apparatus**

The experiment was conducted on a Dell PC equipped with a 21.5-inch LCD screen (resolution 1920x1080; refresh rate 60 Hz). Stimulus presentation and behavioural data collection were programmed using E-Prime 2 (v2.0.8.90 PRO; Schneider, Eschman, & Zuccolotto, 2002). Arithmetical problems were presented
orally through headphones. The latencies of the verbal responses to arithmetic problems were recorded with an interfaced microphone while accuracy was assessed on-line by the experimenter.

Participants’ eye movements were recorded using an Eyelink 1000 desktop-mounted eye tracker (SR Research, Canada; sampling rate of 1000 Hz; average accuracy range 0.25° to 0.5°, gaze tracking range of 32° horizontally and 25° vertically). Participants sat at a distance of 60 cm from the eye tracker camera and 70 cm from the screen; using a chin and forehead stabilizer prevented head movements.

Tasks, stimuli and procedure

The participants performed two consecutive tasks at each trial. First, they had to solve orally an auditorily presented arithmetical problem, then they had to detect a target appearing on the left or right side of the screen. They were instructed to respond as quickly as possible while keeping errors to a minimum by pressing with their left or right hand the left or right response key, respectively. The response keys were separated by 17 cm (i.e., keys "q" and "m" on an AZERTY keyboard).

A list of multidigit problems (see Experiment 2 in Masson & Pesenti, 2014) was generated on the basis of the following considerations. The magnitude of the first operand (O1) ranged from 22 to 89, the amount of carry and non-carry problems for additions and subtractions was equalized (i.e., 50 %), and 3 range of second operand (O2) were selected (Small: 2 or 3; Medium: 4, 5 or 6; Large: 7 or 8), which resulted in a total of 144 different problems, with 12 problems per condition (e.g. Addition/Carry/SmallO2). The means of results of the problems with each combination of the 3 factors were equilibrated (range: 23-89; mean for additions
58±16; subtractions: 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 that any shifts of spatial attention would only be due to a potential 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 with a right target) to ensure that participants would not memorize the results. The target to detect 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.

The sequence of events was as follows. At the beginning of each trial, a fixation dot was presented in the centre of the screen before the presentation of the problem and participants were requested to focus on it to begin the trial. This was done to ensure an equivalent initial attentional focus for every participant in every trial. Moreover, the fixation dot was used as drift check to confirm the reliability of the eye-gaze calibration. Once the participant's gaze was fixed on the centre, the experimenter manually launched the beginning of the trial. In each trial, the fixation dot disappeared and was followed by a blank screen during the auditory presentation of the arithmetic problem. The problems were presented by a recorded male voice in French; audio files were prepared such that O1, the operator (+ or -), and then O2 were presented sequentially for a 950-ms duration each. The auditory modality was used to prevent participants from performing a visual scan from left to right while reading the problem, and to ensure that their eye movements would not be driven by any actual stimulus on the screen, which remained blank throughout the arithmetic task. The detection of the verbal answer to the problem by the microphone prompted a target to appear to the left or to 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
Fischer et al.’s seminal study (2003). Participants were instructed to respond with
their left hand when the target appeared at the left side of the screen and with their
right hand when the target appeared at the right. Once the participant’s answer was
recorded, another trial started.

The experiment was divided into 6 blocks of 48 trials; the whole experiment
lasted about 60 minutes.

Eye movement data analysis

At the beginning of each block, a standard 9-point protocol was used to
calibrate participants’ eye-gaze position to a display screen using Eye-Link software.
This allowed the computation of the actual gaze position on the screen. Blink events
were subtracted from the original gaze stream by the software.

In order to calculate the time course of the gaze shifts while perceiving the
problem, we computed three time windows in which participants heard O1 (hereafter
TW1), the operator (hereafter TW2), and O2 (hereafter TW3). These time windows
were defined by the onset and the offset of the audio files presenting each element of
the problem. A last time window was computed from the offset of O2 to the moment
the start of the verbal answer to the problem triggered the microphone (hereafter
TW4), a period during which the participants were calculating. The means of
horizontal and vertical eye-gaze deviations were computed for each participant within
each time window by subtracting the coordinates of the last fixation of the previous
time window from the coordinates of the last fixation of the present time window. This
controls for previous movements during the trial before a given time window starts. Deviations were measured in pixels. We computed repeated measures ANOVAs on these horizontal and vertical gaze deviations with the relevant elements of the problems as factors for each time window. For TW1, we used the magnitude of the first operand (Small vs. Medium vs. Large) as factor. For TW2, we used the operator (Plus vs. Minus) as factor. For TW3 and TW4, we used operation (Addition vs. Subtraction) and the magnitude of the second operand (Small vs. Medium vs. Large) as factors. We computed two last ANOVAs for TW4 with the magnitude of the results (Small vs. Medium vs. Large) as a factor.

We further used a data analysis similar to the method of Hartmann and colleagues (2015) to get a finer-grained measure of gaze movements. Within each time window, we analysed the absolute horizontal and vertical gaze position every 10 ms, and we estimated gaze deviation through time within each time window by taking into account the position of the gaze at the beginning of the time window. Missing values (i.e., blinks, loss of signal and samples with coordinates outside of the screen) were replaced by linearly interpolated values. As TW4 duration varied for each trial as a function of the response latencies to the arithmetical problems, the data of this time window were time-normalized using linear interpolation into 138 samples (138*10 ms corresponding approximatively to the mean duration of the TW4). We then compared the mean horizontal and vertical gaze position for additions and subtraction trials. We only considered differences as statistically significant when the p-values of at least 20 samples were below .05, corresponding to a 200 ms interval. For the sake of clarity, these differences are reported within each time window.

Results

Arithmetical performance:
Response Latencies (RLs)

Trials where the answer to the arithmetic problem was incorrect (14.27 %) or where the microphone failed to trigger (1.58 %) were removed from the RLs analysis.

We conducted a repeated measures ANOVA on the median RLs of correctly solved problems with OPERATION (Addition; Subtraction) and O2 RANGE (Small; Medium; Large) as factors. Results revealed a main effect of OPERATION (\(F(1,18)=28.803, p<.001, \eta^2_p=.615\)) indicating that additions (1323±411 ms) were solved faster than subtractions (1445±473 ms). A main effect of O2 RANGE (\(F(2,36)=22.053, p<.001 \eta^2_p=.551\)) showed that small problems (1239±367 ms) were solved faster than medium problems (1407±451 ms; \(t(18)=3.156, p=.005\)), which were solved faster than large ones (1506±524ms; \(t(18)=4.331, p<.001\)). The interaction between OPERATION and O2 RANGE was not significant (\(F(2,36)=.731, ns, \eta^2_p=.017\)).

Error rates

A similar ANOVA on the error rates revealed a main effect of OPERATION (\(F(1,18)=10.553, p=.004; \eta^2_p=.37\)) indicating that participants made more errors for subtractions (16.7±11.11 %) than for additions (11.84±8.66 %). There was also a main effect of O2 RANGE (\(F(2,36)=28.123, p<.001; \eta^2_p=.61\)) showing that participants were better at solving small O2 problems (10.36±9.77 %) than medium O2 problems (13.54±9.5 %; \(t(18)=2.978, p=.008\)), which were better solved than large O2 problems (18.91±10.26 %; \(t(18)=5.695, p<.001\)). Finally, the interaction between OPERATION and O2 RANGE was not significant (\(F(2,36)=.831, ns, \eta^2_p=.044\)).

Target detection performance:
Trials where participants failed to detect the target (0.84 %) or where the answer to the arithmetic problem was incorrect (14.27 %) were excluded from this analysis. An ANOVA was carried out on the median RLs using OPERATION (Addition; Subtraction) and TARGET SIDE as factors (Left; Right). We found a significant interaction between OPERATION and TARGET SIDE ($F(1,18)=10.129$, $p=.005$, $\eta^2_p=.360$; see Figure 1). Paired sample t-tests revealed that participants were faster to detect a target on the right side (303±40 ms) than on the left side (316±40 ms; $t(18)=2.091$, $p=.05$) after solving an addition, whereas no such difference was observed after solving a subtraction (left: 313±38 ms; right: 311±44 ms, $t(18)=.473$, ns). Moreover, right-sided targets were detected faster after solving additions than after solving subtractions ($t(18)=2.394$, $p=.028$). No differences were observed for left-sided targets ($t(18)=.780$, ns). No other significant main effect was observed (all other $p$-values >.2).

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Insert Figure 1 about here
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Eye movements:

These analyses were performed on items for which the answers to the arithmetic problem and to the detection task were both correct (84.89% of the data).

ANOVAs on the mean deviation in pixels in the horizontal and vertical axes with Time Window (1 to 4) and Operation (Addition vs. Subtraction) as factors revealed a significant interaction between Time Window and Operation for the horizontal axis ($F(3, 54)=3.972$, $p=.012$, $\eta^2_p=.181$), but not for the vertical axis ($F(3, 54)=.517$, $p=.672$, $\eta^2_p=.028$). No other main effects reached significance (all $p$-values >.07).
ANOVAs within each time window evaluated the potential influences of the operation, the operator and the magnitude of the operands on gaze deviation (see Figure 2). Full gaze stream analyses tested the presence of differences between the gaze patterns for addition and subtraction trials (see Figure 3 and 4).

**Time window 1: O1**

We conducted two ANOVAs on the mean deviation in pixels in the horizontal and vertical axes with O1 range (Large: >70; Medium: 40 to 70, and Small: <40) as factor. They revealed no significant effect (horizontal gaze position: $F(2,36)=.864$, $p=.43$, $\eta^2_p=.046$; vertical gaze position: $F(2,36)=1.76$, $p=.187$, $\eta^2_p=.089$). The analysis of the full gaze stream did not show any difference between the gaze patterns for addition and subtraction trials.

**Time window 2: Operator**

Two ANOVAs with O1 range and OPERATOR (Plus; Minus) as factors were carried out on the mean deviation in pixels in the horizontal and vertical axis. For horizontal deviation, there was no significant main effect of O1 range ($F(2,36)=.105$, $p=.900$, $\eta^2_p=.006$) or of OPERATOR ($F(1,18)=1.220$, $p=.284$, $\eta^2_p=.063$). The interaction between OPERATOR and O1 range was not significant either ($F(2,36)=.371$, $p=.693$, $\eta^2_p=.02$). For the vertical deviation, no significant main effect of O1 range ($F(2,36)=1.237$, $p=.302$, $\eta^2_p=.064$) or of OPERATOR ($F(1,18)=.227$, $p=.639$, $\eta^2_p=.012$) was observed, and the interaction between the two factors was not significant either ($F(2,36)=.708$, $p=.495$, $\eta^2_p=.16$).

Within this time window, there was a deviation of $-11.7\pm40.5$ pixels along the horizontal axis and of $-6\pm33.8$ pixels along the vertical axis for additions, which did not differ from the initial fixation point (horizontal deviation: $t(18)=1.257$, $p=.225$;
vertical deviation: $t(18) = .773, p = .449$). For subtractions, there was a deviation of $-8.2 \pm 38.9$ pixels along the horizontal axis and of $-3.2 \pm 28.3$ pixels along the vertical axis, which also did not differ from the initial fixation point (horizontal deviation: $t(18) = .918, p = .371$; vertical deviation: $t(18) = .499, p = .624$). The analysis of the full gaze stream did not show any difference between absolute gaze position and deviation for addition and subtraction trials.

**Time window 3: O2**

We conducted two ANOVAs on the mean deviation in pixels in the horizontal and vertical axis with OPERATOR and O2 RANGE (Large vs. Medium vs. Small) as factors. For the horizontal deviation, there was no significant effect of O2 RANGE ($F(2,36) = .111, p = .895, \eta^2_p = .006$) or of OPERATOR ($F(1,18) = .262, p = .615, \eta^2_p = .014$). The interaction between OPERATOR and O2 RANGE was not significant either ($F(2,36) = .810, p = .453, \eta^2_p = .043$). For the vertical deviation there was also no significant effect of O2 RANGE ($F(2,36) = .787, p = .463, \eta^2_p = .042$) or of OPERATOR ($F(1,18) = .504, p = .487, \eta^2_p = .027$). The interaction between the two factors was not significant either ($F(2,36) = .664, p = .521, \eta^2_p = .036$).

Within this time window, there was a deviation of $-4.6 \pm 36.8$ pixels for addition trials and of $-7 \pm 31.3$ pixels for subtraction trials along the horizontal axis. Both did not differ from the initial fixation point (addition: $t(18) = .543, p = .594$; subtraction: $t(18) = .973, p = .343$). Along the vertical axis, there was a mean deviation of $-27.1 \pm 54.4$ pixels for addition trials and of $-23.1 \pm 39.2$ pixels for subtractions that were both significantly different from zero (addition: $t(18) = 2.172, p = .043$; subtraction: $t(18) = 2.564, p = .02$). The full gaze stream analysis did not show any difference between absolute gaze position and deviation for addition and subtraction trials.
Time window 4: Calculation Period

We conducted two ANOVAs on the mean deviation in pixels within the calculation period with OPERATION (Addition vs. Subtraction) and O2 RANGE as factors. For the horizontal deviation, this revealed a main effect of OPERATION ($F(1,18)=5.552$, $p=.03$, $\eta^2_p=.236$) indicating that the position of the gaze deviates more to the right when solving additions ($22.28\pm36.29$ pixels) than when solving subtractions ($-7.94\pm26.98$ pixels). This deviation was significantly different from zero (i.e., deviation) for addition ($t(18)=2.675$, $p=.015$) but not for subtraction($t(18)=1.283$, $p=.216$). No other significant interaction or main effect was observed (all $p$-values $>.4$). For the vertical deviation, no significant main effect or interaction reached significance (all $p$-values $>.1$). The mean deviation in the vertical axis was of $-19.9\pm44.2$ pixels for additions ($t(18)=1.967$, $p=.065$) and of $-20.8\pm32.9$ pixels for subtractions ($t(18)=2.757$, $p=.013$).

In order to test if the absolute magnitude of the result of the problem could influence any gaze shifts, we computed an ANOVA with OPERATION and RESULT RANGE (i.e., Large >70; Medium 40 to 70 and Small <40) as factors on the mean deviation in pixels on the horizontal and vertical axes. For the horizontal deviation, we observed a significant main effect of OPERATION ($F(1,18)=4.498$, $p=.048$, $\eta^2_p=.2$) indicating that participants’ gaze was shifted more rightward for additions ($22\pm27$ pixels) than for subtractions ($-8\pm47$ pixels). The main effect of operation was not significant for the vertical axis ($F(1,18)=.171$, ns) indicating that the deviation was not different between additions ($-21\pm11$ pixels) and subtractions ($-24\pm9$ pixels). No other main effect or interaction reached significance for the horizontal deviation (all $p$-value $>.3$) or for the vertical deviation (all $p$-value $>.1$).
The full gaze stream analysis revealed an effect of the operation for the horizontal axis, for both the absolute position and deviation. A significant difference was observed 310 ms after the onset of O2 and lasted until the onset of the response of the participants, which ended TW4. Finally, the full gaze stream analysis revealed no effect of the operation for the vertical axis.

Correlations between target detection task and the final gaze position

For each participant, we subtracted the median RLs for detecting a rightward target to the median RLs for detecting a leftward target (dRL: Left RLs-Right RLs). This was done first globally for all trials (global dRL), then separately for the trials in which the target followed an addition (Addition dRL) or a subtraction (Subtraction dRL). A positive dRL indicated that the participant was faster at detecting a rightward target and a negative dRL indicated that the participant was faster at detecting a leftward target. We correlated each of these dRLs with the mean final horizontal position of the eye (i.e., when participant gave their answer) for their corresponding trials (i.e., for all the trials, for additions and for subtractions). We observed significant positive correlations between the mean horizontal position of the eye and global dRL ($r_{BP}=.887, p<.001$; see Fig. 5A), addition dRL ($r_{BP}=.847, p<.001$; see Fig. 5B), and subtraction dRL ($r_{BP}=.863, p<.001$; see Fig. 5B). Altogether, these correlations indicate that the more the participants were looking to the right when the started producing their verbal answer, the faster they detected a rightward target in comparison to a leftward target, and vice versa.
Discussion

It has been suggested that mental arithmetic involves mechanisms akin to those underlying spatial attention. Solving subtractions and additions has been associated to leftward or rightward shifts of attention respectively in several behavioural studies (e.g., Masson & Pesenti, 2014; Mathieu et al., 2016; Pinhas & Fischer 2008; Werner & Raab, 2014; Wiemers, Bekkering, & Lindemann, 2014) and brain imaging studies (Knops, Thirion et al., 2009). However, the role of these attentional shifts is still debated. In this study, we analysed the time course of spontaneous eye movements while participants were solving addition or subtraction problems, in order to determine whether overt attentional shifts in mental arithmetic would be elicited by the magnitude of each element of the problem (i.e., operands and answer), by hearing the operator, and/or by the calculation procedure.

The analysis of the arithmetic performances showed that the more difficult the problems, the longer the participants took to solve them, and the higher the error rate. Indeed, subtraction problems are usually more difficult than additions, and the magnitude of the operands is known to make the solving more difficult (Ashcraft, 1992; Campbell, 2008). The behavioural findings of the present study thus fit these classical effects. This is important as it shows that participants did perform the arithmetic task as expected. In the target detection task, participants were faster to detect a rightward target after solving an addition than after solving a subtraction. This result is in line with previous studies that have observed horizontal spatial
associations with mental arithmetic (Knops, Thirion et al., 2009; Masson & Pesenti, 2014; Marghetis et al., 2014; Pinhas & Fischer 2008; Werner & Raab, 2014).

Turning to gaze metrics, we analysed in four sequential time windows the gaze deviation of participants who were hearing and solving addition and subtraction problems. Our results show that, 310 ms after the participants had heard all the elements of the problems and were thus calculating, their gaze was shifted more rightward during addition than during subtraction solving. This effect was found even after controlling gaze position at the offset of the presentation of the second operand, indicating that these horizontal eye movements were made irrespective of the previous position of the eyes. Because this effect appears about one second before the production of the verbal answer, it is unlikely that the gaze shift takes only place during the preparation of the response. This spatial shift lasted for at least 450 ms after the onset of the response of the participant was detected, as there was an interaction between the operation and the side of the target in the detection task. Because we used two effectors to answer to the target detection task in the present study and in our previous study (Masson & Pesenti, 2014), the question remained open whether the interaction between the position of the target and the operation could result from the accelerated motor preparation of right hand rather than of an attentional shift. Thanks to the suggestion of an anonymous Reviewer, we now show that the horizontal position of the eyes when the participants were giving their answer correlates with their performance in the target detection task. Indeed, the more the participants were looking to the right, the more they were faster to detect a rightward target in comparison to a leftward target, and vice versa. This suggests that the bias observed in the target detection task is closely linked to an actual attentional bias. Previous studies have already shown that eye movements could be related to
numerical processing (e.g. Grade et al., 2013; Loetscher et al., 2010; Myachykov, Ellis, Cangelosi, & Fischer, 2016; Ranzini et al., 2015; 2016; Ruiz Fernandez et al., 2011). The horizontal gaze shifts we observed here might thus be the behavioural counterparts of the activations elicited within the PSPL that were found partially similar for arithmetic solving and eye movements (Knops, Thirion et al., 2009).

The idea that solving an addition or a subtraction is equivalent to executing a "mental walk" along a mental number line with an amplitude determined by the magnitude of the second operand is not supported, given the absence of enhanced effect in gaze deviation for larger second operands, and by the spatial biases observed in previous studies that used problems including zero as second operand (Marghetis et al., 2014; Masson & Pesenti, 2014; Pinhas & Fischer, 2008). Pinhas and Fischer (2008) suggested that spatial biases related to arithmetic might be the consequence of a semantic link between the operation and space (i.e., addition-right and subtraction-left) and a competition between localized activation of the operands. Each operand and the answer to the problem would activate the left or right side of space according to their magnitude. The sum of these lateralized activations would eventually lead to a final spatial bias. Our gaze shift measurement allowed us to observe which element of the problems elicited sequentially overt attentional shifts while processing the terms of the problem, the target detection aiming at measuring the final state of these shifts. Our results do not support the sum of activation theory (Pinhas & Fischer, 2008) as no cascade of left and right attentional shifts while hearing the problem was detected. The only factor that influenced the direction of gaze shifts was the operation (i.e., addition or subtraction), whatever the magnitude of the operands and the answer to calculate. Moreover, the sum of activation account predicts that the final spatial bias should be less important in additions than in
subtractions. Indeed, because all the operands are smaller than the answer for additions, they would activate left portions of space relative to the answer and thus would dilute the semantic association between the plus sign and the right side of space. For subtractions, a second operand with a magnitude smaller than the answer (e.g. 72-5=67), as was always the case in our list of problems, would activate the left part of space and therefore maximize association between minus sign and the left side of space. This was not the case in our detection task, which again goes against the hypothesis of a sum of activation proposed by Pinhas & Fischer (2008). This holds true for overt shifts of attention; whether covert shifts of attention are elicited by processing the elements of the problems or whether processing the elements has a remote impact later in the solving process cannot be assessed with the gaze metrics we used here.

A recent study reported early downward gaze shifts while processing the minus sign suggesting that horizontal spatial associations in mental arithmetic are nothing more than experimental biases (Hartmann et al., 2015), and thus that left-right attentional shifts do not take part functionally in the computational processes that are crucial for arithmetic solving. These authors claim that a horizontal mapping was always salient when participants were solving the problems in previous studies due to some peripheral aspects of the experimental set-up (e.g. the horizontal mapping of the proposals; the lateralized targets; an horizontal flanked line, etc.; Marghetis et al., 2014; Masson & Pesenti, 2014; Pinhas & Fischer, 2008), which might have enhanced artificially a horizontal mapping that would overcome a more natural vertical mapping. It is worth noting that the results of Hartmann et al. (2015) were obtained with problems that were not matched for the magnitude of the results, which is critical given that larger magnitudes per se can induce attentional shifts to the right,
and smaller magnitudes to the left (e.g. Fischer et al., 2003), and that half of their subtractive problems involved negative solution size that may be processed or represented differently than positive numbers (Fischer, 2003; Fischer & Rottmann, 2005; Ganor-Stern, Pinhas, Kallai, & Tzelgov, 2010; Nuerk, Iversen, & Willmes, 2004), perhaps by specific strategies relying on verbal working memory (Robert & LeFevre, 2013). Crucially, one cannot exclude the possibility that participants solved subtractions problems where the result was close to the second operand by using strategies based on complementary additions (e.g. 8-5=? solved as 5+?=8; Geary, Frensch, & Wiley, 1993; LeFevre, DeStefano, Penner-Wilger, & Daley, 2006), which could have masked any spatial effects occurring while the participants were solving the problem in Hartmann et al.'s study (2015) since both additions and subtractions would be solved with additive procedures.

The absence of leftward deviation for subtraction solving could be explained by the fact that subtraction solving might require mixed strategies and might reduce the impact of leftward attentional shifts. We previously reported that the size of the spatial bias after solving a large subtraction (i.e., using 2-digit problems similar to the present study) was smaller than when participants had to solve arithmetical facts (Masson & Pesenti, 2014). We have also reported that rightward optokinetic stimulation facilitated the solving of large additions while leftward optokinetic stimulation did not facilitate the solving of large subtractions (Masson, Pesenti, & Dormal, 2016). We hypothesized that applying several computation steps when solving large subtraction problems might weaken rather than strengthen the recruitment of visuo-spatial attentional mechanisms. This would therefore decrease the leftward gaze deviations in subtraction trials in the present study. Future studies should investigate whether participants that use complementary additions strategies
would show rightward attentional biases in subtraction solving. However, it is worth noting that some other previous studies reported attentional shifts while solving both operations (e.g., Masson & Pesenti, 2016; Mathieu et al., 2016; Wiemers et al., 2014) suggesting that spatial attentional mechanisms are also related to subtraction solving.

We cannot exclude that the detection task might have induced horizontal deviations because the targets to detect were presented on the left or right parts of the screen facing the participants who might thus have tried to anticipate the position of the next target. However, we argue that the presence of horizontal targets to detect cannot explain the direction of association between operation and the side of space in the horizontal plane. At best, the horizontal experimental setting might have reduced the vertical mapping, but without shaping a left to right association between operation and space.

One might also argue that spatial shifts in arithmetic are exclusively semantic associations that play no part in the functional processes that are critical to solve addition or subtraction problems. However, observing that operation signs can prime spatial associations even in tasks that do not require calculation (i.e., classify operation signs; Pinhas et al., 2014) or when being confronted with a zero problem (Marghetis et al., 2014; Masson & Pesenti, 2014; Pinhas & Fischer, 2008) does not per se exclude that attentional shifts may take part in the procedures required to solve additions or subtractions. The fact that gaze shifts only occurred while solving the problem and not while hearing the operands and operator suggests that attentional mechanisms are part of the solving procedure, contrarily to what was suggested by Hartmann and colleagues (2015). Indeed, it has also been shown that congruent movements of the hand (Wiemers et al., 2014), of the eyes (Masson et al.,
or of the body (Anelli, Lugli, Baroni, Borghi, & Nicoletti, 2014; Lugli, Baroni, Anelli, Borghi, & Nicoletti, 2013) could improve participants' performance in solving arithmetic problems. Moreover, a previous experiment showing that the solving of addition problems was slowed down by the (simultaneous) presentation of a lateralized distractor in the right hemifield, whereas left distractors slowed down the solving of subtraction problems, thus suggesting that attentional shifting is part of the calculation procedure (Masson & Pesenti, 2016). Most importantly, a neuropsychological study showed that left neglect patients’ performance was altered for subtraction solving, irrespective of the absolute magnitude of the result, while addition solving was spared (Dormal et al., 2014). These authors suggested that when solving a problem, part of the procedure would imply representing a starting location (i.e., the first operand), and then the approximate location of the result that will be on the left for a subtraction and on the right for an addition. An attentional shift is then needed within this temporary mapping to access the representation of the response to the problem in a direction driven by the operation. This idea implies that the absolute magnitudes of the first operand and of the result are not critical for the direction of the attentional shifts. Interestingly, these mechanisms recall those that are recruited in numerical comparison to a standard task. Indeed, it has been shown that left neglect patients have difficulties to respond to a number smaller than the standard but close to it, whatever its absolute magnitude (Masson, Pesenti, & Dormal, 2013, 2016; Salillas, Granà, Juncadella, Rico, & Semenza, 2009; van Dijck, Gevers, Lafosse, & Fias, 2012; Vuilleumier, Ortigue, & Brugger, 2004; Zorzi et al., 2012), which fits nicely with their difficulties for solving subtraction problems (Dormal et al., 2014). Attentional shifts may thus be critical whenever a number has to be represented to the right or to the left relative to another on a mental space.
Comparing left but also right neglect patients’ performance in arithmetic and numerical comparison tasks is needed to test this proposal.

In conclusion, the present study showed that arithmetical problems elicited overt attentional shifts to the right while solving additions suggesting that attentional mechanisms are part of the solving procedure. Finally, as we did not show significant leftward deviations during subtraction solving, future research should investigate the impact of strategies on attentional shifts in subtractions solving by comparing problems that are usually known to be solved with additive strategies and those that are solved without such strategies.
Bibliography


Figures captions

Figure 1: Median (±S.E.) response latencies for the target detection task as a function of operation (addition vs. subtraction) and side of the target (left vs. right).

Figure 2: Mean (±S.E.) horizontal (A) and vertical gaze deviation (B) as a function of operation (addition vs. subtraction) and time window (TW1: Operand 1; TW2: Operator; TW3: Operand 2; TW4: Calculation).

Figure 3: Time course of the mean horizontal gaze position as a function of operation (Addition vs. Subtraction). Grey area indicates statistically significant differences for at least 20 consecutive samples. (TW1: Operand 1; TW2: Operator; TW3: Operand 2; TW4: Calculation).

Figure 4: Time course of the mean vertical gaze position as a function of operation (Addition vs. Subtraction). (TW1: Operand 1; TW2: Operator; TW3: Operand 2; TW4: Calculation).

Figure 5: Mean Global dRL for detecting targets (Left Response Latencies – Right Response Latencies) as a function of the mean horizontal gaze position at the onset of the verbal answer of participants (A) for all trials, and (B) for addition and subtraction problems separately (plain line and filled dots: subtraction; dashed line and empty dots: addition).