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The predictive role of eye movements in mental arithmetic

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Abstract

Behavioural studies have suggested that number manipulation involves shifting attention along a left-to-right oriented continuum. However, these studies provide little evidence about the time course of attention shifts during number processing. We used an eye-tracker with high spatio-temporal resolution to measure eye movements during the mental solving of addition (e.g., 43+4) and subtraction problems (e.g., 53-6), as a proxy for the rightward and leftward attention shifts that accompany these operations. A first difference in eye position was observed as soon as the operator was heard: the hearing of "plus" shifted the eye rightward compared to "minus". A second difference was observed later between problem offset and response onset: addition shifted the eye rightward and upward compared to subtraction, suggesting that the space used to represent the problem is bidimensional. Further analyses confirmed the fast deployment of spatial attention and evidenced its relationship with the carrying and borrowing procedures triggered by the problem presentation. The predictive role of horizontal eye movements, in particular, is essential to understand how attention contributes to narrow down the range of plausible answers. We propose that attention illuminates significant portions of the numerical continuum anticipatively to guide the search of the answer and facilitate the implementation of solving procedures in verbal working memory.

Key words: mental arithmetic; visuospatial attention; attention shift; eye tracking

Mental arithmetic provides a unique paradigm to study the cognitive mechanisms underlying abstract thinking. Historically, mathematics emerged to support the development of human societies in various domains such as architecture, trade and sciences. The manmade rules that govern arithmetic go far beyond the protonumerical skills identified in animals and newborns, and mastering these rules requires years of teaching. One influential view assumes that arithmetic skills rely on spatial processes. Numbers would be mentally represented on a left-to-right continuum ordered according to their magnitude, and their manipulation would involve attention shifts along this spatial continuum (Dehaene, 1992; Hubbard, Piazza, Pinel, & Dehaene, 2005). This action is supported by the joint contribution of the anterior intraparietal sulcus (IPS) to number encoding in working memory, and of the posterior parietal cortex (PPC) to attention orienting within the working memory contents (Dehaene, Piazza, Pinel, & Cohen, 2003; Dumontheil & Klingberg, 2012; Sahan, Majerus, Andres, & Fias, 2018; Zago et al., 2008). In the PPC, in particular, the regions activated by number comparison or calculation overlap the regions activated by overt (i.e., saccades; Knops, Thirion, Hubbard, Michel & Dehaene, 2009) and covert attention shifts (i.e., retro-cued attention, Sahan et al., 2018). Accordingly, several studies evidenced a quicker detection of leftward targets during subtraction and of rightward targets during addition, suggesting an attentional shift toward the visual hemifield congruent with the spatial direction of the arithmetic operation (Liu, Cai, Verguts, & Chen, 2017; Masson & Pesenti, 2014; see also Mathieu et al., 2016).

However, these studies left several issues unanswered. First, theoretical elaboration requires specifying the time course at which attention shifts emerge during arithmetic problem solving. This issue is further complicated in paradigms where attention shifts are temporally bound to the apparition of a visual target that participants need to detect (Liu et al., 2017; Glaser & Knops, 2020; Masson & Pesenti, 2014; Masson, Andres, Alsamour, Bollen, & Pesenti, 2020). A second, corollary issue concerns the origin of attention shifts that can either reflect a

functional process or an epiphenomenon (for a discussion of this issue, see Andres, Salvaggio, Lefèvre, Pesenti, & Masson, 2020). The measures obtained with chronometric methods do not allow us separating these options because they typically index any phenomenon that takes place between the stimulus and the response. As an alternative to chronometric methods, two studies recorded eye movements to track attention while participants were solving arithmetic problems. Hartmann and colleagues (2015) evidenced attention shifts concomitant to the encoding of the arithmetic problem but only on the vertical axis, suggesting that addition directed attention upward relative to subtraction. Masson and colleagues (2018) found attention shifts along the horizontal – but not the vertical – axis while participants were computing the answer. These conflicting results raise a third issue related to the dimensions of the mental space used for number manipulation. The vertical axis is often used to teach or represent numbers in daily life and the introspective reports of number synaesthetes witness the importance of this dimension (Seron et al, 1992, Piazza 2006). Finally, an important aspect of calculation concerns the procedures used to solve arithmetic problems. Large problems put a different load on working memory, especially when they imply carrying or borrowing procedures (LeFevre, Sadesky & Bisanz, 1996; Logie, Gilhooly & Wynn, 1994), potentially increasing the need to rely on a visuospatial medium.

We made the assumption that eye movements contribute to narrow down the range of plausible answers by guiding the search of the answer on a left-to-right oriented continuum as information about the operator (addition/subtraction) and the calculation (carry/borrow) is processed. If the eye position reflects a dynamic search process, the gaze should drift leftward or rightward as soon as the direction of the operation is known. We used eyetracking as a proxy to investigate how the cognitive system progressively integrated the information carried by the numbers, the operator or their association, to predict the location of the answer on the mental numerical continuum. Furthermore, we examined the role of cognitive load by comparing the

eye movements elicited by arithmetic operation in carry and non-carry problems. Finally, we also explored vertical eye movements as previous studies suggested they might play a role in arithmetic problem solving (Hartmann et al., 2015). To do so, we took advantage of the high temporal resolution of the eye-tracker enhanced by the fragmented presentation of the different elements of two-digit addition and subtraction problems. The task was coupled with the passive viewing of landscape pictures, and their mirror version, both carefully counterbalanced over the different conditions of the experiment to exclude perceptual biases. The rationale was to provide participants with a rich visual context that stimulates eye movements and thereby increases sensitivity to number-related attention shifts. The use of a background image is common to other studies and proved superior to the use of a blank screen, as evidenced by the number of saccades elicited during a trial and the effective detection of number-related attention shifts (Salvaggio, Masson & Andres, 2019; Sahan, van Dijck & Fias, 2021).

Method

Participants

Thirty-two French-speaking University students with normal or corrected-to-normal vision took part in this experiment in exchange for course credits (twelve males; three left-handed; mean age and standard deviation, M=22.8, SD=4.2). Sample size was estimated using *G*Power 3*.1 (Faul, Erdfelder, Lang, & Buchner, 2007). A sample size of 28 participants achieves a 95% power to detect a true difference between addition and subtraction in horizontal eye position (Cohen's d = 0.6; Masson, Letesson & Pesenti, 2018) with $\alpha = 0.05$ using a one-tailed paired t-test. The experimental procedure was approved by the ethical committee of the Psychological Sciences Research Institute at UCLouvain (B403201629166).

Apparatus

The experiment was run on a PC equipped with a 22-inch LCD screen (1920x1080 pixels; refresh rate: 60Hz). The participant wore Sennheiser PC8 USB headphones equipped

with a microphone (Sennheiser, Wedemark, Germany). The software E-Prime 2 (Schneider, Eschman, & Zuccolotto, 2002) controlled stimulus presentation and recording of the verbal response. An Eyelink 1000 tower-mounted camera was used to track eye movements (SR Resarch, Mississauga, Canada; sampling rate: 1000Hz; average accuracy range: 0.25° angle to 0.5° angle; gaze tracking range of 32° angle horizontally and 25° angle vertically). Participants were placed at 60 cm from the screen. Prior to each experimental block, the eye tracker was calibrated to the screen using a built-in 9-point protocol.

Stimuli materials

The arithmetic problems consisted of 144 unique 2-digit ± 1-digit problems that participants heard through headphones. The first operand (O1) ranged between 11 and 79. The unit of O1 could be 1, 2, 3, 7, 8 or 9 and the decade of O1 ranged from 10 to 60 for the addition problems, and from 20 to 70 for the subtraction problems. The second operand (O2) was either 4 or 6. Therefore, carrying procedures were required to solve addition problems with O1 units 7-9 and borrowing procedures were required to solve subtraction problems with O1 units 1-3. Overall, addition and subtraction problems were matched for the magnitude of their results (mean and SD of addition results: 45±18; mean and SD of subtraction results: 45±18). The numbers and operators were recorded in Belgian French, and the audio file duration was adjusted to 750 ms for O1 and 500 ms for the operator and O2. The visual stimuli consisted in 18 high-definition coloured pictures of urban and natural landscapes and their horizontal flip (1920x1080 pixels). The same set of pictures were used for addition and subtraction problems, with and without a carry, which means that each picture was presented once in all four conditions. Within each condition, the different pictures were randomly associated with arithmetic problems to exclude any systematic association with a given problem. We presented both the original pictures and their horizontal flip to be sure that if something in the original

picture grabbed the participant's attention on a particular side, it would be mirrored in the same condition later.

Task and Procedure

During the task, the gaze was free, but participants were instructed to move their eyes back on the central fixation cross (size: 0.5° x 0.5°) displayed at the beginning of each trial, in black on a grey background, during 500 ms. After the fixation cross disappeared, the first operand (O1) was presented for 750 ms, followed by a 625-ms blank interval, and then the operator (+/-) for 500 ms; after another 625-ms blank interval, the second operand (O2) was presented for 500 ms. The total duration of the problem presentation was thus 3000 ms. Participants were asked to respond to the arithmetic problem verbally, with a deadline of 6000 ms from problem onset. The picture was displayed at the time of O1 onset and remained on screen for all the duration of the trial. The next trial started immediately after the offset of the picture.

Data analysis

Erroneous trials (18%) were excluded from the rest of the analyses ($N_{ADDITION}$ = 8 %,; $N_{SUBTRACTION}$ = 10 %). Response latencies (RL), measured from problem offset, were entered into a repeated measure analysis of variance (ANOVA) with OPERATION (subtraction vs. addition) and CARRY (carry vs. no carry) as within-subject factors. The spatial and temporal parameters of eye movements were extracted using Eyelink® Data Viewer (SR Research Ltd., Mississauga, Ontario, Canada). Eyetracking data were considered as outliers if they corresponded to locations outside the screen. The pupil size derivative was also systematically inspected to refine the search for outliers due to signal loss. The signal loss was associated with a departure from linearity in the derivative data (typically > 50 SD), which clearly denotes an abnormality given the relatively low frequency of pupil size variations. This method is preferable to the visual inspection of eye position because the signal loss is immediately

reflected in the pupil velocity profile, whose better signal-to-noise ratio leaves no place for ambiguity, and the decision to remove the data is independent of the analysis of lateralized eye movements. We interpolated the missing data only if the signal loss was less than 500 ms, which corresponds to the time interval of an eye blink (Schiffman, 1990). Moreover, if signal losses cumulated beyond the limit of 2000 ms within a single trial, we removed the trial from the dataset. The percentage of excluded trials resulting from outlier detection (4%) added up to the percentage of error trials (18%), for a total of 22% of excluded trials across the full dataset. In the remaining data (78%), the vertical and horizontal coordinates of eye position were aggregated in bins of 10 ms on a time period of 6000 ms running from the onset of the number word. The difference between subtraction and addition problems was tested in every bin using a paired t-test and clusters were constituted by grouping all bins that showed a significant difference (p<.05) and a maximal gap of 100 ms (10 bins) between them. Effect size was estimated at the cluster level by taking the t statistic of the maximum difference across all the bins contained in the cluster and dividing it by the square of the number of participants. The multiple comparison problem was addressed by means of a nonparametric random permutation procedure (for details, see Salvaggio, Masson & Andres, 2019; Maris & Oostenveld, 2007). The analyses were made with MATLAB 2018a (MathWorks Inc., 2018) and SPSS 24.0 (IBM Corp., 2016).

Results

Response latency

There was no effect of OPERATION, $F(1, 31) = 3.47$, $MSE = 9637$, $p = .072$, $\eta_p^2 = .101$ ($M_{ADDITION}$ = 948 ms from problem offset, $SD_{ADDITION}$ = 268; $M_{SUBTRACTION}$ = 974 ms from problem offset, $SD_{SUBTRACTION}$ = 235), but a main effect of CARRY, $F(1, 31) = 134.8$, $MSE = 28797$, $p < .001$, $\eta_p^2 = .813$, indicating a higher RL when arithmetic problems involved shifting to the superior or inferior decade (M= 1132 ms, SD= 288) compared to when they did not (M= 787

ms , SD= 236). A significant interaction was found between these two factors, $F(1, 31) = 14.3$, $MSE = 7440$, $p = .001$, $\eta_p^2 = .316$, indicating that the CARRY effect was larger for subtraction ($M_{CARRT} = 1167$ ms, $SD_{CARRY} = 291$; $M_{NO\ CARRY} = 771$ ms, $SD_{NO\ CARRY} = 226$; $t(31)=11.54$, $p <.001$) than for addition ($M_{CARRT} = 1078$ ms, $SD_{CARRY} = 309$; $M_{NO\ CARRY} = 796$ ms, $SD_{NO\ CARRY} = 266$; $t(31)=9.07$, $p <.001$; see Figure 1).

Horizontal eye drift

The statistical comparison of horizontal eye position evidenced a rightward deviation in addition trials relative to subtraction trials (Figure 2A and 2B), on two different time periods, just after the operator onset, from 1770 to 2210 ms ($p<.001$, Cohen's $d=.48$, maximal difference = 13 pixels or 0.32° angle), and during the response production stages, from 3900 to 4040 ms after problem onset ($p=.001$, $d=.39$, maximal difference = 16 pixels or 0.39° angle). Figure 2 shows an initial deflection toward the left side of space, irrespective of the arithmetic operation, before addition re-directed attention rightward to the screen center, creating a difference with subtraction.

In the second analysis, we separated carry and no-carry problems to test whether the early move of attention along the horizontal axis anticipated the need to implement carrying/borrowing procedures. Of note, in the present experiment, the structure of the problems made it possible to anticipate such carrying or borrowing procedures from operator onset: if the first operand ended with 7-8-9, addition required a carry in any case (+4 or +6); if the first operand ended with 2-3-4, subtraction required a borrowing in any case (-4 or -6). In the carry condition, addition showed a rightward deviation relative to subtraction just after the operator onset (+ or -), between 1720 to 1920 ms ($p<.001$, $d=.48$, maximal difference = 22 pixels or 0.52° angle), and during the response production stages, between 3670 to 4160 ms ($p<.001$, $d=.42$, maximal difference = 19 pixels or 0.47° angle). In the no-carry condition, however, no difference was observed between the two arithmetic operations (Figure 3). The

response time analysis showed that the execution of carrying/borrowing procedures induce an extra time cost. In order to control for the possible influence of response latency on the difference in eye position between the two operations, we conducted an additional analysis over the 1000 ms preceding each oral response (i.e. the time interval between the problem offset and the response). This response-locked analysis replicated the continuous rightward deviation of the gaze in addition trials relative to subtraction trials for the carry problems only (p<.001, d=.52, from 1000 ms to 230 ms before the response, maximal difference = 22 pixels or 0.52° angle).

In the third analysis, we exploited another particularity of the stimulus set to further investigate the predictive role of attention shifts and disentangle the influence of number magnitude and arithmetic operation on their direction. In order to match the two arithmetic operations in response magnitude, we created a subset of addition problems with a first operand between 11 and 19 (plus 4 or 6) and a subset of subtraction problems with a first operand between 71 and 79 (minus 4 or 6). Because these problems were exclusively linked to addition or subtraction, it was possible for participants to perform attention shifts anticipatively, before the operator onset (+ or -), from the decade of the first operand (11-19 or 71-79). We tested whether these problems could have influenced the time course of horizontal attention shifts. First, we replicated the main analysis after excluding these problems, thus limiting the eye-tracking data to problems that were associated both with addition and subtraction (i.e. problems with a first operand between 20 and 60). This control analysis revealed the same pattern of results as described above: a difference in horizontal eye position between subtraction and addition was observed between 1780 ms and 1990 ms (p<.001, d=.57 maximal difference = 17 pixels or 0.41° angle), right after hearing the operator, and between 3880ms and 4050ms (p<.001, d=.54, maximal difference = 18 pixels or 0.44° angle), during the response production. Second, we specifically compared the two subsets of problems where it was possible to guess

the operation from the decade of the first operand (11-19 or 71-79). In these problems, a significant difference in horizontal eye position was observed very early, before the onset of the operator, from 1390 ms to 1550 ms (p<.001, d=.47, maximal difference = 38 pixels or 0.93° angle; see Figure 4). These findings corroborate the idea that participants noticed the regularities in the stimulus set and moved their attention anticipatively when the side of the numerical continuum where the answer lies could be inferred from the first operand. Another important implication of this analysis is that it clearly shows it is the operation and not the number magnitude that is responsible for the direction of attention shifts. The mental number line is usually considered as a long term memory representation where numbers occupy a fixed position. If the position assigned to numbers on this mental number line played a role in arithmetic problem solving, then the subset of addition problems with numbers 11-19 should shift attention leftward compared to the subset of subtraction problems with numbers 71-79. We found the opposite, meaning that attention shifted in the direction implied by the arithmetic operation, i.e. rightward for addition and leftward for subtraction, irrespective to the position of the operands on the two ends of the numerical continuum.

Vertical eye drift

A significant difference in vertical eye position was observed during the response production stages, from 3500 ms to 4200 ms after problem onset, indicating a late deviation downward in subtraction relative to addition trials (p<.001, d=.43, maximal difference = 9 pixels or 0.21° angle). This late contribution contrasts with the predictive nature of horizontal attention shifts (see Figure 2C and 2D).

Discussion

We used a high-temporal resolution eye-tracker to measure eye movements during the solving of addition and subtraction problems, as a proxy for the spatial attention shifts associated with numerical cognition. Pictures were presented on screen to stimulate eye

movements and the arithmetic problems were presented in a fragmented manner to isolate attention shifts over time. The main analysis showed that arithmetic operation shifted eye position at two distinct time windows. A first difference was observed just after hearing the operator: the plus sign shifted the eye rightward compared to the minus sign. A second difference was observed later between problem offset and response onset: addition shifted the eye rightward and upward compared to subtraction. Supplementary analyses confirmed the early onset of horizontal attention shifts and showed they resulted from the comparison of problems that required carrying and borrowing procedures. These results allow three important conclusions regarding the cognitive mechanisms that govern number and space interactions during arithmetic processing.

First, horizontal attention shifts occur predictively, i.e. before exact computation has started. The results showed that addition deviated the gaze rightward, compared to subtraction, as soon as the operator was heard. In problems where the first operand implied an addition or a subtraction due to systematic associations in the stimulus set, attention moved in the direction of the expected operation even before the operator was presented. These data demonstrate the fast deployment of spatial attention during arithmetic processing. This predictive role is essential to understand how attention potentially contributes to narrow down the range of plausible answers. We propose that attention illuminates significant portions of the numerical continuum anticipatively to facilitate the incremental process during exact computation. A similar proposal is that attentional shifts could contribute to give an approximative idea of plausible answers that would then be compared to the solution obtained by an exact procedure, preventing absurd errors (Marghetis, Nunez, & Bergen, 2014). Our results are compatible with this proposal but refines it by highlighting the dynamic nature of the approximation, which actually takes place as soon as it is possible to predict the direction of the operation. The predictive role of spatial attention in mental arithmetic has been noticed in former chronometric

studies showing for example that the display of a first operand and an arithmetic sign is sufficient to prime the detection of lateralized targets (Liu et al., 2016; Masson, et al., 2020; Yáñez et al., 2020). Our study brings direct evidence for such predictive shifts by combining the interleaved presentation of operands with eye-tracking.

Second, horizontal attention shifts are driven by the execution of arithmetic procedures in working memory. Two results force this conclusion. When the analysis is restricted to problems where number magnitude and arithmetic operation predict shifts in opposite directions, eye movements clearly reflect the direction implied by the operation. In other words, addition deviated the gaze rightward relative to subtraction even when addition problems were made of numbers located on the leftmost end of the continuum and subtraction problems were made of numbers located on the rightmost end of the continuum. Close examination of the data shows that each trial started with a leftward ocular drift that cannot be explained by arithmetic operation or number magnitude. This initial deflection toward the left side of space has been observed in several other studies using auditory verbal stimuli (Myachykov, Cangelosi, Ellis & Fischer, 2015; Myachykov, Ellis, Cangelosi & Fischer, 2016; Salvaggio, Masson & Andres, 2018; Sahan, van Dijck & Fias, 2021). It is reminiscent of our natural tendency to scan visual scenes from left to right, possibly due to the dominant role of the right hemisphere in the deployment of spatial attention (Foulsham, Gray, Nasiopoulos, & Kingstone, 2013). Because of the generic deployment of attention from left to right, we assume that the first operand was positioned on the left side of the mental space, irrespective of its magnitude, and served as an anchor for searching the answer of the calculation. Then, the analyses showed that horizontal attention shifts were mainly driven by those problems that implied a carrying or borrowing procedure. The rightward deviation induced by addition problems, relative to subtraction problems, was actually observed only when the computation of the answer required crossing decades. Response time data showed that carrying and borrowing procedures are costly, which

suggests that spatial attention is involved to alleviate the working memory load. Of note, in the present experiment, the structure of the problems made it possible to anticipate such carrying or borrowing procedures from operator onset: if the first operand ended with 7-8-9, addition required a carry in any case (+4 or +6); if the first operand ended with 2-3-4, subtraction required a borrowing in any case (-4 or -6).

Third, vertical attention shifts were detected, suggesting that the space used to represent arithmetic problems is bidimensional. The analysis of vertical attention shifts is admittedly exploratory and requires a cautious interpretation for two reasons. One of the limitations is that the pictures used in our experiment were not flipped vertically. Hence, the particular bottom-to-top orientation of the visual scenes, with close objects in the inferior part and far objects in the superior part, could have primed an association between addition (i.e. incrementing) and upward movement (i.e. moving away) and the reverse for subtraction. After all, a top-to-bottom orientation was equally plausible to represent the incremental process if one thinks of the progression of a text on a page or the progression of rows in a table of figures. Moreover, contrary to the horizontal gaze deviation, the difference in vertical eye position was observed in the late stages of calculation, from 3500 ms to 4200 ms after problem onset. We did not investigate further the origin of vertical attention shifts because the absence of evidence for an early contribution in the main analysis did not justify a study of their predictive role in follow-up analyses. The conclusion is that arithmetic problem solving entertains movements of attention along the vertical axis, as well, but their late onset forces us to adopt a different perspective on their role. We propose that horizontal attention shifts help to narrow down the range of plausible answers predictively and keep them active in working memory especially when cognitive load is high. In contrast, vertical attention shifts might contribute to refine the spatial frame in later stages of calculation, for example by representing small increments on the portion of the numerical continuum where the answer has been identified in the former stages.

This interpretation is compatible with some introspective reports of number forms, which refer to a horizontal continuum regularly interleaved with volutes describing the organization of digits within a decade (Galton, 1880; Hubbard et al., 2005), and with eye-tracking data suggesting a contribution of both dimensions to number comparison and arithmetic (Hartmann et al., 2015; 2016; Masson et al., 2017; Salvaggio et al., 2019). However, the present experiment does not allow us to exclude that vertical attention shifts are epiphenomenal to the resolution of the problem, given their late time course, and confirmatory research is needed to establish their role in mental arithmetic. Another interesting idea that remains to be investigated is that the bidimensional representation of numbers can be flexibly used, as a function of one's personal experience or of the task at hand, and could eventually extend to a third dimension defining close and far space (Aleotti, Di Girolamo, Massaccesi & Priftis, 2020).

Classical cognitive architectures of numerical cognition posit that small arithmetic facts are solved through verbal memory retrieval (Dehaene & Cohen, 1991), whereas large arithmetic problems require the manipulation of magnitude representations (Mc Closkey, Caramazza & Basili, 1985; Dehaene, 1992), in particular when the problem implies carry or decomposition (Campbell & Xue, 2001; LeFevre, DeStefano, Penner-Wilger, & Daley, 2006; LeFevre, Sadesky, & Bisanz, 1996; Pesenti et al., 2001). However, these classical models do not specify the mechanisms involved in the manipulation of number magnitude during arithmetic problem solving. Recent proposals acknowledge the role of spatial attention in arithmetic problem solving but they were mostly developed on theoretical or neurophysiological grounds (Chen & Verguts, 2012; Dehaene, Piazza, Pinel & Cohen, 2003; Hubbard et al., 2005; Knops, Thirion, Hubbard, Michel & Dehaene, 2009), providing little insight into the cognitive mechanisms that elicit the transient mapping of numbers on a spatial continuum and cause directional attention shifts. Our eye-tracking study highlights the predictive role of attention in converting the arithmetic problem into a spatial frame that represents the plausible answers, thereby reducing

the cognitive load and paving the way for the implementation of efficient solving strategies. Supporting evidence for this view comes from studies of patients with unilateral spatial neglect, a brain disorder affecting the ability to orient attention to the contralesional hemispace (Heilman, 1979). It has been shown that subtraction problems give rise to more errors than addition problems in right-brain-damaged patients exhibiting left neglect (Dormal et al., 2014). In contrast, a single case with right neglect, following left brain damage, was reported to have more difficulties with addition than subtraction problems (Masson et al., 2017). This double dissociation cannot be explained by current numerical cognition models unless one considers that the ancillary role of spatial attention in arithmetic problem solving. The impairment of attention orientation along the vertical axis has received less attention in the literature, though a few cases of vertical neglect have been reported (e.g., Rapcsack, Cimino & Heilman, 1988; Shelton, Bowers & Heilman, 1990; Andres, Geers, Marnette, Coyette, Bonato, Priftis & Masson, 2019), and the question of whether vertical neglect might impact on mental arithmetic remains to be further tested.

Our time course analysis thus shows that the cognitive system optimally integrates the terms of the problem to direct spatial attention toward the probable location of the answer on the mental numerical continuum. It is clear from the predictive nature of these attention shifts, which typically occur before the presentation of the second operand, that their primary role is not to identify the exact answer but to reduce uncertainty about its probable location. Moreover, the solving of arithmetic problems cannot be uniquely spatial because this would imply that the location of the answer is known before an attention shift is triggered, which is not compatible with the early attention orienting response revealed by our eye-tracking data. Our results favour a probabilistic model where attention shifts are embedded in working memory processes: the number word sequence provides positional information (landmark) to anchor the spatial frame of the problem, whereas (directional) attention shifts contribute to adjust the frame as

calculation progresses thereby reducing the part of the number sequence maintained in verbal working memory. The role of spatial attention would thus be ancillary to verbal working memory in the incrementation process, just as the movement of a flashlight guides our steps into darkness. Beyond the arithmetic domain, our results converge with others to support a working memory model attributing a role to spatial attention in the serial processing of verbal information (Abrahamse, van Dijck, Majerus, & Fias, 2014; Sahan, van Dijck & Fias, 2021; van Dijck, Abrahamse, Majerus & Fias, 2013). Grounding the resolution of arithmetic problems in the interaction between spatial attention and verbal working memory is a promising avenue for further research.

To sum up, our results demonstrate that the recruitment of spatial attention is linked to the arithmetic procedures triggered by the problem presentation. The operator triggers the setting of a spatial frame oriented leftward or rightward, relative to the first operand, to represent the numerical relationships relevant to the arithmetic task. We tentatively assume that horizontal and vertical attention shifts observed later, around response production, reflect a re-calibration of the spatial frame as computation progresses. In this view, attention shifts are not the signature of movements along a mental number line where numbers occupy a fixed position but they rather reflect working memory processes operating on a spatial representation created to face the actual demands of arithmetic processing, for instance the implementation of carrying or borrowing procedures in working memory.

Conflict of interest statement

On behalf of all authors, the corresponding author states that there is no conflict of interests.

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Availability of data and material

The custom codes written for the current study and the datasets generated during and/or analysed during the current study are available on OSF following this link.

References

Aleotti, S., Di Girolamo, F., Massaccesi, S., & Priftis, K. (2020). Numbers around Descartes: A preregistered study on the three-dimensional SNARC effect. *Cognition*, 195, 104111. https://doi.org/10.1016/j.cognition.2019.104111

Andres, M., Geers, L., Marnette, S., Coyette, F., Bonato, M., Priftis, K., & Masson, N. (2019). Increased cognitive load reveals unilateral neglect and altitudinal extinction in chronic stroke. *Journal of the International Neuropsychological Society, 21*, 644-653. https://doi.org/10.1017/S1355617719000249

Andres, M., Salvaggio, S., Lefèvre, N., Pesenti, M., & Masson, N. (2019). Semantic associations between arithmetic and space: Evidence from temporal order judgements. *Memory and Cognition, 48 (3),* 361-369. https://doi.org/10.3758/s13421-019-00975-9

Chen, Q., & Verguts, T. (2012). Spatial intuition in elementary arithmetic: A neurocomputational account. PloS one, 7(2), e31180. https://doi.org/10.1371/journal.pone.0031180

Campbell, J. I., & Xue, Q. (2001). Cognitive arithmetic across cultures. J*ournal of experimental psychology: General*, 130(2), 299.

Cousineau, D. (2005). Confidence intervals in within-subject designs: A simpler solution to Loftus and Masson's method. *Tutorials in Quantitative Methods for Psychology*, 1, 42–45. http://dx.doi.org/10.20982/ tqmp.01.1.p042

Dehaene, S., & Cohen, L. (1991). Two mental calculation systems: A case study of severe acalculia with preserved approximation. *Neuropsychologia*, 29(11), 1045-1074. https://doi.org/10.1016/0028-3932(91)90076-K

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition*, *44*(1–2), 1–42. https://doi.org/10.1016/0010-0277(92)90049-N

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Psychology*, *20*(April), 487–506. https://doi.org/10.1080/02643290244000239

Dormal, V., Schuller, A. M., Nihoul, J., Pesenti, M., & Andres, M. (2014). Causal role of spatial attention in arithmetic problem solving: Evidence from left unilateral neglect. *Neuropsychologia*, *60*(1), 1–9. https://doi.org/10.1016/j.neuropsychologia.2014.05.007

Dumontheil, I., & Klingberg, T. (2012). Brain activity during a visuospatial working memory task predicts arithmetical performance 2 years later. *Cerebral Cortex*, *22*(5), 1078–1085. https://doi.org/10.1093/cercor/bhr175

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175-191.

Foulsham, T., Gray, A., Nasiopoulos, E., & Kingstone, A. (2013). Leftward biases in picture scanning and line bisection: A gaze-contingent window study. *Vision research*, 78, 14-25. https://doi.org/10.1016/j.visres.2012.12.001

Furst, A. J., & Hitch, G. J. (2000). Separate roles for executive and phonological components of working memory in mental arithmetic. *Memory and Cognition*, *28*(5), 774–782. https://doi.org/10.3758/BF03198412

Galton, F. (1880). Visualised numerals. *Nature*, 21(533), 252-256. https://doi.org/10.1038/021252a0

Glaser, M., & Knops, A. (2020). When adding is right: temporal order judgements reveal spatial attention shifts during two-digit mental arithmetic. *Quarterly Journal of Experimental Psychology*, 73(7), 1115-1132.

Hartmann, M., Mast, F. W., & Fischer, M. H. (2015). Spatial biases during mental arithmetic: Evidence from eye movements on a blank screen. *Frontiers in Psychology*, *6*(JAN), 1–8.

https://doi.org/10.3389/fpsyg.2015.00012
Hartmann, M., Mast, F. W., & Fischer, M. H. (2016). Counting is a spatial process: Evidence from eye movements. *Psychological Research*, 80(3), 399-409.
Heilman, K. M., & Valenstein, E. (1979). Mechanisms underlying hemispatial neglect. *Annals of Neurology*, *5*(2), 166–170. https://doi.org/10.1002/ana.410050210
Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews Neuroscience*, *6*(6), 435–448. https://doi.org/10.1038/nrn1684
Klein, E., Moeller, K., Dressel, K., Domahs, F., Wood, G., Willmes, K., & Nuerk, H. C. (2010). To carry or not to carry - Is this the question? Disentangling the carry effect in multi-digit addition. *Acta Psychologica*, *135*(1), 67–76. https://doi.org/10.1016/j.actpsy.2010.06.002
Knops, A., Thirion, B., Hubbard, E. M., Michel, V., & Dehaene, S. (2009). Recruitment of an area involved in eye movements during mental arithmetic. *Science, 324*(5934), 1583-1585. https://doi.org/10.1126/science.1171599
LeFevre, J. A., Sadesky, G. S., & Bisanz, J. (1996). Selection of procedures in mental addition: Reassessing the problem size effect in adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 22(1), 216. https://psycnet.apa.org/doi/10.1037/0278-7393.22.1.216
LeFevre, J. A., DeStefano, D., Penner-Wilger, M., & Daley, K. E. (2006). Selection of procedures in mental subtraction. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, 60(3), 209.
Liu, D., Cai, D., Verguts, T., & Chen, Q. (2017). The Time Course of Spatial Attention Shifts in Elementary Arithmetic. *Scientific Reports*, *7*(1), 921. https://doi.org/10.1038/s41598-017-01037-3
Logie, R. H., Gilhooly, K. J., & Wynn, V. (1994). Counting on working memory in arithmetic problem solving. *Memory & Cognition*, *22*(4), 395-410. https://doi.org/10.3758/BF03200866
Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, *164*(1), 177–190. https://doi.org/10.1016/j.jneumeth.2007.03.024
Marghetis, T., Núñez, R., & Bergen, B. K. (2014). Doing arithmetic by hand: Hand movements during exact arithmetic reveal systematic, dynamic spatial processing. *The Quarterly Journal of Experimental Psychology*, 67(8), 1579-1596.
Masson, N., & Pesenti, M. (2014). Attentional bias induced by solving simple and complex addition and subtraction problems. Quarterly Journal of Experimental Psychology, 67(8), 1514-1526.https://doi.org/10.1080/17470218.2014.903985
Masson, N., Pesenti, M., Coyette, F., Andres, M., & Dormal, V. (2017). Shifts of spatial attention underlie numerical comparison and mental arithmetic: Evidence from a patient with right unilateral neglect. *Neuropsychology*, *31*(7), 822. https://psycnet.apa.org/doi/10.1037/neu0000361
Masson, N., Letesson, C., & Pesenti, M. (2018). Time course of overt attentional shifts in mental arithmetic: Evidence from gaze metrics. *Quarterly Journal of Experimental Psychology*, 71(4), 1009-1019. https://doi.org/10.1080%2F17470218.2017.1318931
Masson, N., Andres, M., Alsamour, M., Bollen, Z., & Pesenti, M. (2020). Spatial biases in mental arithmetic are independent of reading/writing habits: Evidence from French and Arabic speakers. *Cognition*, 200, 104262.
Mathieu, R., Gourjon, A., Couderc, A., Thevenot, C., & Prado, J. (2016). Running the number line: Rapid shifts of attention in single-digit arithmetic. *Cognition, 146*, 229–239. https://doi.org/10.1016/j.cognition.2015.10.002

McCloskey, M., Caramazza, A., & Basili, A. (1985). Cognitive mechanisms in number processing and calculation: Evidence from dyscalculia. *Brain and cognition*, 4(2), 171-196. https://doi.org/10.1016/0278-2626(85)90069-7

Morey, R. D. (2008) Confidence Intervals from Normalized Data: A correction to Cousineau (2005), *Tutorials in Quantitative Methods for Psychology*, 4(2), 61-64. doi: 10.20982/tqmp.04.2.p061

Myachykov, A., Cangelosi, A., Ellis, R., & Fischer, M. H. (2015). The oculomotor resonance effect in spatial–numerical mapping. *Acta psychologica*, 161, 162-169. https://doi.org/10.1016/j.actpsy.2015.09.006

Myachykov, A., Ellis, R., Cangelosi, A., & Fischer, M. H. (2016). Ocular drift along the mental number line. *Psychological research*, 80(3), 379-388. https://doi.org/10.1007/s00426-015-0731-4

Nuerk, H.-C., Moeller, K., Klein, E., Willmes, K., & Fischer, M. H. (2011). Extending the Mental Number Line. *Zeitschrift Für Psychologie*, *219*(1), 3–22. https://doi.org/10.1027/2151-2604/a000041

O'Brien, F., & Cousineau, D. (2014). Representing error bars in within-subject designs in typical software packages. *The quantitative methods for psychology*, 10(1), 56-67.

Pesenti, M., Zago, L., Crivello, F., Mellet, E., Samson, D., Duroux, B., Seron, X., Mazoyer, B., Tzourio-Mazoyer, N. (2001). Mental calculation in a prodigy is sustained by right prefrontal and medial temporal areas. *Nature Neuroscience*, 4(1), 103–107. https://doi.org/10.1038/82831

Rapcsak, S.Z., Cimino, C.R., Heilman, K.M. (1988) Altitudinal neglect. *Neurology*, Cleveland, 38, 277-281.

Sahan, M. I., Majerus, S., Andres, M., & Fias, W. (2019). Functionally distinct contributions of parietal cortex to a numerical landmark task: An fMRI study. *Cortex, 114*, 28-40.. https://doi.org/10.1016/j.cortex.2018.11.005

Sahan, M. I., Van Dijck, J.-P. & Fias, W. (2021). Eye-movements reveal the serial position of the attended item in verbal working memory. *Psychonomic Bulletin and Review*, 1–11. https://doi:10.3758/s13423-021-02005-9.

Salvaggio, S., Masson, N., & Andres, M. (2019). Eye position reflects the spatial coding of numbers during magnitude comparison. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 45*(10), 1910. https://psycnet.apa.org/doi/10.1037/xlm0000681

Seitz, K., & Schumann-Hengsteler, R. (2002). Phonological Loop and Central Executive Processes in Mental Addition and Multiplication. *Psychologische Beiträge*, *44*(2), 275.

Seron, X., Pesenti, M., Noël, M. P., Deloche, G., & Cornet, J. A. (1992). Images of numbers, or "when 98 is upper left and 6 sky blue." *Cognition*, *44*(1–2), 159–196. https://doi.org/10.1016/0010-0277(92)90053-K

Shelton, P. A., Bowers, D., & Heilman, K. M. (1990). Peripersonal and vertical neglect. *Brain*, 113(1), 191-205. https://doi.org/10.1093/brain/113.1.191

Yáñez, A. D. B., Couderc, A., Longo, L., Merchie, A., Chesnokova, H., Langlois, E., ... & Prado, J. (2020). Learning to run the number line: the development of attentional shifts during single-digit arithmetic. *Annals of the New York Academy of Sciences*, 1477(1), 79-90. Doi : 0.1111/nyas.14464.

Zago, L., Petit, L., Turbelin, M. R., Andersson, F., Vigneau, M., & Tzourio-Mazoyer, N. (2008). How verbal and spatial manipulation networks contribute to calculation: An fMRI study. *Neuropsychologia*, *46*(9), 2403–2414. https://doi.org/10.1016/j.neuropsychologia.2008.03.001

Figures

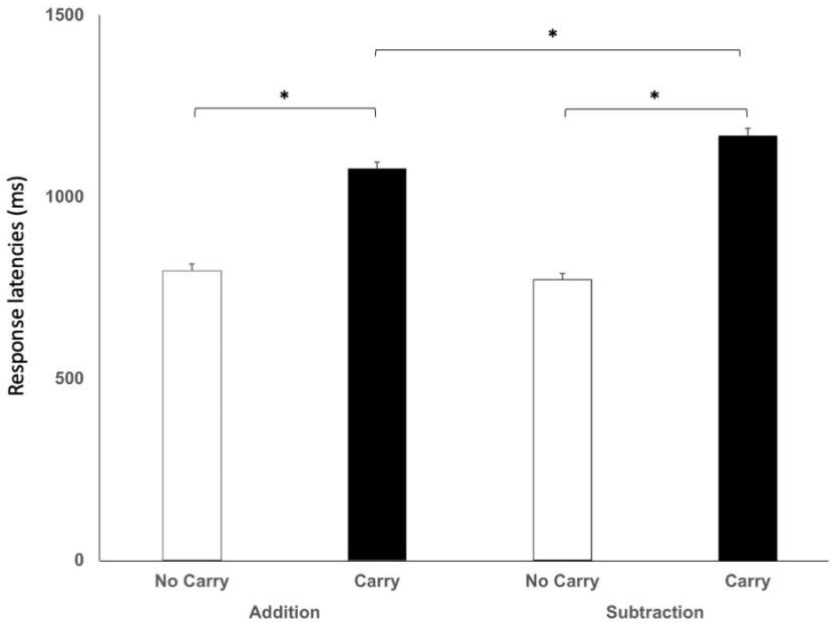


Figure 1. Response latencies as a function of arithmetic operation and carrying procedure. Asterisks indicate a significant difference between conditions after correction for multiple comparisons ($p<.001$). Error bars represent standard errors corrected for within-subject designs (Cousineau, 2005; Morey, 2008; O'Brien & Cousineau, 2014)

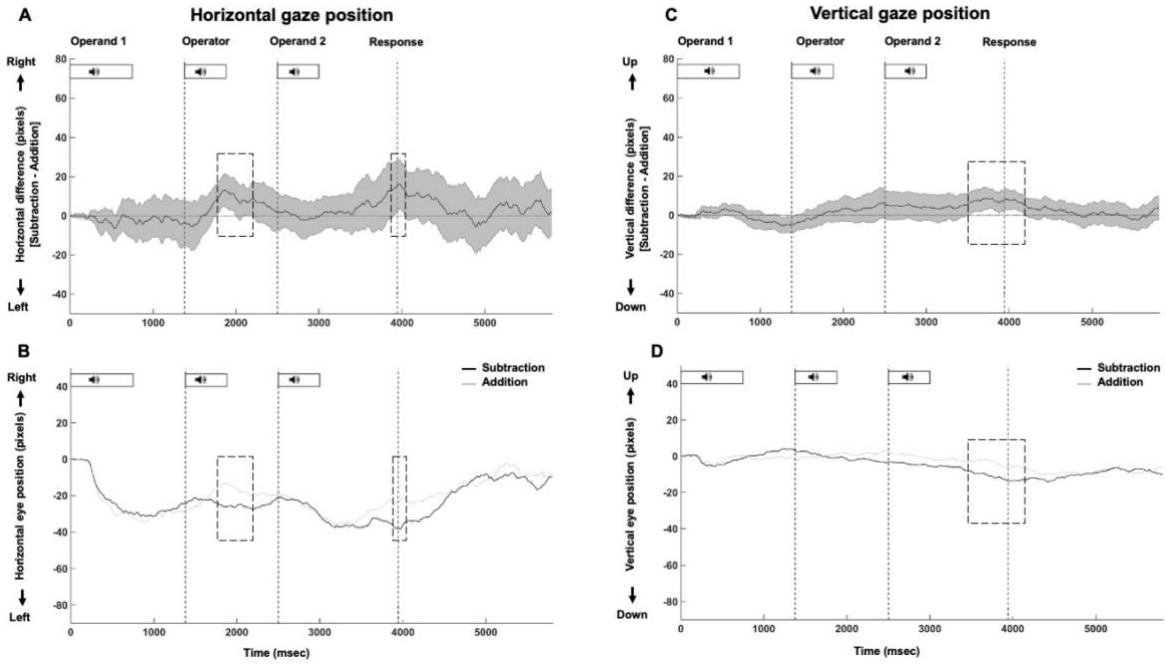


Figure 2. Effect of arithmetic operation on horizontal and vertical eye position in pixels. The first row represents the difference in horizontal (A) or vertical (C) position between subtraction and addition, with 0 corresponding to a null difference. The second row represents the horizontal (B) and vertical (D) position, for each operation, with 0 corresponding to the center of the screen. Positive values indicate a rightward or upward deviation of the gaze. The dotted rectangles represent the time window where a significant difference was observed between addition and subtraction. The grey shading indicates the 95% confidence interval.

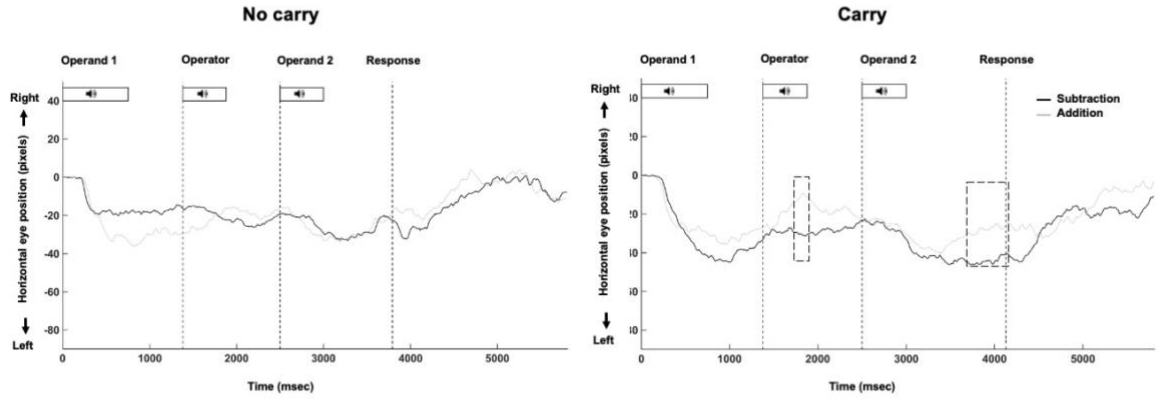


Figure 3. Horizontal eye drift for no-carry (left) and carry (right) problems. The graphs represent the horizontal eye position for each operation, with 0 corresponding to the centre of the screen. The dotted rectangles represent the time window where a significant difference was observed between addition and subtraction.



Figure 4. Horizontal eye drift for problems where it was possible to infer the arithmetic operation from the value of the first operand due to systematic associations in the stimulus set (i.e., addition problems with a first operand between 11 an 19 vs. subtraction problems with a first operand between 71 and 79). The grey arrow indicates that the rightward deviation observed in addition trials, relative to subtraction trials, occurred earlier in this subset of problems than in other problems, confirming the predictive role of eye movements.