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RESEARCH ARTICLE

Eye movements reveal that young school children shift attention when solving additions and subtractions

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Abstract: Adults shift their attention to the right or to the left along a spatial continuum when solving additions and subtractions, respectively. Studies suggest that these shifts not only support the exact computation of the results but also anticipatively narrow down the range of plausible answers when processing the operands. However, little is known on when and how these attentional shifts arise in childhood during the acquisition of arithmetic. Here, an eye-tracker with high spatio-temporal resolution was used to measure spontaneous eye movements, used as a proxy for attentional shifts, while children of 2nd (8 y-o; $N = 50$) and 4th (10 y-o; $N = 48$) Grade solved simple additions (e.g., 4+3) and subtractions (e.g., 3-2). Gaze patterns revealed horizontal and vertical attentional shifts in both groups. Critically, horizontal eye movements were observed in 4th Graders as soon as the first operand and the operator were presented and thus before the beginning of the exact computation. In 2nd Graders, attentional shifts were only observed after the presentation of the second operand just before the response was made. This demonstrates that spatial attention is recruited when children solve arithmetic problems, even in the early stages of learning mathematics. The time course of these attentional shifts suggests that with practice in arithmetic children start to use spatial attention to anticipatively guide the search for the answer and facilitate the implementation of solving procedures.

KEYWORDS
cognitive strategies, development, eye-tracker, mental arithmetic, space-number associations, spatial attention

Research Highlights

- Additions and subtractions are associated to right and left attentional shifts in adults, but it is unknown when these mechanisms arise in childhood.
- Children of 8–10 years old solved single-digit additions and subtractions while looking at a blank screen.
- Eye movements showed that children of 8 years old already show spatial biases possibly to represent the response when knowing both operands.

- Children of 10 years old shift attention before knowing the second operand to anticipatively guide the search for plausible answers.

1 | INTRODUCTION

Mathematics, including mental arithmetic, is difficult to acquire for children and often remains a challenge for adults. The cognitive mechanisms responsible of mathematical abilities are still a matter of debate despite being the object of intensive research. It was suggested that humans rely on space to cope with this highly demanding cognitive task. Indeed, numerous studies showed spatial-numerical associations (hereafter SNAs) indicating that numerical magnitude is represented spatially from left to right in an ascending order (for recent reviews see Hawes & Ansari, 2020 or Toomarian & Hubbard, 2018). The hallmark of SNAs is the SNARC effect (Spatial-Numerical Association of Response Codes; Dehaene et al., 1993): in binary classification tasks (i.e., parity or magnitude judgement), Western participants respond faster to small magnitude numbers with their left hand, and to large magnitude numbers with their right hand. Aside to the SNARC effect, other studies demonstrated that small and large numbers elicit spatial attentional shifts to the left or the right, respectively (e.g., Salvaggio, Andres et al., 2022; Stoianov et al., 2008). It was also reported that processing small numbers spontaneously deviates the gaze to the left while large numbers deviate the gaze to the right (Bulf et al., 2016; Loetscher et al., 2010; Myachykov et al., 2015; Salvaggio et al., 2019). As such, gaze position is now considered as a reliable and sensitive measure to reveal online mental representations and processing of numerical magnitude, illustrating the old proverb referring to the eye as a window to the mind.

Interestingly, various behavioral experimental paradigms recently revealed that arithmetic processing in adults elicits SNAs with subtractions being associated to the left and additions to the right (e.g., Glaser & Knops, 2020; Knops et al., 2009; Marghetis et al., 2014; Masson & Pesenti, 2016; 2023; Pinhas & Fischer, 2008). For instance, the detection of leftward or rightward targets was accelerated during subtractions and additions, respectively, suggesting that attention is shifted from the first operand toward the position of the response while searching for the answer (Liu et al., 2017; Masson & Pesenti, 2014). It was also shown that for single-digit arithmetic problems, presenting the second operand (hereafter O2) on the right or left accelerated response times for additions and for subtractions, respectively (Mathieu et al., 2016). The interpretation of that effect was that the lateralized O2 attracted the attention into one hemifield and that this bottom-up shift of attention, when made in the congruent direction, facilitates the solving procedure by accelerating the exact computation of the problem that is akin to a rapid and internal shift along a mental number line. Neuropsychological studies further revealed that the acquired inability to orient attention to the left (i.e., left neglect) is associated with impairment for solving multi-digit subtractions (Dormal et al., 2014) while the inability to orient attention to the right (i.e., right neglect) is associated to impairment for solving multi-digit additions (Masson, Pesenti, Coyette et al., 2018). Classical models proposed that calculation of additions and subtractions involves mental manipulation of number magnitude representations that were conceived as abstract (McCloskey et al., 1985) or analogical (Dehaene, 1992), taking the form of a spatial continuum where numbers are aligned in ascending order (Hubbard et al., 2005). However, in these models, no distinction was made between the procedures and representations underlying the solving of addition versus subtraction problems. Arithmetic impairments being associated with specific neglect orientations, this suggests that addition and subtraction rely on distinct components to shift attention. In other words, the double dissociation between additions and subtractions and SNA direction results from distinct mechanisms which underlie leftward and rightward attention shifts along a (similar) spatial-numerical continuum. Accordingly, manipulating the locus of attention while participants are calculating showed that orienting attention in the incongruent direction impairs arithmetic problem-solving in healthy adults (Masson et al., 2017; Masson & Pesenti, 2023; Wiemers et al., 2014). While these neuropsychological and interfering studies support a functional role of spatial attention for multi-digit arithmetic, this remains debated for single-digit problems. Indeed, retrieval accounts suggest that adults solve small single-digit additions by directly retrieving their answers from long-term memory (e.g., Ashcraft, 1992; Campbell & Xue, 2001). This has recently been challenged by behavioral studies suggesting that adults solve small additions through automated counting procedures, akin to movements along a mental continuum, that are so fast that they are unconscious and mistaken for retrieval (e.g., Mathieu et al., 2016; Uittenhove et al., 2016).

Several studies also reported spatial biases in the vertical plane, with additions and subtractions being associated to upward or downward spatial biases respectively (Blini et al., 2019; Wiemers et al., 2014). It is, however, still under debate whether SNAs in different planes attest an active adaptation to the task demands (Bächtold et al., 1998), distinct mental representations (Aleotti et al., 2020), or distinct roles in the solving procedure (Salvaggio, Masson et al., 2022). To fully understand how space is used to solve mental arithmetic, it will consequently be necessary to investigate SNAs in the horizontal and vertical planes simultaneously.

Beyond the orientation of the spatial biases, it is crucial to decipher the exact role attention plays when solving arithmetic problems. Most theoretical propositions suggest that the attentional shifts reflect the computing procedures when participants are searching for the answer by combining the two known operands (e.g., Knops et al., 2009; Mathieu et al., 2016; McCrink et al., 2007). In this view, attentional shifts can only occur within the period between the moment when participants know all the elements of the problem (i.e., both operands and the operator) and the onset of their answer. However, recent empirical data are not fully compatible with this view as it was shown that attention is also deployed earlier, when participants are only aware of the first operand and the operator (i.e., before knowing the number to add or subtract; Hartmann et al., 2015; Liu et al., 2017; Salvaggio, Masson et al., 2022). This implies that attentional shifts, depending on when they occur, reflect distinct functional mechanisms: the early shift serves at converting the arithmetic problem into a spatial frame to reduce the cognitive load of the problem by representing the plausible answers on the right or left from the first operand (Salvaggio, Masson et al., 2022). The first anticipatory shift would thus prepare for an efficient processing and use of the second operand which triggers a second shift during the exact computation occurring before the production of the answer (Liu et al., 2017; Salvaggio, Masson et al., 2022).

Critically, the origin and the developmental trajectory of these SNAs in arithmetic remain unknown and poorly investigated because it is assumed that they follow the same developmental trajectory than SNAs for processing single numerical magnitudes. Indeed, SNAs for a single numerical magnitude (e.g., SNARC-effect) are first biologically oriented from left-to-right as revealed by studies on non-human species and preliterate children (e.g., Bulf et al., 2016; Rugani & de Hevia, 2017; Rugani et al., 2015). Progressively, through the observation of the cultural directional habits of the caregivers and by the acquisition of reading, the orientation of the SNARC effect follows the orientation of cultural reading habits (e.g., McCrink & Opfer, 2014; Patro et al., 2016; Shaki et al., 2009). However, unlike SNAs in single numbers, SNAs in arithmetic were recently shown to be independent from the orientation of reading and writing direction as monolingual adults of opposite reading directions (i.e., Arabic and French-speaking participants) showed an identical rightward spatial bias for additions and leftward bias for subtractions (Masson et al., 2020). These different underlying roots for single numbers and arithmetic SNAs are in line with recent theoretical proposals suggesting that SNAs, despite their behavioral resemblance, could tap into distinct and independent cognitive mechanisms (Cipora et al., 2018). It is thus essential to define (1) at what age SNAs for arithmetic can first be observed and (2) how space is used for mental arithmetic at different developmental stages.

Surprisingly, up-to-date SNAs in arithmetic were almost exclusively investigated in adults. It is thus not known when these biases appear during development and whether they are useful in the acquisition of mathematical skills. Currently, the only developmental study that directly tested SNAs in arithmetic suggests that children do not exhibit spatial biases for additions and subtractions until Grade 4. The authors used a paradigm developed by Mathieu et al. (2016), consisting in a task in which children had to solve simple arithmetical problems with the second operand presented to the right or to the left 300 ms after the presentation of the operator (Díaz-Barriga Yáñez et al., 2020). In their first experiment, the authors showed that presenting the second operand on the left facilitated subtraction solving in 5th Graders but not in 3rd and 4th Graders. A second experiment revealed that 4th and 5th Graders responded faster for additions when the second operand was displayed on the right. However, this effect for additions was totally absent in Experiment 1 in a sample of similar age, questioning the sensitivity and reliability of this behavioral method to detect subtle and time-sensitive effects (see Campbell et al., 2021). Behavioral paradigms in which attention shifts are temporally bound to the apparition of a visual stimuli that participants need to process might miss the period during which the attentional shift is made. Díaz-Barriga Yáñez et al. (2020) used a task developed for adult participants showing that spatial biases peak at 300 ms after the presentation of the operator. The authors assumed that the timing of the deployment of attention in adults and children would be equivalent and did not consider that adults might shift their attention earlier or later than children. If so, attentional shifts would consequently remain undetected in children with the original paradigm and might already exist before the 3rd Grade. Such putative shifts could, however, be detected with an eye-tracker as it allows following the attentional locus all along a trial without temporal constraint (Hartmann et al., 2015; Masson et al., 2018; Salvaggio, Masson et al., 2022).

Our study aims to highlight attentional biases elicited by mental arithmetic in children. We will describe gaze movements as a proxy of spatial attention during an arithmetic task in 4th (Experiment 1) and 2nd graders (Experiment 2) to uncover at what age attentional biases emerge and what cognitive mechanisms they support. Using an eye-tracker with a high temporal resolution will allow a detailed assessment of both the spatial and temporal dynamics of attentional shifts. Since adults display attentional effects in both orientations (Blini et al., 2019; Hartmann et al., 2015; Salvaggio, Masson et al., 2022; Wiemers, et al., 2014), we will thus investigate both horizontal and vertical shifts. Moreover, we will also test whether children of 2nd and 4th Grade display the two types of attentional shifts previously observed in adults during the problem presentation and the exact computation phases, respectively.

2 | EXPERIMENT 1: 4th GRADERS

2.1 | Methods

2.1.1 | Participants

The only previous study investigating spatial-attentional shifts in arithmetic among primary school children revealed an effect size of $d = 0.51$ (Díaz-Barriga Yáñez et al., 2020). We calculated that a sample size of 44 participants achieves a 95% power to detect an effect of that size with $\alpha = 0.05$. In order to anticipate data loss due to technical issues with the eye-tracker and exclusion of participants because of low accuracy, we tested 55 participants (mean age 10 ± 0.8 years old; 24 females, 31 males; 45 right-handed). Due to ethical rules and data protection rules, the race of participants and their socio-economic status could not be collected in this study. Children were recruited from 4th grade classes within two schools, one in the French part of Belgium ($n = 29$), and another one in Luxemburg ($n = 26$). Written informed consent was obtained from the children and their parents. Seven participants were removed from the sample because we had to remove more than 40% of their trials from the analysis (see Data Analysis below). After exclusion, the sample was constituted by 48 children. All participants had normal vision. No participant was diagnosed with mathematical learning difficulties. The procedures were in accordance with the ethical standards established by the Declaration of Helsinki, and the experiment was approved by the local ethical Committees.

2.1.2 | Apparatus

Stimulus presentation and data collection were monitored on an Asus Display Laptop PC using Opensesame (Mathôt et al., 2012). All the stimuli were presented on a 19-inch monitor (LCD; 1280 × 1024 resolution; refresh rate 60 Hz). The participant was positioned at a viewing distance of approximately 57 cm from the centre of the screen at eye level. The participant wore Logitech USB headphones equipped with a microphone. A portable Eyelink 1000+ desktop-mounted camera was used with a head-free mode to track eye movements (SR Research, Mississauga, Canada; sampling rate: 500 Hz; average accuracy range: 0.25° angle to 0.5° angle; gaze tracking range of 32° angle horizontally and 25° angle vertically). Prior to each experimental block, the eye-tracker was calibrated to the screen using a built-in 9-point protocol.

2.1.3 | Stimulus material

The auditory stimuli consisted of number words for single digit numbers and operators (plus and minus) presented in French or German, depending on the school. The number words were recorded in a stereo audio file whose duration was adjusted to 500 ms. Arithmetic problems were the same as Experiment 1 of Díaz-Barriga Yáñez et al. (2020). They were made of nonidentical pairs of numbers so that there were 20 different additions and 20 different subtractions. Ten small problems per operation were built with numbers ranging from 1 to 5 and ten large problems per operation with numbers ranging from 5 to 9. For both additions and subtractions, the first operand (O1) was always the larger number so that the result of subtractions was always a positive number, and that it could not be possible for the participants to predict the sign of the operation when hearing the O1. Of note, the list of problems comprised only single-digit operands. German and French number words systems are equivalent for this range of problems.

2.1.4 | Task and Procedure

Children were tested individually in a quiet room within their school. Participants were asked to respond orally as fast and as accurately as possible to arithmetic problems presented auditorily. Each trial was preceded by a 1-point eye-tracker recalibration, used for drift correction, consisting in a central dot on a black background that the participant was asked to fixate. Then, a small picture of a rabbit head (0.5° x 0.5°) was displayed on the screen until the end of the trial at a position that was updated every 2 ms with a gaze contingency procedure so that the position of the rabbit head fitted with the position of participants' gaze. Children were asked to make sure that the rabbit head remained on the screen. This allowed the experimenter to verify online that the children were looking at the screen during the whole experiment and ensured that gaze was recorded properly. As soon as the rabbit was displayed, the presentation of the problem started. A trial lasted 8600 ms and started at the onset of O1. Each element of the problem was presented auditorily (500 ms each) spaced by pauses of 1000 ms. Operator and O2 were thus presented 1500 and 3000 ms after O1 onset, respectively. Problem presentation ended 3500 ms after the onset of O1 and there was an additional 5100 ms period during which children could provide their answer to the problem. Between each trial, a warning signal (i.e., "Warning! Next problem is coming," in German or French) was displayed for 1000 ms in the center of the screen so the child could prepare for the next problem. Gaze position was recorded during the whole trial, from the onset of the O1 to the onset of the next warning signal. Response latencies were measured with a voice key from the onset of the O1; a microphone was used to record the participant's answers to the problem; answers were also written down by the experimenter and accuracy was determined offline. The session lasted about 50 min and comprised one training block of six trials and six experimental blocks of 20 trials.

2.1.5 | Data analysis

Erroneous trials or trials without answer were excluded from further analyses (6.9% of dataset). The spatial and temporal parameters of the eye movements and the pupil diameter were extracted using Eyelink® Data Viewer (SR Research Ltd., Mississauga, Ontario, Canada). Missing data resulting from eye blinks were linearly interpolated if they were shorter than 500 ms. Moreover, if signal losses cumulated beyond the limit of 2000 ms within a single trial, we removed the trial from the dataset. In the remaining data (86.56%), the vertical and horizontal coordinates of eye position were aggregated in bins of 10 ms over a period of 8900 ms running from the onset of the first operand. The trimming procedures led us to remove seven participants from the sample because less than 60% of the recording were suited for further analysis. The final sample consisted of 48 participants. Separate analyses were made on Small and Large problems for vertical and horizontal coordinates. 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 ($p < 0.05$) 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 a similar procedure, see Maris & Oostenveld, 2007; Sahan et al., 2022; Salvaggio et al., 2019; Salvaggio et al., 2022). Significant clusters were isolated using the same criteria as those described for the analysis of the non-permuted data. Following a conservative criterion, the largest detected cluster was selected, and all its t-values were summed. The same procedure was repeated 1000 times and the sum of t-values obtained after each permutation was stored. The decision was taken by comparing the sum of the t-values obtained for each cluster revealed by the analysis of the non-permuted data to the distribution of the sums of the t-values derived from the random permutations. The probability of observing a significant difference between conditions in a cluster was inferred from the position of the sum in the normal distribution created by random permutations. The p-value was equal to 1 minus the percentile of this position. The test was significant if the p-value was inferior to $\alpha = 0.05$. The eye-tracking analyses were made with MATLAB 2018a (MathWorks Inc., 2018).

2.2 | Results

At the behavioral level, participants responded to the problems on average 5763 ± 61 ms after O1 onset (Large: 6068 ± 77 ms; Small: 5529 ± 60 ms) with a mean error rate of 6.9 ± 1% (Large: 10.4 ± 1.6%; Small: 3.2 ± 0.7%). Belgian and Luxemburgish participants did not differ neither for response latencies nor for accuracy ($ps > 0.2$). We computed an attentional bias score (Gaze Position Addition—Gaze Position Subtraction) in the horizontal and vertical axis for every bin for each participant and compared this score between Belgian and Luxemburgish participants. As no differences were observed between the two sub-samples, we pooled Belgian and Luxemburgish participants together for the subsequent analysis.

In every condition, we first observed a rightward and downward drift of the gaze that was modulated by the operation (Addition vs. Subtraction) and the size of the problem (Small vs. Large). For the Small problems, the statistical comparison of horizontal eye position revealed a rightward deviation in addition trials relative to subtraction trials (Figure 1a), on six different time periods. The two first occurred from 1770 to 1830 ms ($p = 0.023$, Cohen's d = 0.3, maximal difference = 5 pixels or 0.2° visual angle), and from 2680 to 2850 ms ($p < 0.001$, $d = 0.289$, maximal difference = 10 pixels or 0.3° visual angle), a time period located after the operator onset. There was also a significant cluster from 5430 to 6030 ms ($p < 0.001$, $d = 0.25$, maximal difference = 14 pixels or 0.4° visual angle) which is situated around the mean response time. The three last clusters were observed from 6780 to 7000 ms ($p < 0.001$; $d = 0.139$, maximal difference = 14 pixels or 0.4° visual angle), from 7110 to 7240 ms ($p < 0.001$, $d = 0.26$, maximal difference = 14 pixels or 0.4° visual angle) and from 7590 to 8050 ms ($p < 0.001$, $d = 0.477$, maximal difference = 18 pixels or 0.52° visual angle) and thus after the response was given.

For the vertical position in Small problems (Figure 1c), we observed a single significant cluster lasting from 5240 to 5300 ms (i.e., before the mean response onset). During this period, the gaze position was shifted higher for additions than for subtractions ($p = 0.039$, $d = 0.303$, maximal difference = 8 pixels or 0.2° visual angle).

For the Large problems (Figure 1b), the analysis of horizontal gaze position showed a late significant cluster situated from 8290 to 8380 ms (i.e., after participants gave their response) indicating that the gaze was oriented more rightwards for additions than for subtractions ($p < 0.001$, $d = 0.33$, maximal difference = 8 pixels or 0.2° visual angle).

Finally, the vertical gaze position revealed that for Large problems (Figure 1d) participants shifted their gaze more upwards for additions than for subtractions between 4220 and 4540 ms, a period situated after the onset of the O2 and before the onset of the answer ($p < 0.001$, $d = 0.33$, maximal difference = 8 pixels or 0.2° visual angle).

2.3 | Discussion of experiment 1

Our results for the horizontal orientation show that there is a general rightward drift whatever the operation and size of problem. This rightward deviation is reminiscent of the 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 (e.g., Foulsham et al., 2013). Interestingly, this rightward deviation was more pronounced for additions in comparison to subtractions attesting the presence of spontaneous horizontal SNAs in mental arithmetic at different periods of problem presentation and resolution. 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. Anchoring attention to the left side at the beginning of each trial may have masked leftward shifts in subtraction trials so that the results are best described as a rightward movement in addition relative to subtraction problems. Children might also have adopted a strategy consisting in imagining a written problem that would be scanned during the presentation of the problem. However, as subtractions elicited less rightward drift than additions even during the presentation of the problems, it suggests that if this visualization strategy really occurred, gaze patterns were additionally driven by attentional mechanisms taking place along a mental continuum of numbers.

The horizontal gaze biases differing between additions and subtractions converge with and significantly extend the only previous study that investigated SNAs when primary school children solve arithmetic problems (Díaz-Barriga Yáñez et al., 2020). For Small problems, the temporal course of these shifts is strikingly identical to the pattern observed in adults (Liu et al., 2017; Salvaggio et al., 2022), with a first shift occurring anticipatively after the presentation of the first operand and the operator, and another shift before the onset of the answer, suggesting that this double step strategy is already mature in 4th Graders. Although we also observed horizontal shifts for Large problems, these shifts only occurred after the response was made, possibly reflecting semantic associations between the operation and space (Andres et al., 2020; Pinhas & Fischer, 2008; Pinhas et al., 2014). Our results are in line with the idea that there are distinct procedures that are recruited for Small and Large problems as previously suggested by chronometric experiments in adults (Barrouillet & Thevenot, 2013; Uittenhove et al., 2016) and children (Bagnoud et al., 2021). In these studies, response times for single-digit problems with operands

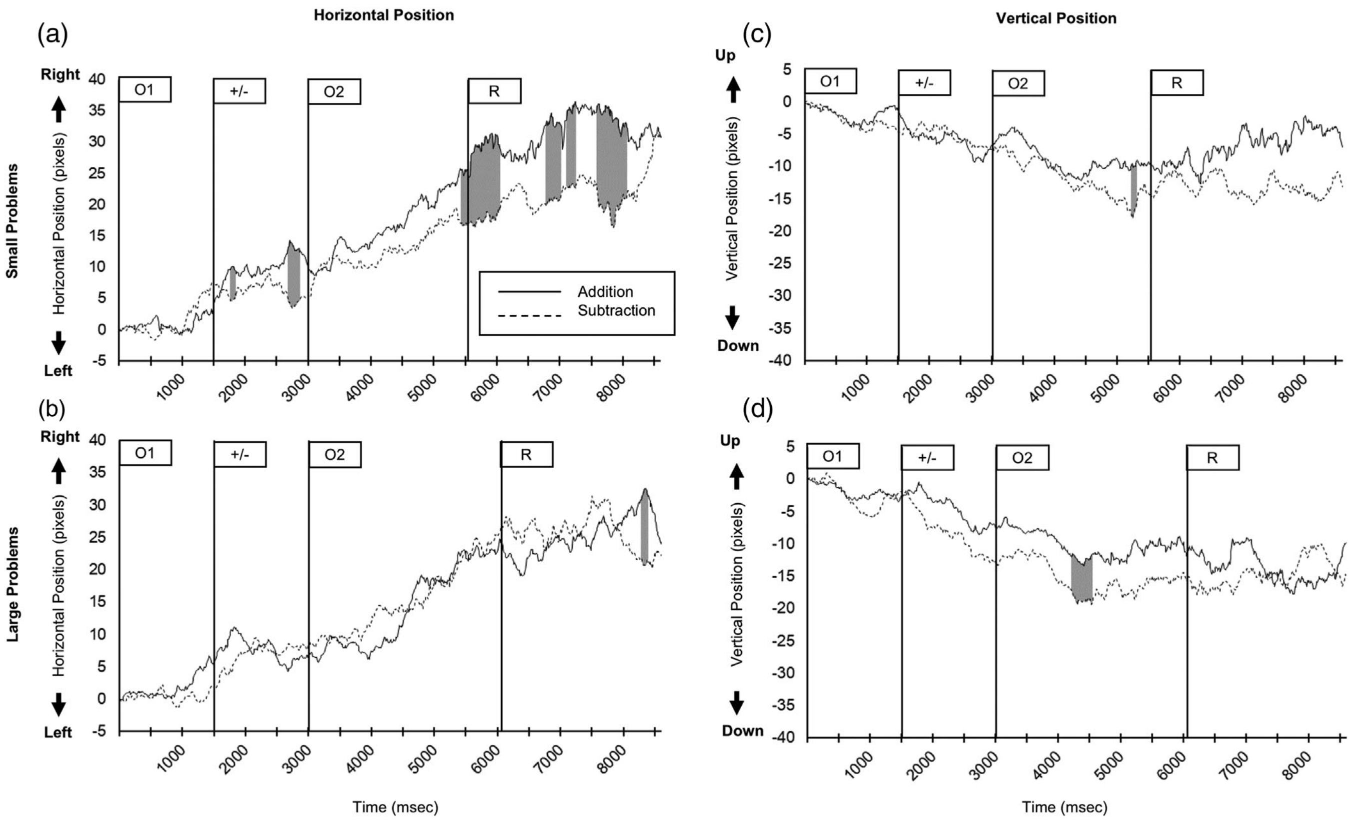

FIGURE 1 Eye position in pixels as a function of time for each operation for children of Grade 4 (Experiment 1). On each graph, vertical lines indicate the onset of the Operand 1 (O1), Operator (+/-), Operand 2 (O2) and the Mean Response Time (R). The upper graphs represent the eye position for Small problems in the (a) horizontal and (c) vertical axis. The lower graphs represent the eye position for Large problems in the (b) horizontal and (d) vertical axis. Positive values indicate the rightward or upward side of the screen and 0 corresponds to the centre. The gray areas indicate the clusters in which a significant difference between additions and subtractions was detected.

below 4 revealed a linear increase of response times as a function of the operands (i.e., size effect) that was interpreted as the signature for a rapid counting akin to a mental scanning of a portion of a spatial continuum (Mathieu et al., 2016). A counting procedure of up to four units along a spatial continuum was thought to be achieved rapidly in a single attentional shift and could outrun a retrieval procedure (Uittenhove et al., 2016). For Large problems, no such linear response time increase was observed and the authors suggested that a retrieval procedure would be faster than a counting strategy with more steps. Such a rapid counting procedure is compatible with the spatial bias observed between the offset of O2 and the response onset in Small problems. It was also suggested that this counting procedure can be pre-activated by the presentation of the operator (e.g., Fayol & Thevenot, 2012; Poletti et al., 2023) potentially explaining the early shifts. Such a preparation would not occur for Large problems solved by retrieval. Children might have anticipated the use of retrieval with the presentation of a Large O1 because both operands were either Small or Large in the present experiment design (see also Salvaggio et al., 2022 for a discussion about the impact of predictability on the recruitment of spatial attention for arithmetic solving). Future studies in children should manipulate the combination of large and small operands to explore whether the recruitment of a counting procedure and spatial attention is modulated by the predictability of O2 in children.

Additionally, we observed for the first time upward vertical attentional biases in arithmetic in children, with the gaze being shifted more upward for additions than for subtractions. These shifts occurred between the presentation of the second operand and the response time suggesting that they might help for the exact computation of the answer, possibly through small incrementation on the portion of the numerical continuum where the answer was previously located in similar problems (Salvaggio et al., 2022). Several accounts suggested that vertical SNAs are more robust because they are grounded into universal sensorimotor experiences (Blini et al., 2019; Fischer & Brugger, 2011; Wiemers et al., 2014). Indeed, the numerical quantity of sets of objects correlates with their height. In the context of proto-arithmetic operations, children experience since young age that adding objects results into increasing the height of the set while withdrawing objects from the set would result into diminishing it. To find out whether children of younger age and with less expertise in arithmetic already exhibit horizontal and/or vertical spatial attentional shifts for additions and subtractions, we used a similar procedure focussing on Small problems with participants of 2nd Grade.

3 | EXPERIMENT 2: 2nd GRADERS

3.1 | Methods

We tested 61 children (mean age 8 ± 0.8 years old; 35 females, 26 males; 42 right-handed) that were recruited from 2nd Grade classes within the two same schools as in Experiment 1 (Belgium: $n = 30$; Luxemburg: $n = 31$). Written informed consent was obtained from the children and their parents. We excluded 11 participants (final sample $n = 50$) because more than 40% of their trials were not suited for data analysis after applying the same processing than in Experiment 1. All participants had normal vision and none was diagnosed with mathematical learning difficulties. We used the same Small problems as in Experiment 1. We chose not to present Large problems because, in their study, Díaz-Barriga Yáñez et al. (2020) reported that children of 3rd to 5th Grade had so poor accuracy for Large problems that it prevented them from analysing these trials. As our sample was composed of even younger participants than theirs, we chose not to present Large problems to 2nd Graders. Therefore, we presented Small problem trials twice to match the number of trials used in Experiment 1.

3.2 | Results

At the behavioral level, participants responded on average about 5662 ms ± 60 ms after the onset of the trial (and thus 2662 ms after O2 onset) and had a mean error rate of 6.8 ± 7.1%. Belgian and Luxemburgish participants did not differ either for response latencies or accuracy ($p > 0.111$). We computed an attentional bias score (Gaze Addition—Gaze Subtraction) for the horizontal and vertical axes at every bin for every participant. No differences were observed in this score between Belgian and Luxemburgish participants which were thus pooled together for the analysis of gaze patterns.

For the horizontal axis, there were two significant clusters in which eye position was more on the right for additions than for subtraction (Figure 2a). The first cluster lasted from 5390 to 5520 ms after trial onset ($p < 0.001$; maximal difference = 13 pixels or 039° visual angle) which is situated just before the mean response time. The second cluster occurred after the mean response time and lasted from 7010 to 7220 ms ($p < 0.001$; maximal difference = 16 pixels or 0.48° visual angle). For the vertical axis (Figure 2b), eye position was higher for additions than for subtractions after the response was made during a period of time lasting from 6520 to 6270 ms ($p < 0.001$; maximal difference = 13 pixels or 0.37° visual angle).

As an exploratory analysis suggested by an anonymous reviewer, we conducted direct comparisons between the gaze position observed in Experiment 1 and Experiment 2 for Small problems in the horizontal and vertical orientations. We computed an attentional bias score (Gaze Position Addition—Gaze Position Subtraction) for each participant of both experiments within the time periods in which we observed a significant cluster in Experiment 1 (i.e., in 4th graders). There was a marginal difference between the two groups in the horizontal orientation for the period lasting between 1770 to 1810 ms indicating that 4th Graders had a larger bias score than 2nd Graders ($p = 0.088$; maximal difference = 5 pixels or 0.14° visual angle).

4 | GENERAL DISCUSSION

There is now considerable evidence that arithmetic problem-solving in adults involves shifting attention in space (e.g., Hartmann et al., 2015; Liu et al., 2017; Masson et al., 2017; Mathieu et al., 2016). In particular, eye-tracking studies revealed that attention is shifted at two distinct moments revealing two complementary mechanisms: (1) an early shift occurs as soon as the first operand and the operator are known to narrow down the range of plausible answers and (2) another shift occurs before the answer accompanying the exact computation of the result or the processing of the answer. It was suggested that adults use space as a support to alleviate the cognitive charge when solving mental arithmetic. As the acquisition of arithmetical skills is long and effortful it could be expected that throughout education children would rely on spatial attentional mechanisms to help them to cope with such a complex task. At odds with this idea, it was recently suggested that space would only be recruited by children after they mastered arithmetic, by 4th or 5th Grade (Díaz-Barriga Yáñez et al., 2020; Mathieu et al., 2018). To our knowledge, the only study that behaviorally tested the existence of spatial attentional shifts in mental arithmetic among children supports this latter claim as it could not evidence any attentional shifts for additions and subtractions before Grade 4 (i.e., Díaz-Barriga Yáñez et al., 2020). Up to now, it was thought that relying on space to solve arithmetic problems requires a certain level of brain maturation or automatization of the repeated use of counting, both arising only in older school children (4th grade and higher) (Mathieu et al., 2018).

Our study challenges this claim. Indeed, we were able to reveal that children, as early as in 2nd Grade, spontaneously deploy attention in the horizontal and vertical planes when solving simple additions and subtractions. When using an eye-tracker, which allows to track attention with high spatial and temporal resolution, we indeed observed that children of 2nd and 4th Grade already shift their gaze more rightward and upward when solving additions than when solving subtractions. Since we observed spatial attentional biases in our youngest group of children, this study does not allow determining at what age or stage of education spatial attentional shifts in arithmetic appear, but it clearly undermines the idea that the use of spatial attentional mechanisms is recruited only after an extensive practice of arithmetic acquired after years of education. In order to refine the moment in which space is starting to play a role for mental arithmetic, the investigation of these effects in even younger children who are beginning to learn the very basics of arithmetic will be needed. As such, follow-up studies should investigate children in 1st Grade with simple arithmetic problems or even in kindergarten with an adapted material (e.g., non-symbolic notation; verification task; …).

A recent study showed that spatial biases in arithmetic were similarly oriented from left to right in participants with opposite reading habits (i.e., Arabic vs. French-speakers; Masson et al., 2020), which suggests that SNAs in arithmetic are not rooted into the same factors

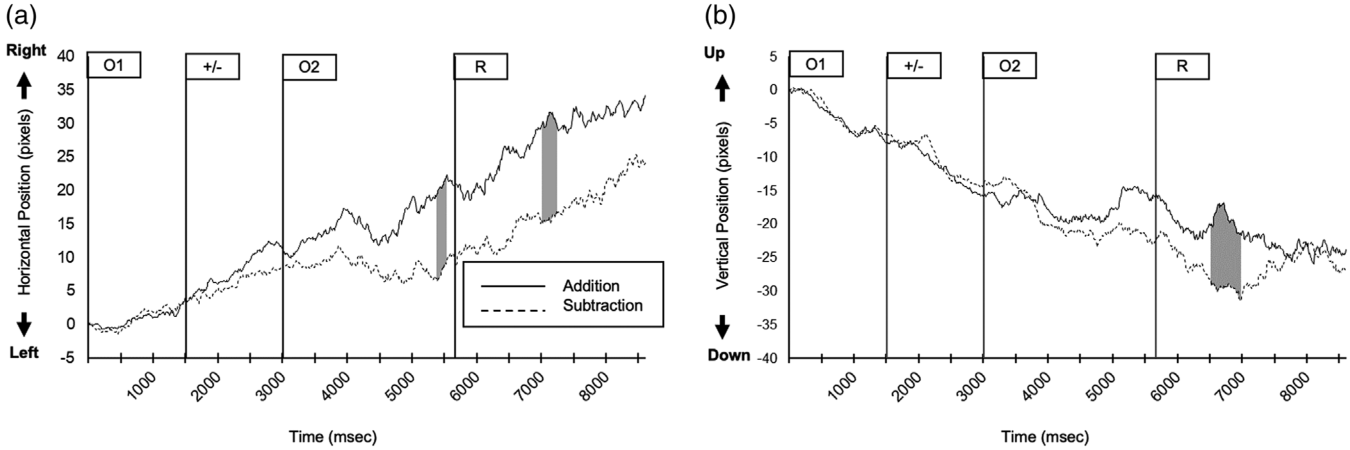

FIGURE 2 Eye position in pixels on the (a) horizontal and (b) vertical axis as a function of time for each operation for children of Grade 2 (Experiment 2). On each graph, vertical lines indicate the onset of the Operand 1 (O1), Operator (+/-), Operand 2 (O2) and the Mean Response Time (R). Positive values indicate the rightward or upward side of the screen and 0 corresponds to the centre. The gray areas indicate the clusters in which a significant difference between additions and subtractions was detected.

than the SNARC. If reading direction does not impact on attentional mechanisms in the context of adding and subtracting, it is however possible that other cultural factors might have shaped the SNAs in arithmetic that we observed in the present study. Interestingly, Luxemburg (MNFP, 2011) and the French part of Belgium (SeGEC, 2013) both recommend in their curricula the use of spatial layouts when apprehending cardinality since Grade 1. Future studies should compare participants from countries that do or do not explicitly refer to spatial continuums in their school curricula to test whether SNAs in arithmetic are related to such cultural educational practices. Alternatively, some recent theoretical proposals suggest that SNAs are rooted into biological factors (Rugani & de Hevia, 2017). Indeed, preverbal infants (e.g., Bulf et al., 2016; de Hevia et al., 2017; Di Giorgio et al., 2019) and animals were shown to exhibit SNAs for small and large numerosities (e.g., Giurfa et al., 2022; Rugani et al., 2015), casting doubt on the long-lasting idea that SNAs are mandatorily driven by cultural directional habits (i.e., reading direction; Shaki et al., 2009). One might suggest that they are driven by biological traits which are similar to those observed in animals. As arithmetic capacities are likely to build on innate systems shared by other species to keep track of changing quantities in their environment (e.g., Cantlon et al., 2016; Rugani et al., 2009), it would be interesting to investigate whether these proto-arithmetic capacities would elicit left-to-right spatial bias. SNAs related to the concepts of adding or withdrawing numerosities in non-human species or newborn humans would be an optimal approach to untangling the cultural or biological account of SNAs and describing their developmental and evolutionary roots.

Importantly, our results go beyond the mere observation of attentional shifts induced by arithmetic at a young age. By presenting the elements of the problems sequentially (i.e., operands and operator), and by measuring gaze movements with high temporal resolution, we were able to identify when, and more importantly, what elicited the shifts of attention. Our results show that attentional shifts in arithmetic are not caused by a unique mechanism akin to a walk along the mental number line as initially suggested by seminal studies (Knops et al., 2009; Mathieu et al., 2016; McCrink et al., 2007) or by the mere activation of different portions of a mental number line corresponding to the magnitude of each operand and the result (Pinhas & Fischer, 2008). Instead, we suggest that horizontal spatial attention shifts for arithmetic is an active strategy to reduce the cognitive load that is deployed as soon as the participants have sufficient information to narrow down the plausible answers. Indeed, we observed in 4th Graders that an attentional shift was initiated before the exact computation started, as soon as children were told the first operand and the operator. This suggests that 4th Graders, like adults (Liu et al., 2017; Salvaggio et al., 2022), can dynamically create a mental framework centred on the first operand and activate a portion of a mental space on the right for additions or on the left for subtractions in which the result should be located. In other words, the early attentional shift would reflect the process that refines the possible solution and give an approximate idea of plausible answers. We also observed a second shift that occurs before the answer is given. Even if we assume that the actual gaze movement is preceded by an internal shift of attention along a mental continuum and the preparation of an oculomotor program, this period is very close to the onset of the answer. This proximity in time makes it difficult to disentangle whether the second shift reflects the exact counting procedure (Mathieu et al., 2016) or the representation of the answer relative to the first operand, as a plausibility check procedure to avoid the production of an aberrant answer (Marghetis et al., 2014). This dynamic two-step procedure is reminiscent of the findings of a study during which adult participants had to indicate on a physical line the approximate answer of a complex arithmetic problem (Klein et al., 2014). By examining eye movements, the authors noticed a two-stage process in which participants first fixated the position of the most probable response (i.e., the average response for an operation) and then made a corrective saccade toward a position corresponding to the exact response. The active and anticipative attentional procedure that was observed in adults (Salvaggio et al., 2022) and here in 4th Graders seems to require some expertise to emerge as it was not observed in 2nd Graders. It is also possible that instead of practice or expertise, this early anticipative deployment of attention requires the maturation of certain attentional mechanisms. It was already shown that brain activations elicited by ocular saccades correlated with activations elicited by merely perceiving a plus sign in children. This correlation was observed in the posterior superior parietal lobule and in the frontal eye field in adults (Mathieu et al., 2018) and in the hippocampus in children of 7th and 8th Grade (i.e., around 12–13 years old), while no such associations were observed in younger participants (Mathieu et al., 2018). These activations in older children were interpreted as a process of progressive automatization of the ability to navigate along a spatial continuum for solving arithmetic problems. The authors suggested that the early spatial attentional effects triggered by the presentation of a plus or minus sign are not possible until the brain network responsible for linking attentional mechanisms and arithmetic is sufficiently developed. However, as we already observed early attentional shifts in younger children of 4th and 2nd Grade, it remains to be clarified whether our results and the hippocampal activations elicited by the mere presentation of an operator rely on similar mechanisms. Further investigation of the link between attentional biases, expertise, and brain correlates is necessary to fully grab the picture of how attention sustains the acquisition of mathematical skills in children.

One might suggest that the previous investigation of spatial biases in arithmetic among young children was underpowered or that the behavioral paradigm used was not appropriate to detect attentional shifts related to arithmetic. While this is indeed possible, we instead propose that Díaz-Barriga Yáñez et al. (2020) failed to report horizontal attentional biases in 3rd Graders because of the difference between 2nd and 4th Graders in the onset of attentional shifts. Their behavioral paradigm, in which the position of the second operand was manipulated, likely measures the anticipative attentional shift triggered by the operator instead of the later shift reflecting the exact computation of the result. Indeed, the shorter response latencies when the second operand appears on the right for additions and on the left for subtractions were only observed in adults (Mathieu et al., 2016), in 4th and 5th Graders (Díaz-Barriga Yáñez et al., 2020), but not in 3rd Graders. Thus, when perceiving a plus or a minus sign, participants of at least 4th Grade might have deployed their attention on the right or left, respectively, which modulated the detection speed of the lateralized second operand (i.e., acceleration if localized in the congruent hemifield; delay if localized in the incongruent hemifield) which will in turn impact on how fast they start to solve the problem and provide an oral answer. For 2nd Graders, we showed that attention is not shifted horizontally before the presentation of the second operand, and we suggest that, in light of Diaz-Barriga Yanez's results, this effect would also not be present in 3rd Graders. Thus, our study clearly shows that eye-tracking methodology outperforms classical behavioral paradigms to uncover cognitive mechanisms underlying attentional biases during arithmetic problem solving. Not only because it is more sensitive to subtle spatial effects but mostly because of its high temporal resolution that precisely informs about the temporal course of distinct and sequential mechanisms that occurred during the presentation and the solving of the problems.

It was predicted that vertical attentional shifts would be more robust in young children because they are supposed to be built on the universal sensorimotor experiences developed since birth during which children learn that "more is up" (Fischer, 2012; Winter et al., 2015). However, the only attentional shifts that were noticeable in 2nd Graders before the answer was given were horizontal instead of vertical. Vertical attentional biases occurring before the answer seem to emerge between the 2nd and 4th Grade. Along the 3rd or 4th Grade, children therefore start to exhibit the vertical biases when processing additions and subtractions in complement to the early installed horizontal bias. Our results are more compatible with the hypothesis that the relation between numerical processing and vertical space originates from the gradual use of cultural tools such as graphs, thermometers, or elevator floors (Holmes & Lourenco, 2012). Longitudinal studies should clarify how and when children start to use diverse orientations, including the sagittal plane (see Aleotti et al., 2020) to map numbers to help them at solving arithmetic problems.

We also observed very late attentional shifts that occurred long after the response was made which are difficult to interpret in terms of functional mechanisms. In most studies, such late effects are interpreted as semantic associations between space and the operation (Andres et al., 2020; Salvaggio et al., 2022). The polarity correspondence principle, for example, assigns a positive linguistic polarity to the concepts of right and addition, and a negative linguistic polarity to the concepts of left and subtraction (Andres et al., 2020; Gevers et al., 2006; Proctor & Cho, 2006). However, it is possible that these late attentional shifts would serve as a final verification to estimate if the answer that was given is plausible or not (for a similar view, see Marghetis et al., 2014). This last procedure could thus prevent children from absurd errors (e.g., answers that are larger than the first operand for subtractions). Though we only recorded the first answer given by the participants, we noticed that wrong answers were often later followed by spontaneous autocorrections, attesting that the children were still calculating after the verbal recording of the answer and that this verification procedure could have elicited these later shifts. This was particularly true for the Large problems with a higher error rate than the Small problems (likely because they involve carry operation for additions). For these difficult problems, no horizontal attentional shifts were detected, except for one period situated long after the response was made. We suggest that, as in Small problems, this late shift is caused by the verification mechanism.

It remains to be clarified whether spatial strategies are universal or if only a subset of children tend to use them and if such spatialization is functional and associated with arithmetic performance. This question is beyond the objective of this experiment and would necessitate the investigation of a very large sample of children. Moreover, this relationship between performance in arithmetic and the use of space might evolve with time which would require longitudinal studies or the investigation of large cohorts of children. One might predict that young children who are learning basic arithmetic principles could optimize their ability to solve simple additions and subtractions by relying on mental spaces. After a few years and the need to solve more complex problems, the most efficient children could abandon such spatial strategies when solving easier problems. Such a developmental trajectory using an attention orienting strategy as a scaffold during early phases of arithmetic learning could be comparable to the use of finger counting for additions observed at preceding stages. Indeed, finger counting is associated with better arithmetic performance in kindergarten but this correlation gradually inverts with time (Jordan et al., 2008). We must also acknowledge that observing attentional shifts while solving arithmetic problems does not mandatorily mean that these SNAs are functional. Indeed, the time course of the spatial biases that we observed just before the mean response times question what procedure they are reflecting and what is happening between the presentation of O2 and the production of the answer. Future interference studies should investigate this point by manipulating the locus of spatial attention and observing the impact on addition and subtraction solving. This approach was already successfully used in adults to demonstrate the functional relationship between attention and arithmetic (e.g., Blini et al., 2019; Hartmann, 2022; Masson & Pesenti, 2023; Wiemers et al., 2014) and could be extended to developmental studies.

Finally, we must acknowledge that with the present gaze pattern paradigm, we cannot discriminate the respective role of subtraction and addition in the observed differences in eye position. Indeed, it is still to be defined if both operations elicit gaze shifts in opposite directions or if the effects are driven by one or the two operations. The challenge for future eye-tracking studies resides in finding a baseline condition that does not require shifting attention while controlling for general (verbal or non-verbal) factors susceptible to cause non-specific attention shifts such as the initial rightward deflection observed here. To circumvent this issue, future studies could exploit the pupil light response to evaluate covert attentional shifts by manipulating the luminance of lateralized hemifields (e.g., Mathôt et al., 2013; Strauch et al., 2022). Leftward attentional shifts for subtraction should be associated to pupil size dilation when the left side of the screen is dark and contraction when it is bright. And the opposite should be observed for additions. The spatial bias could thus be estimated separately for additions and subtractions, withholding the need for a baseline to discriminate their respective influence. This approach has already proven to be successful to measure covert shifts of attention in a numerical comparison task (Salvaggio et al., 2022) and could thus be adopted in the context of mental arithmetic. Previous neuropsychological studies reported selective deficits for subtraction in left neglect (Dormal et al., 2014) and for additions in right neglect (Masson et al., 2017) suggest that additions and subtractions should trigger shifts of attention in opposite direction in adults, but we agree that this remains an open question in children. The limitations of gaze analysis should not undermine the usefulness of our current approach that crucially allowed to uncover the temporal course of the SNAs. The pupil light response being very slow, it would have been impossible to track the temporal deployment of attention and uncover what strategies they might reflect.

In sum, the present data obtained by tracking spontaneous gaze movements while 2nd and 4th graders were solving arithmetic problems undermine the hypothesis that attentional shifts are only used by adults or children with extensive practice of arithmetic. Eye-tracking allowed to reveal a clear pattern of horizontal and vertical attention shifts during single-digit additions and subtractions. While children of both age groups shifted their attention just before answering to the problem, only the more experienced 4th graders started to shift their attention anticipatively, before knowing the second operand, to narrow down the range of plausible answers. Future transversal and longitudinal studies will need to clarify the exact developmental stage at which each of these shifts arises and how they relate to individual differences in arithmetic.

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CONFLICT OF INTEREST STATEMENT

The authors report no conflict of interest.

DATA AVAILABILITY STATEMENT

The study and analyses presented here were not preregistered. The experimental scripts, datasets generated during and/or analysed during the current study, as well as the scripts to analyse the data are accessible on OSF following this link: https://osf.io/v8u9t/

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