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Summing up: A functional role of eye movements along the mental number line for arithmetic☆

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ABSTRACT

In Western cultures, small-left and large-right spatial-numerical associations are constantly found in various simple number processing tasks. It has recently been suggested that spatial associations are also involved in more complex number processing, for example that individuals make rightward or upward "mental" movements along the number line during addition, and leftward or downward movements during subtraction. In line with this, it has been shown that participants' spontaneous eye movements on a blank screen during upward and downward counting follow such associations. The present research investigated whether eye movements along the number line are simply an epiphenomenon of the recruitment of a spatial reference frame, or whether they play a functional role for the arithmetic computation. This question was addressed by using multi-step problems (e.g., 59 + 5 + 4 + 3) that show a larger proportion of computation (vs. retrieval) when compared to single-step problems (e.g., 59 + 5), as confirmed in Pretest 1. Moreover, the question was addressed only for addition problems and vertical eye movements, because spatial-arithmetic associations were not found in the other conditions (subtraction, horizontal eye movements) in Pretest 2. In the main experiment, participants ($n = 29$) solved addition problems while following a moving dot with their eyes (smooth pursuit) either in a congruent (upward) or incongruent (downward) direction, or while keeping their eyes fixated on to the center of the screen, or while moving their eyes freely on a blank screen. Arithmetic performance was faster in the congruent condition (upward eye movements) when compared to the other conditions (downward eye movements, central fixation, free viewing). These results suggest that vertical shifts in spatial attention along the mental number line are functionally involved in addition. The results support the view of shared mechanisms for directing spatial attention in external (visual) and representational (number space). Implications for embodied views of number processing are discussed.

Embodied cognition and conceptual metaphor theories propose that individuals recruit sensorimotor-based sources of knowledge when dealing with abstract information (e.g., Barsalou, 2008; Gallese & Lakoff, 2005; Lakoff & Johnson, 2003). A case in point are numbers, which are assumed to be cognitively represented by means of a spatial reference frame (Barsalou, 2010; Walsh, 2015). The most influential support for the pervasive number–space associations comes from the SNARC effect (spatial–numerical association of response codes), showing faster left-sided responses for small numbers and faster right-sided responses for large numbers when compared to the opposite response pairing in various simple number processing tasks (Dehaene et al., 1993; Fischer & Shaki, 2014; Wood et al., 2008). The SNARC effect has been well established for the horizontal dimension of space but recent research also shows magnitude associations along the vertical dimension (Aleotti et al., 2020; Cooney et al., 2021; Loetscher et al., 2010; Winter, Matlock, et al., 2015). For example, when participants call out numbers at random, they produce smaller numbers during downward than during upward body motion (Hartmann et al., 2012; Winter & Matlock, 2013). While horizontal spatial-numerical associations are typically interpreted as evidence of a culturally shaped mental number line that is determined by reading and writing habits (e.g., Fias & Fischer, 2005; Göbel et al., 2011; Shaki et al., 2009), vertical spatial-numerical associations possibly reflect more "grounded" sensorimotor experiences such as "more is up" (Fischer, 2012; Lakoff & Johnson, 2003), but the exact

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mechanisms behind the different spatial-numerical associations still remain debated (e.g., Guida et al., 2020; Hartmann et al., 2014, 2021; Santens & Gevers, 2008; Shaki & Fischer, 2018; van Dijck & Fias, 2011; Winter, Matlock, et al., 2015).

Yet another question of interest is whether the spatial associations found during simple number processing tasks (e.g., magnitude and parity judgment tasks) are also involved in more complex number processing, such as counting and mental arithmetic (Fischer & Shaki, 2014). An initial hint for dynamic spatial processes during arithmetic has been found for approximate addition and subtraction of non-symbolic numerosities, where the overestimation of addition, and underestimation of subtraction results (i.e., the "operational momentum effect") has been interpreted as the result of movements along the mental number line (Knops, Viarouge, et al., 2009; McCrink et al., 2007). There is also an increasing number of studies reporting spatial-arithmetic associations in exact arithmetic with symbolic numbers (see Fischer & Shaki, 2014, for a review). For example, Masson and Pesenti (2014) found that lateral visual targets were faster detected on the right side following addition, and vice versa, for targets on the left side following subtraction problem solving (see also Glaser & Knops, 2020; Liu, Cai, et al., 2017). In a similar vein, it has been shown that spontaneous eye movements on a blank screen shift rightward and upward during upward counting (Hartmann et al., 2016; Masson et al., 2018; Salvaggio et al., 2022). These results suggest that mental arithmetic interacts with spatial processing in an operation-specific way, with addition leading to a rightward, and subtraction to a leftward shift in spatial attention (Mathieu et al., 2016).

While the studies described so far focused on the effect of arithmetic operation on spatial processing, other studies investigated the reverse effect by manipulating spatial behavior and assessing its impact on arithmetic performance (Anelli et al., 2014; Blini et al., 2019; Lugli et al., 2013; Masson & Pesenti, 2016; Wiemers et al., 2014). For example, Lugli et al. (2013) found that people were faster in upward counting when they move upwards (vs. downwards) in an elevator. Such spatial-arithmetic compatibility effects are particularly interesting because they highlight the bidirectional influence between arithmetic and spatial processing, and they point to the possibility of a functional role of spatial mechanisms in arithmetic (Dormal et al., 2014; Masson et al., 2017; Masson & Pesenti, 2016; Montefinese et al., 2017).

Despite these striking findings, important questions about arithmetic-spatial associations remain unclear. Specifically, most of these results cannot be taken as direct evidence that mental addition and subtraction lead to shifts in spatial attention along the number line, and that such spatial shifts support the mental computation of numbers. Several limitations need to be considered. First, previous studies used arithmetic problems in which the operation sign was presented during computation (e.g., $5 + 3$) (e.g., Hartmann et al., 2015; Masson & Pesenti, 2014, 2016; Wiemers et al., 2014). It has been shown that participants respond faster with the right hand to the "+" sign, and with the left hand to the "-" sign (Pinhas et al., 2014), and a recent brain imaging study further suggested that the presentation of the operation sign alone is enough to activate brain areas involved in orienting spatial attention (Mathieu et al., 2018). Second, most previous studies used rather simple two-operand problems, in which one number has to be added or subtracted to/from another (e.g., Hartmann et al., 2015; Masson & Pesenti, 2014, 2016; Wiemers et al., 2014). Such one-step problems may involve only a small amount of actual arithmetic computation. For example, the result of $4 + 5$ can easily be retrieved from memory, without making mental movements along the number line. Although it has been shown that such problems still induce some counting principles and rapid shifts of spatial attention (Barrouillet & Thevenot, 2013; Mathieu et al., 2016), the potential for interactions with spatial processes is certainly limited. For these reasons, it remains unclear whether spatial-arithmetic associations truly reflect the involvement of spatial mechanisms in the actual arithmetic computation, or rather spatial associations of the operation sign ("+"/right, "-"/left) and/or semantic association of operation (addition/right, subtraction/left) (Andres et al., 2020; Gevers et al., 2010; Hartmann et al., 2015; Liu, Cai, et al., 2017; Pinhas et al., 2014; Zhu et al., 2018). Obviously, these limitations make it also difficult to draw firm conclusions about a possible functional role of shifts in spatial attention along the number line for mental arithmetic.

As a further limitation with regards to the question about functionality, many previous studies focused on compatibility effects, that is, differences between a congruent (e.g., addition-right) and incongruent (e.g., addition-left) conditions (e.g., Masson & Pesenti, 2014, 2016). A congruity effect can occur because (1) the incongruent condition impairs processing, (2) the congruent condition facilitates processing, or (3) a mixture of both. Thus, in order to assess whether spatial mechanism support arithmetic processes, it is important to also incorporate a neutral baseline condition in which neither a congruent nor an incongruent situation is created. To the best of my knowledge, there are only three studies so far that used a congruent and incongruent spatial intervention and compared it to a baseline condition. Two of these studies used optokinetic stimulation (OKS) (Blini et al., 2019; Masson et al., 2017). OKS consists of full-field visual stimuli (e.g., stripes) that move coherently toward a specific direction. The moving stimuli induce slow pursuit eye movements and thus a shift in spatial attention in the direction of the movement (Blini et al., 2019). Blini et al. (2019) found that vertical but not horizontal OKS increased addition performance relative to baseline. Specifically, participants made less positive decade errors (overestimation of result by a multiple of ten units) during upward OKS for addition, and during downward OKS for subtraction. These results suggest that the procedures involved in multi-digit calculation (e.g., carrying for additions, borrowing for subtractions) partly rely on spatial/attentional processes, at least with respect to the vertical dimension of space. In contrast, Masson et al.'s results showed that, when compared to leftward or baseline, rightward OKS facilitated the solution of addition problems. In the third study, Wiemers et al. (2014) investigated the impact of leftward, rightward, upward and downward hand and eye movements on mental arithmetic and compared it to a no-movement control condition. They found that addition and subtraction problems were solved more efficiently in the congruent condition in the vertical (but not in the horizontal) dimension of space (addition-up; subtraction-down). Interestingly, they found that performance in both the congruent and incongruent conditions was lower when compared to the no-movement baseline condition for arm movements (Experiment 1), while incongruent eye movements (Experiment 2) resulted in lower performance when compared to congruent eye movements or the no-movement baseline condition. Thus, there is to date only limited direct evidence for a functional involvement of spatial mechanisms during arithmetic, and it remains unclear which type of spatial intervention (e.g., horizontal, vertical) leads to a facilitation or impairment in arithmetic processing.

The aim of this study was to further investigate spatial-arithmetic associations and particularly the possible functional contribution of shifts in spatial attention along the number line by means of eye movement manipulations. Eye movements are tightly associated with shifts in spatial attention (Altmann, 2004; Corbetta et al., 1998; Grant & Spivey, 2003; Sheliga et al., 1994; Van Gompel et al., 2007). Furthermore, several studies have indicated that number processing and eye movements interact in a way that is congruent with the concept of a mental number line (e.g., Hartmann et al., 2016; Knops, Thirion, et al., 2009; Loetscher et al., 2008, 2010; Myachykov et al., 2015, 2016; Ranzini et al., 2016; Salvaggio et al., 2019). In the present study, participants' spatial attention along the mental number line was manipulated by guiding their eye movements across the screen using a moving dot (smooth pursuit task; see also Ranzini et al., 2016).

The limitations described above were addressed as follows. First, instead of using simple two-operand problems, multi-step addition and subtraction problems (e.g., $59 + 5 + 4 + 3$) were used. These multi-step problems should increase the computational component (or respectively, make it difficult to retrieve the solution from memory without calculation) and consequently allow for more interactions with spatial processing. Second, participants were informed before each trial whether they need to add or subtract the upcoming numbers, and the operands were then presented without any operation signs. Thus, any spatial-arithmetic association cannot be attributed to the spatial associations of the operation sign. Third, the performance in a congruent or incongruent arithmetic-space condition will be compared to two baseline conditions in which participants either were instructed to fixate their eyes at the center of the screen, or to freely move their eyes on the blank screen during computation.

1. Overview of the present study

In order to assess the functional role of eye movements along the number line in arithmetic computation in an efficient way, two pretests were conducted. Pretest 1 served to test the assumption that multi-step arithmetic problems lead to more computation when compared to one (e.g., 59 + 5) or two step (e.g., 59 + 5 + 4) problems (without applying spatial manipulations). Moreover, the presence of spatial-arithmetic compatibility effects is obviously mandatory for the assessment of the functional role of eye movements along the mental number line. However, with the modifications in this study (verbally presented multi-operand problems without operation sign), arithmetic-space compatibility effects reported in previous studies, even with similar spatial manipulations (Wiemers et al., 2014), cannot be taken for granted. The aim of Pretest 2 was therefore to estimate the size of spatial-arithmetic compatibility effects for addition and subtraction in the horizontal and vertical spatial dimension. As mentioned previously, spatial-arithmetic compatibility effects are sometimes more pronounced in the horizontal, and sometimes more in the vertical dimension of space (Blini et al., 2019; Liu, Verguts, et al., 2017; Masson et al., 2017; Masson & Pesenti, 2014; Wiemers et al., 2014). Moreover, spatial-arithmetic compatibility effects are sometimes only found for addition but not for subtraction problems (Glaser & Knops, 2020; Masson et al., 2017). If spatial-arithmetic compatibility effects turn out to be clearly stronger for specific conditions in Pretest 2 (horizontal, vertical, addition, subtraction), then the assessment of the functional role in the main experiment will be restricted to that/those specific condition(s).

2. Pretest 1

In Pretest 1, the assumption that multi-step arithmetic problems lead to a larger proportion of computation (vs. fact retrieval) was tested.

2.1. Method

2.1.1. Participants

Fourteen undergraduate students from the University of Bern participated in Pretest 1 in return for course credit (10 female; mean age = 23.3, ranging from 19 to 28, all indicated that German was their native language). Participants gave informed consent prior to the study. The study protocol was approved by the local Ethics Committee.

2.1.2. Stimuli and procedure

Each participant completed 48 addition and 48 subtraction trials, with 16 one-step, 16 two-step, and 16 three-step problems for each operation presented in random order (see Appendix). The trial started with an information screen that indicated whether participants were required to add or subtract in the current trial (by the labels "addition" or "subtraction"), along with a two-digit starting number. They pressed the space bar to start the presentation of the operands. The numbers 3, 4, 5 or 6 were used as operands. Operands were presented successively in the center of the screen for 1650 ms, with a 100 ms blank screen between each operand. The last operand remained in the center of the screen, and two possible solutions appeared 750 ms after the onset of the last operand on the left and right side (+/− 95 pixels, or 3°). Participant were instructed to choose the correct solution as quickly as possible by pressing a corresponding left ("f") or right ("j") key. The three numbers (the last operand and the two possible solutions) remained on the screen until the participant responded. The correct solution appeared equally often on the left and the right side. An error feedback ("wrong") was provided for incorrect responses for 2000 ms. After the response, a horizontal visual analog scale was presented, with the left end labeled as "mostly retrieved" and the right end labeled as "mostly computed", and participant clicked with the mouse cursor to the preferred position to indicate how they solved the arithmetic problem in the current trial. The next trial started following a blank screen of 1000 ms. The size of the numbers was fixed to 2° of visual angle (~ 80 pixels) for an assumed distance to the screen of 60 cm. The experiment was run on an ordinary laptop using PsychoPy2 (Peirce, 2007).

2.2. Results and discussion

Incorrect responses (7.8 %) were excluded from the analysis. Participants required on average 1391 ms ($SEM = 226$) to select the correct response after the onset of the two possible solution numbers. Mean rating values (0 = retrieved, 1 = computed) per operation and step size is illustrated in Fig. 1. The repeated measures ANOVA with the variables operation (addition, subtraction) and number of steps (one, two, three) on the ratings revealed a significant main effect for number of steps, $F(2,26) = 21.83$, $p < .001$, $\eta_p^2 = 0.63$. The proportion of computation (vs. recall) was 0.30 ($SEM = 0.06$) for one-step problems, 0.46 ($SEM = 0.05$) for two-step problems, and 0.51 ($SEM = 0.04$) for three-step problems. Pairwise comparison showed that all three numbers of steps differ from each other (all $ps < 0.042$). There was no main effect of operation, $F(1,13) = 0.61$, $p = .451$, $\eta_p^2 = 0.04$, and no interaction between operation and number of steps, $F(2,26) = 0.17$, $p = .846$, $\eta_p^2 = 0.01$. The finding that the three-step problems were not rated more clearly towards computation, and also the absence of a main effect of operation was somewhat surprising. Visual inspection of the mean ratings for the individual problems revealed that, at least for the three-step-problems, the majority of subtraction problems were rated above 0.5 (11 vs. 5), whereas the opposite was true for addition problems (6 vs. 11). Note also that the statistical power of Pretest 1 was limited due to the sample size ($n = 14$). In the context of the present study, it is most important that Pretest 1 confirmed that multi-step arithmetic problems trigger a significantly higher proportion of computation and are therefore used for the further experiments.

3. Pretest 2

The aim of Pretest 2 was to estimate the size of spatial-arithmetic compatibility effects for addition and subtraction in the horizontal and vertical spatial dimension when participants' eye movements were guided across the screen by means of a moving dot (smooth pursuit).

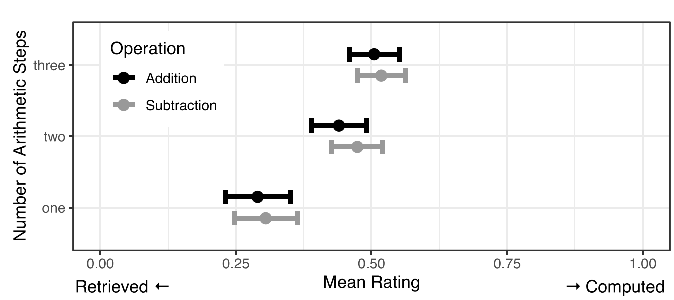

Fig. 1. Retrieval versus Computation Ratings
Note. Mean ratings (0 = retrieved, 1 = computed) for addition (black) and subtraction (grey) problems for the different number of arithmetic steps. Error bars depict +/− 1 *SEM*.

3.1. Methods

3.1.1. Participants

Thirty-two undergraduate students from the University of Bern participated in Pretest 2 in return for course credit (20 female; mean age = 23.5, ranging from 20 to 28; all right-handed by self-report; all indicated that German was their native language). Participants gave informed consent prior to the study. The study protocol was approved by the local Ethics Committee.

3.1.2. Apparatus

An EyeLink II video-based eyetracking system was used to collect eye movement data (SR Research Ltd., Ontario, Canada). Eye position was sampled at 250 Hz with a resolution of 0.01° and an average accuracy of 0.5°. Raw data samples were classified as fixations, saccades or blinks using the default parameter of the manufacturer's event parser (SR Research Data Viewer). Only sample data was used for further analyses. Stimuli were presented on a 21.3 "LCD screen (Eizo FlexScan S2133) with a resolution of 1024 × 768. Stimulus presentation and data collection was controlled by SR Research Experiment Builder, and raw sample data were extracted by SR Research Data Viewer (SR Research Ltd., Ontario, Canada) and further processed in R.

3.1.3. Stimuli and procedure

Participants were randomly assigned either to the horizontal (n = 16) or vertical (n = 16) condition. Participants were seated in front of the screen with a distance of approximately 70 cm. Following a standard 9-point eye-movement calibration procedure, task instructions were presented in white font (size = 17, style = Times New Roman) on a grey background. Participants were instructed to follow a moving dot with their eyes, while at the same time solve addition and subtraction problems as quickly and as accurately as possible. As in Pretest 1, each trial started with a starting number and the label "addition" or "subtraction" that indicated whether participants need to add or subtract the operands in the current trial. They pressed the space bar to continue the task. A white dot (21 × 21 pixels, or 0.7°) appeared in the center of the screen and then started to move after 750 ms, either leftward or rightward in the horizontal, or upward or downward in the vertical condition. The dot moved with a constant velocity of 51.2 pixels/s (or 1.65°/s). The three operands were presented 500, 3000, and 5500 ms after motion onset. The operands were verbally presented through headphones (German male voice, each sound file lasted 500 ms). Shortly (250 ms) after the onset of the last operand, two numbers appeared on the screen further along the motion trajectory, one being the correct solution of the arithmetic problem, and the other an incorrect solution. More precisely, the two numbers appeared 90 pixels (or 2.9°) ahead of the dot position along its current motion trajectory. This position was chosen because it allows participants to complete their computation for another 1750 ms before the dot reaches the position of the solution numbers, where it stopped moving. The incorrect solution was +2 or − 2 of the correct solution. In order to control for additional spatial congruity effects emerging from manual responses, the positions of the two solution numbers (and thus the manual responses) was orthogonal to the direction of the motion trajectory (see Fig. 2). In the horizontal condition, participants pressed the upper arrow key (with the middle finger of their right hand) when the upper number was the correct solution, and the lower arrow key (with the index finger of their right hand) when the lower number was the correct solution. Conversely, in the vertical condition, participants pressed the left arrow key (with the index finger of their right hand) when the left number was the correct solution, and the right arrow key (with the middle finger of their right hand) when the right number was the correct solution. The position of the correct number (up vs. down in the horizontal, and left vs. right in the vertical condition) was counterbalanced across trials. If participants chose the incorrect solution, the German word for incorrect ("falsch") appeared on the center of the screen for 2000 ms. A blank grey screen was presented

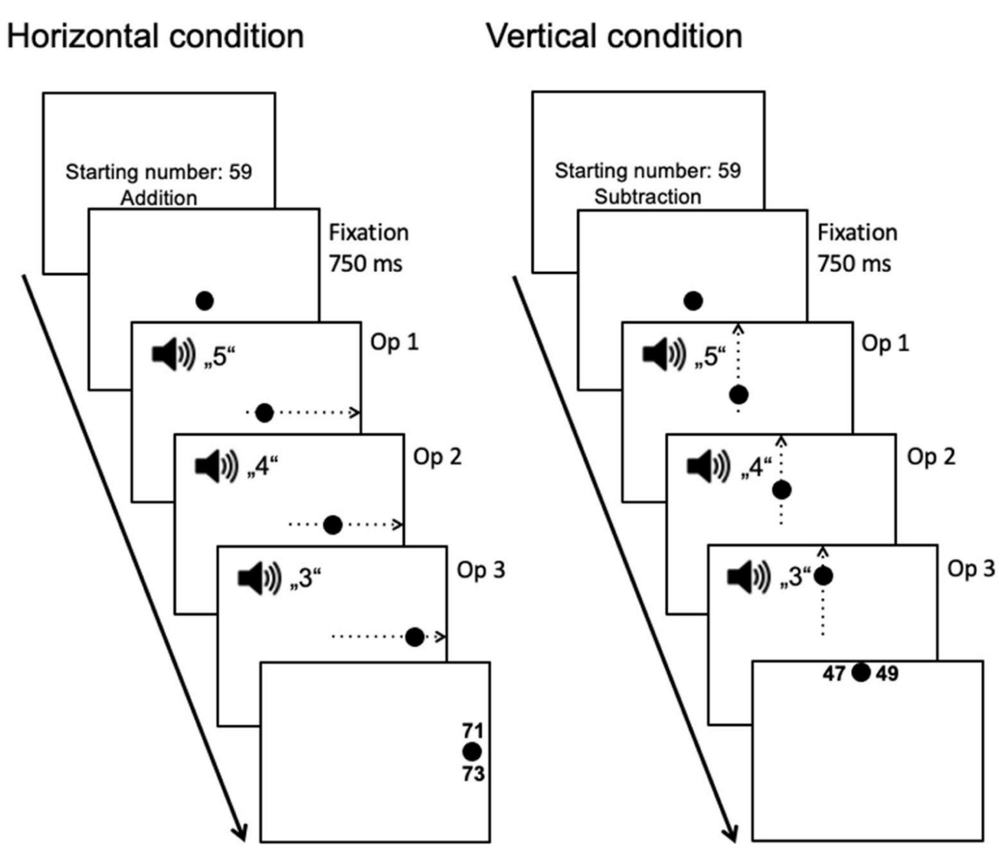

Fig. 2. Trial Examples of the Horizontal and Vertical condition.
Note. Left panel: Example of rightward motion and addition (congruent condition). Right panel: Example of upward motion, subtraction (incongruent condition). The quoted numbers represent the verbally presented operands with onsets of 500, 3000, and 5500 ms from motion start. The dotted lines show the motion trajectories of the dot. 250 ms after the onset of the last operand, two numbers appeared in spatial proximity to the dot, and participants indicate as quickly and accurately as possible which of the two numbers is the correct solution by button press. Op = operand. In the real experiment, it was a white dot on a grey background.

for 500 ms before the next trial started. Each trial started with a drift correction dot that appeared at the center of the screen.

Each participant solved 16 unique three-step problems per operation (addition and subtraction) and motion condition (leftward/rightward, or upward/downward), resulting in a total of 64 trials that were presented in random order (see Appendix for stimulus list). The starting number was a two-digit number, and the operands were either 3, 4, 5, or 6. The three operands within the same trial were always of different magnitudes, and the final result was never a tens number. Each starting number and operand was used equally often for addition and subtraction problems, so that the magnitude of the operands (i.e., the problem size) was constant for addition and subtraction problems.

In addition to these 64 experimental trials, 24 filler trials were implemented. For filler trials, the solution needed to be indicated already after the first ($n = 12$) or second ($n = 12$) operand. In this case, the two possible solutions appeared already 250 ms after the onset of the first or second operand. The filler trials were added in order to prevent participants from using strategies other than the intended continuous multi-step adding/subtracting. Specifically, if there were always only three-step problems, participants might first compute the sum of all three operands (irrespective of the operation), and then add or subtract this sum to/from the starting number at the end of the trial. If, however, they sometimes need to indicate the intermediate solution, then such a strategy might not be helpful. These filler trials were not used for analysis. The total of 88 trials were presented in random order.

3.2. Data analysis

Incorrect responses (10.6 % of trials) and trials for which participants failed to follow the moving dot were excluded from analysis (1.3 % of trials). The latter was determined by computing the deviation between eye position and the moving dot for every sample (4 ms; excluding blink samples and samples 250 ms before and after blinks) during the pursuit period. Trials for which the average deviation per trial was >2.5 *SD* above the individual mean were then removed. Visual inspection of eye movements of each trial confirmed that participants followed the eye movement instructions in all remaining trials. Next, trials for which response times were above 2.5 *SD* of the individual mean per operation were excluded (3.0 % of remaining trials).

Arithmetic-spatial associations were analyzed separately for the horizontal and vertical spatial dimension by means of a 2 × 2 repeated measures ANOVA with the variables operation (addition, subtraction) and congruity (congruent: rightward and upward for addition, leftward and downward for subtraction; incongruent: leftward and downward for addition, rightward and upward for addition; see Fig. 3). Statistical analyses were based on log RT values; means in text and figures are reported in untransformed units (ms), reflecting the time between the onset of the two solution numbers and participants' responses. For completeness, the same ANOVAs were also computed for the error rates.

3.3. Results and discussion

Mean RTs for congruent and incongruent conditions for addition and subtraction problems in the horizontal and vertical spatial dimensions are shown in Fig. 3.

For the horizontal dimension of space, the repeated measures ANOVA on the log RTs revealed a main effect of operation (see Table 1). Participants were faster in solving addition ($M = 1269$, $SEM = 83$) when compared to subtraction problems ($M = 1380$, $SEM = 84$). Importantly, there was no congruity effect or Congruity x Operation interaction. The estimated effect sizes (Cohen's *d*) of the congruity effects were 0.07, 95 % CI [−0.42, 0.56] for addition, and 0.18, 95 % CI [−0.32, 0.67] for subtraction. The same analysis on the error rates revealed no effects (all $Fs < 1$, $ps > 0.545$).

For the vertical dimension of space, the repeated measures ANOVA on the log RTs also revealed a main effect of operation (see Table 1).

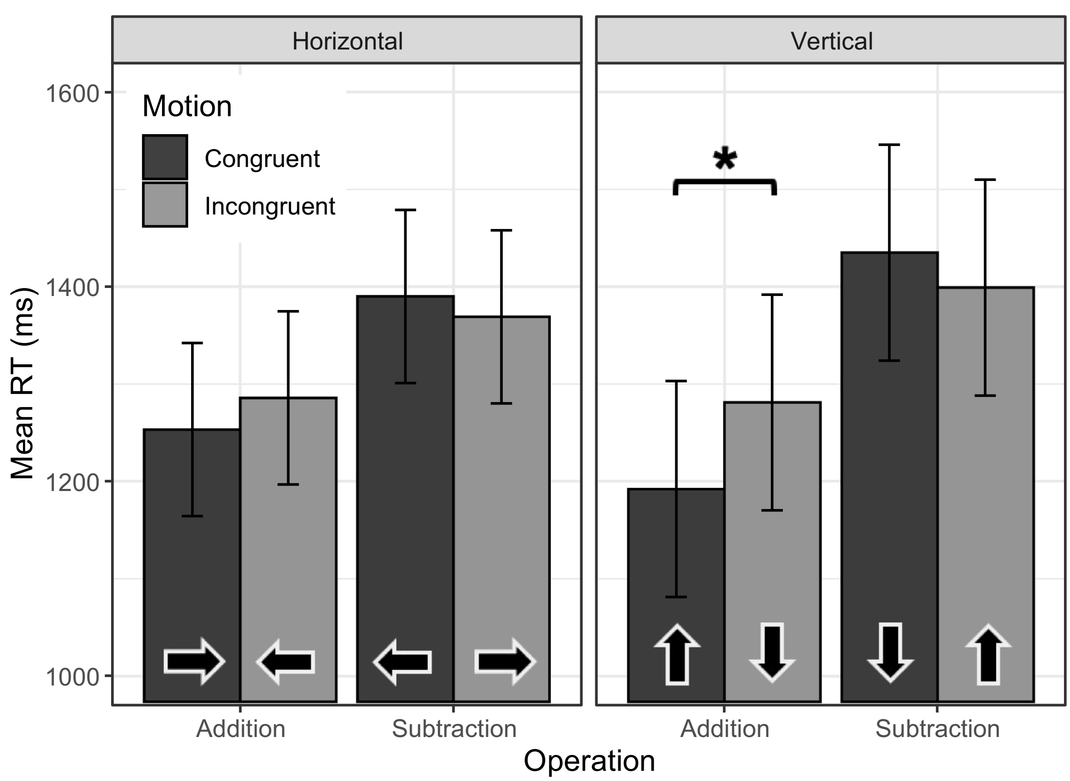

Fig. 3. Mean Response Time (RT) for Congruent and Incongruent Conditions for the Horizontal and Vertical Spatial Dimension
Note. The arrows in the bars show the actual motion direction of the dot during mental arithmetic. The asterisk indicates a significant congruity in the vertical spatial dimension for addition. Error bars depict +/− 1 *SEM*.

Table 1
Result of the ANOVA.

Effect	F (1,15)	p	η_p^2
Horizontal			
Operation	13.88	0.002	0.48
Congruity	0.06	0.816	0.01
Operation x Congruity	0.60	0.453	0.04
Vertical			
Operation	19.28	< 0.001	0.56
Congruity	1.44	0.248	0.09
Operation x Congruity	8.70	0.010	0.37

Participants were faster in solving addition ($M = 1237$, $SEM = 87$) when compared to subtraction problems ($M = 1417$, $SEM = 127$). There was no main effect of congruity, but congruity interacted with operation (see Table 1). Separate pairwise comparison between congruent and incongruent conditions for addition and subtraction revealed a significant congruity effect for addition, $t(15) = -3.40$, $p = .004$, Cohen's $d = 0.85$, 95 % CI [0.26, 1.41] but not for subtraction, $t(15) = 0.70$, $p = .497$. Cohen's $d = -0.17$, 95 % CI [−0.67, 0.32]. For addition, participants were on average 89 ms faster in the congruent condition (upward motion) ($M = 1192$, $SEM = 83$) compared to the incongruent condition (downward motion) ($M = 1281$, $SEM = 94$). The same analysis on the error rates revealed a trend for operation, $F(1,15) = 3.32$, $p = .089$, $\eta_p^2 = 0.18$, with a higher error rate for subtraction ($M = 16.5$ %, $SEM = 2.2$) than for addition problems ($M = 12.9$ %, $SEM = 1.9$). There was no main effect of congruity and no interaction for error rates (Fs < 1.86, $ps > 0.192$).

The results from Pretest 2 revealed that, with the current settings of this study (multi-step arithmetic problems, concurrent smooth pursuit eye movements task), there is evidence for a spatial-arithmetic compatibility effect for addition in the vertical dimension of space. Based on the results from Pretest 2, the question about a functional involvement of eye movements along the mental number line will be assessed only for addition in the vertical dimension of space in the main experiment, because this condition is most likely to generate a spatial-arithmetic compatibility effect.

3.4. Additional analysis

In this study, addition and subtraction problems were matched for problem size (magnitude of operands). Consequently, result sizes were on average larger for addition than for subtraction problems. A potential source of the congruity effect for addition might therefore be the larger result size and not the operation per se. To address this issue, the congruity effect was recomputed only for the lower half of addition problems with starting numbers around 30 (or respectively with result sizes in the range between 41 and 47), and for the upper half of subtraction problems with starting numbers around 60 (or respectively with result sizes in the similar range between 43 and 48). The analysis confirmed a significant congruity effect for addition problems, $t(15) = -2.46$, $p = .026$, Cohen's $d = 0.62$, 95 % CI [0.07, 1.14], but not for result-size matched subtraction problems, $t(15) = -1.10$, $p = .289$, Cohen's $d = 0.28$, 95 % CI [−0.23, 0.77]. This additional analysis suggests that the congruity effect for addition was not due to the larger result sizes.

4. Main experiment

The aim of the main experiment was to test the hypothesis of a functional role of eye movements along the mental number line for mental arithmetic. Based on the results from Pretest 2, the hypothesis was tested selectively for addition problems in the vertical dimension of space, since this was the only condition in which a congruity effect emerged. Crucially, two baseline conditions were incorporated in the main experiment: central fixation and free viewing. Central fixation has similar demand characteristics than the congruent and incongruent condition (i.e., fixating a dot, suppressing eye-movements to other locations) and is therefore an appropriate baseline condition. However, also the comparison to free viewing is important. It can be argued that functionality of eye movements along the mental number line can be claimed most convincingly if participants perform better in the congruent than in the free-viewing condition, because the free viewing condition allows participants to focus on the arithmetic process without the additional task demand of remaining fixated at the central dot.

4.1. Method

4.1.1. Participants

The minimal sample size was determined by a-priori power analysis. The estimated effect size of the spatial-arithmetic compatibility effect for addition in the vertical dimension of space in Pretest 2 of 0.85 can be considered large. However, this estimate refers to the comparison between the congruent and incongruent condition that likely results in the largest difference. Arguably, the performance of the baseline conditions may lay somewhere in between the congruent and incongruent condition. Therefore, a more conservative effects size of 0.65 was chosen, which is halfway between medium (0.5) and high (0.8). Accordingly, a minimum sample size of $n = 27$ was required to reliably (with a probability >0.9) detect an effect, assuming a two-sided criterion for detection that allows for a maximum Type I error rate of $\alpha = 0.05$.

Twenty-nine undergraduate students from the University of Bern participated in the main experiment in return for course credit (25 female; mean age = 23.1, ranging from 19 to 27; all right-handed by self-report; all indicated that German was their native language). Participants gave informed consent prior to the study. The study protocol was approved by the local Ethics Committee.

4.1.2. Apparatus, stimuli and procedure

The same apparatus and arithmetic problems were used as in Pretest 2. The procedure was also identical, with the exception that only addition problems were used, and that participants were instructed to fixate the central dot and (1) either follow with their eyes the moving dot, or (2) in case the dot remains on the center, remain fixated on the dot, or (3) to move their eyes freely on the screen in case the dot disappears (see Fig. 4). In all conditions, the central fixation dot was presented on the screen at the beginning of the computational phase of the trial (i.e., after participant had seen the starting number). After 750 ms, the dot either started to move upward (congruent condition) or downward (incongruent condition) with a constant velocity of 51.2 pixels/s (or 1.65°/s), remained in the center (central fixation condition), or disappeared (free viewing condition). The three operands were presented verbally 500, 3000, and 5500 ms after the offset of the initial fixation screen. The position of the two solution numbers was identical to Pretest 2. In the central fixation and free viewing condition, the two solution numbers appeared to the left and right side of the center (+/− 34 pixels, or 1.1°) 250 ms after the onset of the last operand.

Each participant completed the 16 same problems for each of the four conditions, resulting in a total of 64 experimental trials. As in Pretest 1, 24 filler trials were implemented for which the solution needed to be indicated already after the first ($n = 12$) or second ($n = 12$) operand. These filler trials were not considered for the analysis. The total of 88 trials were presented in random order.

4.1.3. Data analysis

Incorrect responses (7.4 % of trials) and trials for which participants failed to follow the moving dot or fixate the static dot were excluded from analysis. This was determined by computing the deviation between eye position and the moving (or static in the central fixation condition) dot for every sample (4 ms; excluding blink samples and samples 250 ms before and after blinks) during the pursuit period. Trials for which the

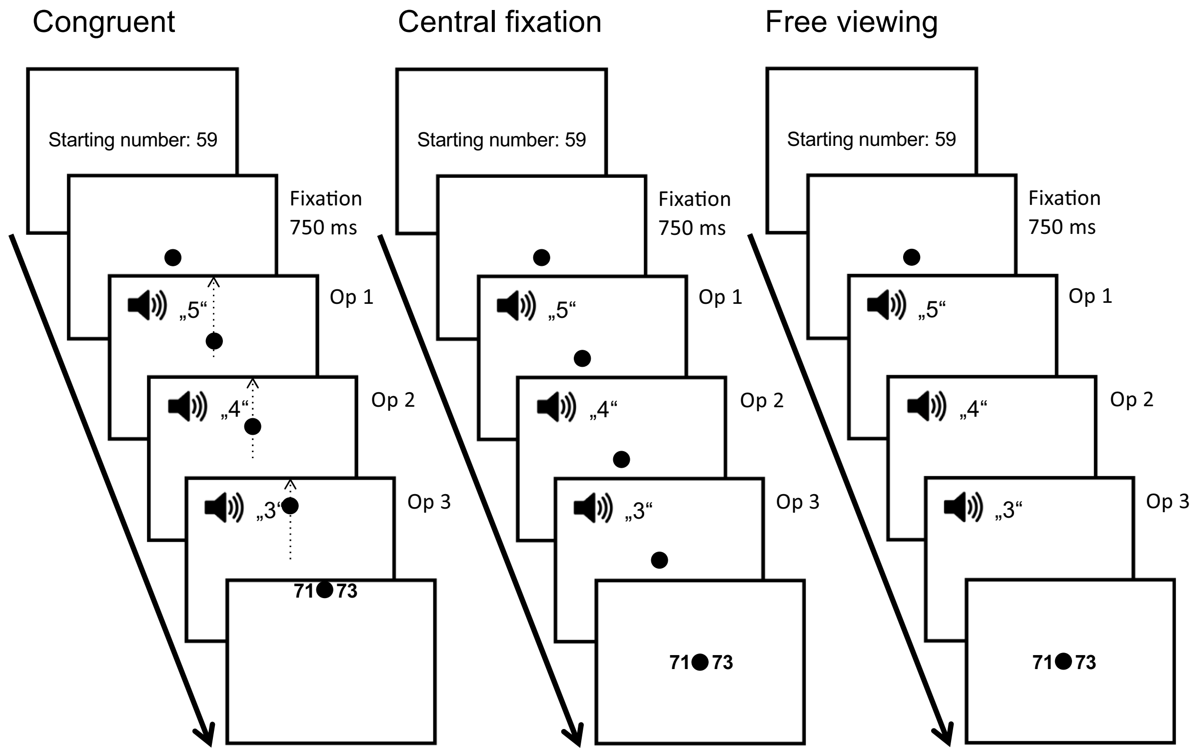

Fig. 4. Trial Examples of the Main Experiment.
Note. Examples of upward motion (left panel), central fixation (middle panel) and free viewing (right panel). The quoted numbers represent the verbally presented operands, and the dotted line in the left panel shows the motion trajectories of the dot. Incongruent condition (downward motion) is not shown. Op = operand. In the real experiment, it was a white dot on a grey background.

average deviation per trial was >2.5 *SD* above the individual mean were then removed (3.5 % of remaining trials). Visual inspection of eye movements of each trial confirmed that participants followed the eye movement instructions in all remaining trials (see Fig. 5). Moreover, trials for which response times were above 2.5 *SD* of the individual mean per operation were excluded (5.1 % of remaining trials).

A repeated measures ANVOA with the variable condition (congruent, incongruent, central fixation, free viewing) was computed, followed by separate planned comparisons (paired *t*-tests) between the congruent and each of the other three conditions (congruent vs. incongruent, congruent vs. central fixation, congruent vs. free viewing), and also between the incongruent and the baseline conditions. Statistical analyses were based on log RT values; means in text and figures are reported in untransformed units (ms), reflecting the time between the onset of the two solution numbers and participants' responses.

4.2. Results

Mean RT per condition are shown in Fig. 6. The ANOVA revealed a main effect for condition, $F(3, 84) = 3.37$, $p = .022$, $\eta_p^2 = 0.11$. Planned comparisons revealed that participants were significantly faster in solving addition problems in the congruent ($M = 1269$, $SEM = 60$) when compared to the incongruent ($M = 1341$, $SEM = 74$; $p = .025$, Cohen's $d = 0.44$, 95 % CI [0.05, 0.82]), central fixation ($M = 1362$, $SEM = 78$; $p = .009$, Cohen's $d = 0.52$, 95 % CI [0.13, 0.91]), and the free viewing condition ($M = 1386$, $SEM = 64$; $p = .025$, Cohen's $d = 0.44$, 95 % CI [0.06, 0.82]). In contrast, there was no difference between the incongruent condition and the central fixation ($p = .598$, Cohen's $d = 0.10$, 95 % CI [−0.27, 0.46]), and the free viewing condition ($p = .852$, Cohen's $d = 0.04$, 95 % CI [−0.33, 0.40]).

The effect size for the congruity effect (congruent vs. incongruent) was lower than in Pretest 2, suggesting that the effect size in Pretest 2 might be overestimated. Nevertheless, it was possible with the selected sample size to replicate the congruity effect.

The same analysis on the error rates revealed no effect of condition, $F(3, 84) = 1.42$, $p = .243$, $\eta_p^2 = 0.05$.

5. General discussion

The aim of this study was to further investigate spatial-arithmetic compatibility effects and particularly to test a possible functional role of eye movements along the number line for mental arithmetic. To this end, participants made smooth pursuit eye movements while they at the same time solved multi-step arithmetic problems. Participants were faster in solving addition problems when making upward compared to downward eye movements. The upward direction of eye movements during addition is congruent with the assumed upward shift in attention along the vertical number line toward larger numbers (e.g., Hartmann et al., 2012; Ito & Hatta, 2004; Schwarz & Keus, 2004; Winter & Matlock, 2013; Winter, Matlock, et al., 2015). The results thus replicate previous findings of a spatial-arithmetic compatibility effect for addition in the vertical spatial dimension (Lugli et al., 2013; Wiemers et al., 2014), and provide further evidence that mental arithmetic is conceptualized as movements along the number line (e.g., Fischer & Shaki, 2014; Masson et al., 2018). Specifically, the present Findings suggest that eye movements along the number line are not simply an epiphenomenon of the recruitment of a spatial reference frame (i.e., mental number line) during arithmetic but rather suggest that the motor and attentional orienting processes involved in eye movements are functionally involved in arithmetic computation. Thus, when participants are forced to “act out” the mental movements along the number line with their eyes on an external space in a way that is congruent to the shifts in attention in the representational space, the computation of numbers seems to be facilitated. This finding supports the idea of shared mechanisms for the control of spatial attention in the external (visual) and representational (number) space (e.g., De Hevia et al., 2008; Dormal

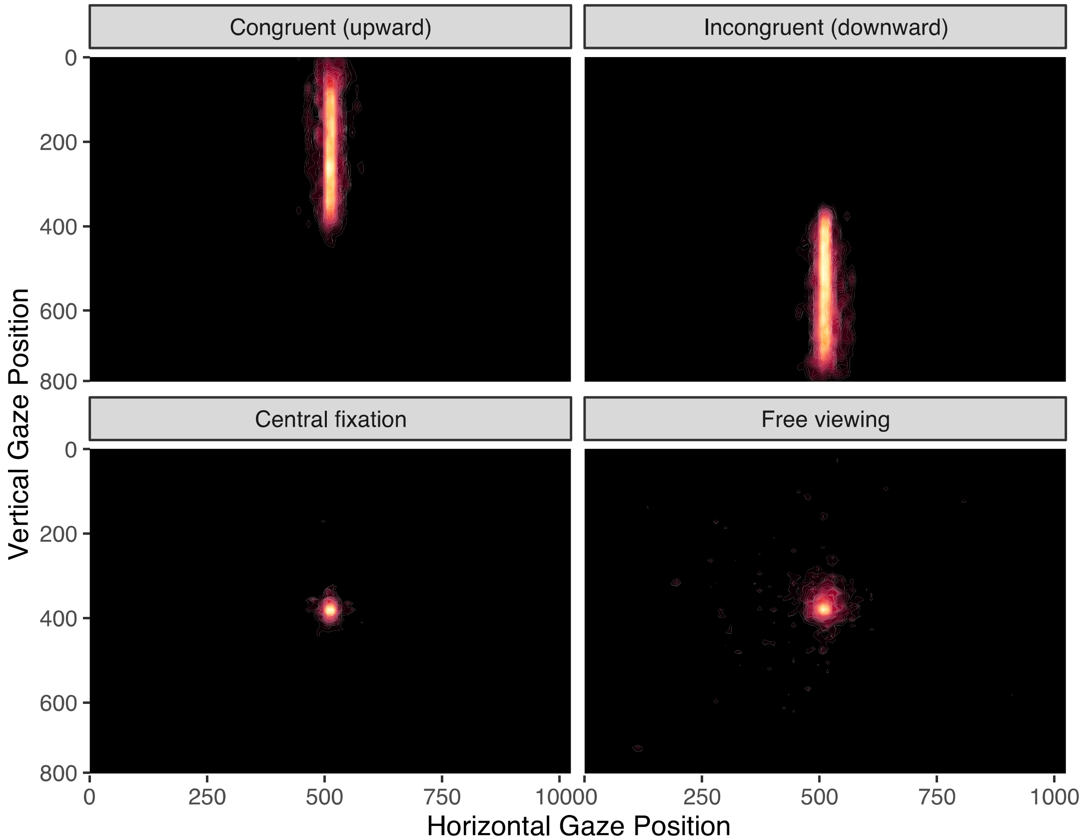

Fig. 5. Distribution of eye fixations for the four different conditions
Note. Figure shows density plots of eye fixation sample positions in the time window between the onset of the first operand and the onset of the solution numbers. Zero is anchored at the top left following the eye tracker's coordinate.

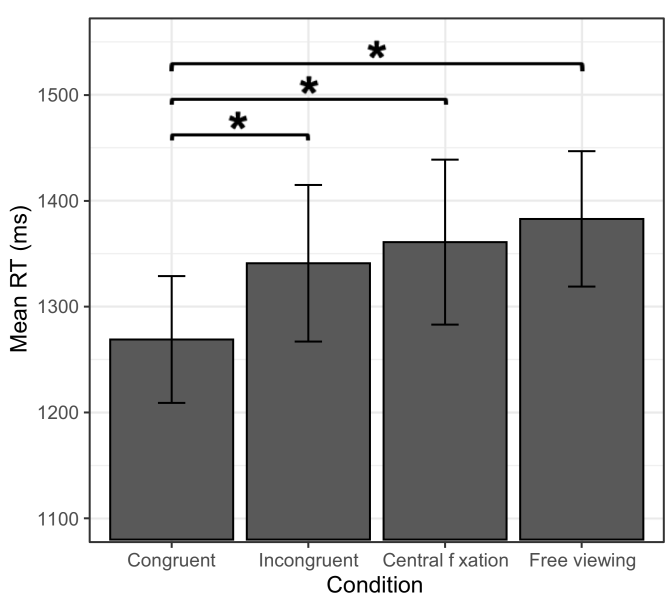

Fig. 6. Mean RTs for the Four Experimental Conditions
Note. Asterisks indicate significant faster responses in the congruent compared to the incongruent, central fixation, and free viewing condition ($ps < 0.05$). Error bars depict +/− 1 *SEM*.

et al., 2014; Hubbard et al., 2005; Vuilleumier et al., 2004; Zorzi et al., 2012). The interference between sensorimotor and arithmetic processing is also in line with embodied cognition theory, which highlights the importance of sensorimotor processes for abstract cognitive processes (Barsalou, 2008; Walsh, 2015). Accordingly, even though mental arithmetic seems to be abstract symbol manipulation at first glance, it still recruits sensorimotor processes that allow for a spatialization of the abstract contents in order to facilitate understanding and manipulation of number magnitudes (De Hevia et al., 2008).

Interestingly, solving addition problems was faster during congruent motion when compared to the central fixation and free viewing condition. The latter finding suggests that the benefit of congruent eye movement versus central fixation cannot be attributed to the cognitive costs associated with fixating a static target. In contrast, there was no difference between the incongruent condition and the central fixation or free viewing condition. Such evidence for a facilitation but not for an interference effect is in line with Masson et al.'s (2017) study who found that rightward OKS facilitated the solving of addition problems, but there was no difference between the baseline and leftward OKS. In contrast, an interference but no facilitation effect was reported in Wiemers et al. (2014). There is no straightforward explanation for these mixed findings. When comparing the present study with Wiemers et al.'s study, one could speculate that the absence of a cost in the present study might be due to the relatively longer duration of the multi-step trials in this study, which potentially allows participants to adapt their strategies in the incongruent condition, such as for example to invert the direction of their mental number line.

The results from Pretest 2 revealed that the spatial-arithmetic association was restricted to addition in the vertical dimension of space. There are several studies that also did not find spatial associations for subtraction problems (e.g.,Glaser & Knops, 2020; Masson et al., 2017). Common explanations are that subtraction problems are more difficult and may involve additional strategies that overrule spontaneous recruitments of a number line (e.g., Ashcraft, 1992; Fayol & Thevenot, 2012; Glaser & Knops, 2020; Liu, Cai, et al., 2017; Masson et al., 2017). For example, subtraction problems might involve complementary addition strategies (e.g., 59–5 =? can be solved as 59 = 5 + X), which may interrupt leftward/downward attentional shifts of spatial attention (Glaser & Knops, 2020; Masson et al., 2017). Furthermore, neuroimaging data have also shown that solving addition problems was related to activation of the posterior part of the superior parietal lobule elicited by eye movements, while no such link was observed for subtraction problem solving (Knops, Thirion, et al., 2009). Thus, it seems that it is generally more straightforward to apply spatial-arithmetic associations to addition than to subtraction problem solving.

The absence of a horizontal spatial-arithmetic association in Pretest 2 is in line with Wiemers et al. (2014)'s findings but contrasts with other findings (e.g., Liu, Verguts, et al., 2017; Masson et al., 2017, 2018; Masson & Pesenti, 2014, 2016; Zhu et al., 2018). Several factors might contribute to these differing results. First, the current study used a design in which no operation signs were presented during the computational process. As mentioned earlier, previous studies found that the operation sign can induce horizontal shifts of spatial attention (Mathieu et al., 2018; Pinhas et al., 2014; Salvaggio et al., 2022). Second, previous studies used one-step arithmetic problems that have a relatively limited computational component, while multi-step arithmetic problems were used in the present study. It was verified in Pretest 1 that these problems indeed provoke a larger computational (vs. retrieval) component. It is therefore possible that the horizontal spatial-arithmetic associations previously reported partly reflect a semantic spatial association of the operation sign ("+"/right, "-"/left) or a semantic association of the operation (addition/right, subtraction/left) rather than a mental movement along the number line during arithmetic (Andres et al., 2020; Gevers et al., 2010; Pinhas et al., 2014). Thus, when these "non-computational" spatial associations are better controlled (as attempted in this study), it is possible that spatial-arithmetic associations are more robust in the vertical than in the horizontal dimension of space (Blini et al., 2019; Wiemers et al., 2014). It has been argued that vertical associations (small-down, large-up) might be more robust than horizontal associations (small-left, large-right) because the former are based on the universal "grounded" sensorimotor experiences that "more" of something usually corresponds to higher positions in space, for example when stacking items or when pouring water in a glass (Blini et al., 2019; Fischer, 2012; Holmes & Lourenco, 2012; Lakoff & Johnson, 1980). Such experiences occur early in development. In contrast, the horizontal association is shaped by culture-specific experiences that occur later in development, such as reading and writing habits (Fischer, 2012; Göbel et al., 2011). Although a recent study showed that horizontal spatial-arithmetic associations cannot be explained by reading/writing direction (Masson et al., 2020), there is plenty of evidence for a flexible use for horizontal representations of ordinal information within Western cultures (e.g., Bächtold et al., 1998; Casasanto & Bottini, 2014; Fischer et al., 2010; Guida et al., 2020). For example, the direction of the horizontal spatial-numerical association reverses when the opposite direction is primed (e.g., Bächtold et al., 1998; Fischer et al., 2010). If there is indeed a higher cognitive flexibility in the use of the horizontal when compared to the vertical number line, then moving the eyes continuously to the left or right side for a certain amount of time within a trial could already induce an adaptation of the direction of number representation, so that larger numbers are arranged further along the leftward motion trajectory, thus overriding the long-term small-left association. In contrast, no such flexible adaptation of the direction of number representation might take place during vertical movements, because the small-down and large-up associations are deeply rooted in sensorimotor experiences and can therefore not easily be overwritten (Blini et al., 2019; Fischer, 2012). The vertical magnitude association might further be strengthened by the use of spatial metaphors in language when describing arithmetic ("counting down", "summing up" etc.) (Winter, Marghetis, et al., 2015).

5.1. Limitations and outlook

Several limitations of this study should be considered. First of all, participants did not look around much in the free viewing condition. Although it is known that some participants prefer not to move their eyes when there is nothing on the screen (Zangrossi et al., 2021), some design aspects of the free viewing condition in the current study might have reduced the spontaneous unfolding of arithmetic-supportive eye movements. Specifically, a fixation cross was presented at the start of the free viewing condition, and the solution numbers were presented at the center of the screen. If a participant for instance spontaneously looked up during addition (e.g., Hartmann et al., 2015, 2016; Salvaggio et al., 2022), moving back to the center for result verification would induce some cost in RTs. These restrictions might explain why there was no advantage in the free viewing condition when compared to the central fixation or incongruent motion condition. Thus, while the comparison between the congruent and the other conditions suggest a functional contribution of eye movements during mental addition, the current study does not allow to conclude whether externally guided congruent movements during arithmetic are superior to those that may occur spontaneously upon the recruitment of a mental number line. To address this issue, future studies could remove the central fixation cross and use a gaze-contingent approach to present verification stimuli in a free moving condition.

Second, a verification task was used to measure problem solving time. The rationale behind this choice was that the eye movement manipulation would constantly bias arithmetic computation during multi-step problem solving, so that the computation of the final result is completed faster in the congruent condition, and the verification time would consequently reflect the impact of the spatial manipulation during the entire arithmetic process. However, the result selection might have introduced some processes that were not related to the arithmetic computation (e.g., comparison, spatial response selection). It is therefore important that the results reported in this study are replicated with a production task (e.g., Masson et al., 2018; Masson & Pesenti, 2014; Wiemers et al., 2014) in order to verify the generalizability of results.

Third, in order to attempt that the spatial-arithmetic congruity effect can be attributed to the arithmetic computation, no operation signs ("plus", "minus") were presented between the operands. However, participants were informed at the beginning of each trial about the operation ("addition", "subtraction"). It cannot be ruled out that the processing of the operation word at the beginning of the trial, or some semantic association with the operation during computation contributed to the congruity effect.

It should also be noted that previous evidence for horizontal spatial-arithmetic associations often comes from attentional paradigms, where participants are required to detect a lateral target following addition or subtraction (e.g., Masson & Pesenti, 2014). The shifts in spatial attention induced by the arithmetic problems are typically limited to a specific time window in the range of <1 s following the operator (e.g., Glaser & Knops, 2020; Liu, Cai, et al., 2017). It is conceivable that similar leftward and rightward shifts in spatial attention were also induced in this study at the beginning of the arithmetic process, but these shifts had no more impact on the selection time of the correct solution at the end of the multi-step computations. It is therefore possible that the task used in this study was not sensitive to capture short-lived horizontal spatial-arithmetic associations. It is also important to highlight that the aim of Pretest 2 was to estimate the size of different spatial-arithmetic associations with the current task in order to find out which condition is the most promising for further assessment in the main experiment, and not to ultimately prove the presence or absence of different spatial-numerical associations. Therefore, further research with this specific aim is needed to assess the nature and limits of the different spatial-arithmetic associations.

The question regarding a functional role of space for arithmetic is not limited to eye movements but can rather be extended to the role of spatial attention more generally. Eye movements reflect overt shifts in spatial attention (e.g., Altmann, 2004; Corbetta et al., 1998; Sheliga et al., 1994). However, spatial attention can also be shifted covertly, without making eye movements. The differentiation between overt and covert shifts in spatial attention has been intensively studied in the domain of memory research. It has been shown that, when remembering visual information of a stimulus from memory, individuals spontaneously look at the spatial location where they encoded the visual stimulus, even though the stimulus is no longer on the screen (e.g., Ferreira et al., 2008; Richardson & Spivey, 2000). Eye movement manipulations have then been employed to assess the role of such "eye movements to nothing", and it has been shown that memory retrieval is facilitated when eye movements are guided to the corresponding when compared to non-corresponding spatial locations (e.g., Johansson et al., 2012; Johansson & Johansson, 2014; Laeng et al., 2014; Laeng & Teodorescu, 2002; Scholz et al., 2016). Based on these results, a functional role of eye movements for memory retrieval has been claimed (Johansson & Johansson, 2014). However, later research showed that similar effects can also be found for covert shifts of spatial attention (Scholz et al., 2018). When these insights from memory research are transferred to the mental number line, it can be expected that also covert shifts of attention may interfere with arithmetic processing. Future studies could therefore compare the role of overt (i.e., eye movements) and covert shifts of spatial attention for mental arithmetic to disentangle more specifically the role of motor activity and actual displacements in external space as opposed to covert shifts in spatial attention that occurs in the "mental" space (Scholz et al., 2018).

Declaration of competing interest

The author confirms that there is no conflict of interest.

Appendix A

Table A1
Arithmetic Problems used in Pretest 1.

Addition			Subtraction		
One-step	Two-step	Three-step	One-step	Two-step	Three-step
28 + 3	28 + 5 + 6	28 + 4 + 5 + 6	28 - 6	28 - 5 - 6	28 - 4 - 5 - 6
29 + 6	29 + 3 + 4	29 + 6 + 3 + 4	29 - 4	29 - 3 - 4	29 - 6 - 3 - 4
31 + 3	31 + 4 + 3	31 + 5 + 4 + 3	31 - 3	31 - 4 - 3	31 - 5 - 4 - 3
32 + 5	32 + 5 + 6	32 + 3 + 5 + 6	32 - 6	32 - 5 - 6	32 - 3 - 5 - 6
28 + 4	28 + 3 + 6	28 + 4 + 3 + 6	28 - 6	28 - 3 - 6	28 - 4 - 3 - 6
29 + 5	29 + 5 + 3	29 + 6 + 5 + 3	29 - 3	29 - 5 - 3	29 - 6 - 5 - 3
31 + 5	31 + 4 + 5	31 + 3 + 4 + 5	31 - 5	31 - 4 - 5	31 - 3 - 4 - 5
32 + 3	32 + 5 + 4	32 + 6 + 5 + 4	32 - 4	32 - 5 - 4	32 - 6 - 5 - 4
58 + 5	58 + 5 + 6	58 + 4 + 5 + 6	58 - 6	58 - 5 - 6	58 - 4 - 5 - 6
59 + 4	59 + 3 + 6	59 + 4 + 3 + 6	59 - 6	59 - 3 - 4	59 - 4 - 3 - 6
61 + 4	61 + 6 + 5	61 + 3 + 6 + 5	61 - 3	61 - 4 - 3	61 - 5 - 4 - 3
62 + 6	62 + 4 + 3	62 + 5 + 4 + 3	62 - 5	62 - 6 - 5	62 - 3 - 6 - 5
58 + 6	58 + 6 + 5	58 + 5 + 6 + 4	58 - 6	58 - 6 - 5	58 - 5 - 6 - 4
59 + 3	59 + 4 + 3	59 + 5 + 4 + 3	59 - 3	59 - 4 - 3	59 - 5 - 4 - 3
61 + 6	61 + 3 + 5	61 + 4 + 3 + 6	61 - 6	61 - 3 - 6	61 - 4 - 3 - 6
62 + 4	62 + 5 + 6	62 + 3 + 5 + 6	62 - 6	62 - 5 - 6	62 - 3 - 5 - 6

Note. The two-digit number at the beginning of each problem is the "starting number" that was presented prior to the operand. The operation signs ("+", "-") were not presented during the task.

Table A2
Arithmetic Problems used in Pretest 2.

Addition	Subtraction
28 + 4 + 5 + 6	28 - 4 - 5 - 6
29 + 6 + 3 + 4	29 - 6 - 3 - 4
31 + 5 + 4 + 3	31 - 5 - 4 - 3
32 + 3 + 5 + 6	32 - 3 - 5 - 6
28 + 4 + 3 + 6	28 - 4 - 3 - 6
29 + 6 + 5 + 3	29 - 6 - 5 - 3
31 + 3 + 4 + 5	31 - 3 - 4 - 5
32 + 6 + 5 + 4	32 - 6 - 5 - 4
58 + 4 + 5 + 6	58 - 4 - 5 - 6
59 + 4 + 3 + 6	59 - 4 - 3 - 6
61 + 3 + 6 + 5	61 - 5 - 4 - 3
62 + 5 + 4 + 3	62 - 3 - 6 - 5
58 + 5 + 6 + 4	58 - 5 - 6 - 4
59 + 5 + 4 + 3	59 - 5 - 4 - 3
61 + 4 + 3 + 6	61 - 4 - 3 - 6
62 + 3 + 5 + 6	62 - 3 - 5 - 6

Note. The two-digit number at the beginning of each problem is the "starting number" that was presented prior to the operand. The operation signs ("+", "-") were not presented during the task.

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