Impact of optokinetic stimulation on mental arithmetic

Nicolas MASSON, Mauro PESENTI, & Valérie DORMAL

Institut de Recherche en Sciences Psychologiques and Institute of Neuroscience,
Université catholique de Louvain, Louvain-la-Neuve, Belgium

*Submitted as a **Research article***

main text: 5525 words (abstract excluded)

Correspondence should be addressed to:

Nicolas Masson or Mauro Pesenti
Institut de Recherche en Sciences Psychologiques
Université catholique de Louvain
Place Cardinal Mercier, 10
B-1348 Louvain-la-Neuve (Belgium)
E-mail: nicolas.masson@uclouvain.be; mauro.pesenti@uclouvain.be
Tel.: +32 10 47 38 39
Fax.: +32 10 47 38 79

Acknowledgements

We thank Laurie Geers and Madeline Slÿpen for their help in data collection.

Abstract

Solving arithmetic problems has been shown to induce shifts of spatial attention, subtraction problems orienting attention to the left side and addition problems to the right side of space. At the neurofunctional level, the activations elicited by the solving of arithmetical problems resemble those elicited by horizontal eye movements. Whether overt orientation of attention (i.e., eye movements) can be linked to the solving procedure is however still under debate. In the present study, we used optokinetic stimulation (OKS) to trigger automatic eye movements in order to orient participants' overt attention to the right or to the left of their visual field while they were solving addition or subtraction problems. The results show that, in comparison to leftward OKS and a control condition, rightward OKS facilitates the solving of addition problems that necessitate a carrying procedure. Subtraction solving was unaffected by leftward or rightward OKS. These results converge with previous findings to show that attentional shifts are functionally related to mental arithmetic processing.

Keywords: Mental arithmetic, Optokinetic stimulation, Eye movements, Visuospatial Attention

Introduction

It has been suggested that exploring external space and internal imagined space relies on similar attentional mechanisms (Bisiach & Luzzatti, 1978). For instance, eye movements allow observers to bring targeted stimuli at the centre of their fovea and thus of their attentional focus, and they are also functionally related to the orientation of internal attention, as they may guide the sequential analysis of the various features composing a mental image (de Vito, Buonocore, Bonnefon, & Della Sala, 2014; Hebb, 1968; Johansson & Johansson, 2014; Laeng & Teodorescu, 2002). Indeed, while remembering or describing a mental image or a visual scene, eye movements are not random but reflect the content of the mental image (e.g., Brandt & Stark, 1997; Laeng & Teodorescu, 2002) or of the visual scene (Johansson, Holsanova, & Holmqvist, 2006).

A broad range of findings has shown that numbers might be mentally represented along a spatial continuum, with small numbers on the left and large numbers on the right of the continuum (Dehaene, 1992; for a review, see Hubbard, Piazza, Pinel, & Dehaene, 2005). In line with this idea, it has been shown that processing numbers induced shift of spatial attention, with small numbers orienting attention to the left part and large numbers to the right part of space (e.g., Bonato, Priftis, Marenzi, & Zorzi, 2009; Casarotti, Michielin, Zorzi, & Umiltà, 2007; Fischer, Castel, Dodd, & Pratt, 2003). Conversely, left-sided visual signals delayed the processing of large numbers and right-sided signals the processing of small numbers (Kramer, Stoianov, Umiltà, & Zorzi, 2011; Stoianov, Kramer, Umiltà, & Zorzi, 2008), showing that the interaction between numerical magnitude and space is bi-directional. These findings support the idea that attention orientation underlies the mental manipulation of numbers on a visuospatial medium. One way to objectify these spatial shifts is by measuring eye movements (for a recent review, see Hartmann, 2015), taken as high spatial and temporal resolution indices of participants' explicit focus of attention, useful for studying on-going mental processes. Several recent studies used such eye movement measures to investigate the link between numbers and space. For instance, when participants had to perform a parity judgement, they were faster for looking to the left in response to small digits and faster for looking to the right in response to large digits (Fischer, Warlop, Hill, & Fias, 2004). When asked to fixate a central visual stimulus, merely listening to small or large numbers induced leftward or rightward ocular drifts (Myachykov, Ellis, Cangelosi, & Fischer, 2016). During random number generation, the direction of eye movements preceding the moment when the numbers were spoken out correlated with their magnitude: rightward and upward saccades were more frequent when the number produced was larger than the previous one, suggesting that eye movements might be involved in accessing the representation of the next number on an internal spatial continuum relative to the previous one (Loetscher, Bockisch, Nicholls, & Brugger, 2010). When allowed to explore their environment in a free-choice task, participants shift their gaze in a direction related to the magnitude of the numbers previously presented on screen: to the left after small-magnitude numbers and to the right after large-magnitudes ones (Ruiz Fernandez, Rahona, Hervas, Vazquez, & Ulrich, 2011). When participants were asked to count upward by steps of 3 while looking at a blank screen, their gaze was shifted rightward whereas no leftward gaze shifts were observed when counting downward, (Hartmann, Mast, & Fischer, 2016). Finally, in random number generation, observing leftward or downward gaze shifts led participants to produce smaller numbers (Grade, Lefèvre, & Pesenti, 2013), suggesting that perceiving gaze shifts also induces exogenous shifts of attention in the internal spatial representation of numbers.

Strong support that orienting spatial attention is critical for numerical processing comes from neuropsychological studies on unilateral left neglect patients. These patients are impaired in detecting, orienting to or reporting stimuli presented in their contralesional hemifield (Halligan, Fink, Marshall, & Vallar, 2003). Most of the time, the left side of space is neglected following a lesion in the right hemisphere, whereas right neglect following a lesion in the left hemisphere is less frequent (Stone, Halligan, & Greenwood, 1993). When asked to indicate the midpoint of a physical line, neglect patients tend to show a significant deviation toward ipsilesional space (e.g., Binder, Marshall, Lazar, Benjamin, & Mohr, 1992; Marshall & Halligan, 1989). While left neglect patients bisect physical lines with a deviation to the right, healthy participants often demonstrate a leftward deviation called "pseudoneglect" (e.g., Bowers & Heilman, 1980; Jewell & McCourt, 2000; Nicholls, Bradshaw, & Mattingley, 1999). Neglect also affects the imaginal space as patients fail to recall the contralesional side of mental images (e.g., Bisiach & Luzzatti, 1978; Bisiach, Luzzatti, & Perani, 1979; Ogden, 1985; Rode, Rossetti, & Boisson, 2001; for a review see Salvato, Sedda, & Bottini, 2014). However, several studies have reported a double dissociation between neglect for physical and representational space suggesting that perceptual spatial attention shifts and imaginal spatial attention shifts may rely on mechanisms at least partially distinct (e.g., Guariglia, Palermo, Piccardi, Iaria, & Incoccia, 2013). Interestingly, left neglect patients have also difficulties accessing the representation of the number just smaller than a reference in numerical comparison tasks (Masson, Pesenti, & Dormal, 2013; in press; Salillas, Granà, Juncadella, Rico, & Semenza, 2009; van Dijck, Gevers, Lafosse, & Fias, 2012; Vuilleumier, Ortigue, &

Brugger, 2004; Zorzi et al., 2012), and deviate toward larger numbers in numerical interval bisection (e.g., Cappelletti, Freeman, & Cipolotti, 2007; Hoeckner et al., 2008; Zorzi, Priftis, & Umiltà, 2002).

Neglect can be transiently improved by revalidation techniques based on bottom-up mechanisms of attention orientation throughout sensorimotor stimulation (for a review, see Kerkhoff, 2003). One of these techniques, optokinetic stimulation (hereafter OKS), consists in presenting to the patient a visual display of stimuli that is moving towards the neglected hemifield (e.g., Kerkhoff, Keller, Ritter, & Marquardt, 2006; Mattingley, Bradshaw, & Bradshaw, 1994; Pizzamiglio, Frasca, Guariglia, Incoccia, & Antonucci, 1990; Thimm et al., 2009). OKS induces an optokinetic nystagmus (OKN), an oculomotor reflex consisting in two different alternating types of movements: first, the eyes automatically follow the moving pattern (i.e., pursuit) in order to stabilize the image of the moving scene on the retina, then, when the eyes reach a certain distance from the initial position, a fast movement (i.e., saccade) in the direction opposite to the pursuit is performed. This technique orients overt attention in the direction of the movement of the display (Kerkhoff, 2003). Crucially, it has been shown that OKN affects numerical processing, possibly through internal shifts of spatial attention. In healthy participants, rightward OKS facilitated the processing of large numbers in a numerical comparison task whereas leftward OKS did not have such an effect on small number processing (Ranzini et al., 2015). This was also found when participants had to make voluntary eye movements (smooth pursuit and saccades) to the right (Ranzini, Lisi, & Zorzi, 2016). Conversely, submitting leftward OKS to left neglect patients abolished their deviation towards large numbers in numerical interval bisection whereas rightward OKS did not modulate their performance (Priftis, Pitteri, Meneghello, Umiltà, & Zorzi, 2012).

Altogether, these studies show that reflexive eye movements to the left or to the right affect number processing by facilitating the orientation of attention to the left or right side of the mental representation of numbers. Thus, perceptual attentional shifts can interact with imaginal attentional shifts by cuing part of the mental representation in internal space.

From this now well-documented association between number magnitude and attentional shifts along a mental continuum, it has been suggested that mental arithmetic could involve similar attentional shifts: solving subtraction and addition problems would imply shifting attention respectively leftward and rightward (Hubbard et al., 2005). Recent studies seem to support this suggestion. For instance, healthy children and adult participants tend to underestimate the results of subtraction and overestimate the results of addition problems (Knops, Dehaene, Berteletti, & Zorzi, 2014; Knops, Viarouge, & Dehaene, 2009a; Knops, Zitzmann, & McCrink, 2013; Lindemann & Tira, 2011; McCrink, Dehaene, & Dehaene-Lambertz, 2007; McCrink & Wynn, 2009). This effect, termed *operational momentum* (hereafter, OM), has mostly been interpreted as reflecting an attentional move that would go too far along the mental continuum (for a discussion about alternative interpretations of the OM, see Marghetis, Nunez, & Bergen 2014). Actual spatial attentional shifts were reported in a target detection task with arithmetic problems as primes (Masson & Pesenti, 2014). Participants were faster to detect a target in the left hemifield after solving a small subtraction and faster to detect a target in the right hemifield after solving a large addition. A leftward or rightward deflection in hand movements has also been shown when participants were asked to indicate by moving a mouse cursor the result of subtraction or addition problems respectively (Marghetis et al., 2014). Recently, it was reported that the orientation of eye movements while solving simple arithmetical problems was also influenced by the relative magnitude of the operands and the results (Yu et al., 2016). Moreover, brain activations elicited by solving large addition problems (e.g., 50 ± 26) resemble activations induced by rightward saccades (Knops, Thirion, Hubbard, Michel, & Dehaene, 2009b). Indeed, a classifier built to predict whether participants were solving addition or subtraction problems from the activation measured in the superior parietal cortex when their eyes shifted to the right or to the left could accurately identify addition trials, although no such precision could be obtained for subtractions. In order to determine whether these attentional shifts were part of the solving procedure, recent studies tested whether manipulating attention could influence mental arithmetic, which would thus show a bi-directional link between spatial attention and mental arithmetic. For instance, presenting interfering flickering targets on the left or right side of the screen selectively affected participants' performance in solving subtraction or addition, respectively (Masson & Pesenti, in press). It was also reported that participants were faster to solve subtraction or addition problems while performing hand movements in a congruent direction (i.e., leftward and downward or rightward and upward, respectively) than in an incongruent direction (i.e., rightward and upward or leftward and downward, respectively; Wiemers, Bekkering, & Lindemann, 2014). Congruent movements of the entire body in the horizontal (Anelli et al., 2014) or vertical plane (Lugli, Baroni, Anelli, Borghi, & Nicoletti, 2013) also facilitated counting up and down. Moreover, when presenting sequentially each terms of a problem visually at different locations, showing the second operand at the left side of the screen facilitated the solving of subtractions while presenting the second operand of the problems at the right side of the screen facilitated the solving of addition problems (Mathieu, Gourjon, Couderc, Thevenot, & Prado, 2016). Crucially, it was also reported that left neglect patients, were impaired in subtraction solving, establishing that the ability to orient attention is critical for solving the problem, possibly for accessing the representation of the answer that is located to the left or to the right relative to the first operand on a numerical continuum (Dormal, Schuller, Nihoul, Pesenti, & Andres, 2014). However, it is still unknown whether inducing automatic horizontal eye movements, and thus inducing exogenous attentional shifts, would have an impact on arithmetical solving performance in healthy participants.

The aim of this study was to investigate whether inducing reflexive horizontal eye movements with OKS, corresponding to overt attentional shifts would influence the performance of participants when solving addition and subtraction problems because perceptual attentional shifts would cue imaginal attentional shifts in mental arithmetic. We asked healthy participants to fixate the centre of a screen and to respond aloud as fast and as accurately as possible to arithmetical problems that were presented auditorily while they were submitted to OKS. We used three different OKS conditions (leftward, rightward and control) and hypothesized that inducing eye movements in the direction presumably congruent with the operation would facilitate the solving of the problem whereas inducing eye movement to the presumably incongruent direction would impair the solving. Concretely, rightward OKN would improve participants' performance for addition problem solving and/or impair subtraction solving, while leftward OKN would improve subtraction problem solving and/or impair addition problem solving. Thus, if eye movements are bi-directionally linked to mentally solving arithmetic problems, an interaction between the direction of the OKS (right or left) and the operation (addition or subtraction) on participants' performance should be observed.

Method

Participants

Twenty-one French-speaking participants (23±1.3 years-old; 11 males; 19 right-handed) gave their informed consent to participate. One participant was excluded for showing abnormal gaze patterns (no OKN detected in OKS conditions). None was aware of the objectives of the study. The experiment was non-invasive, was performed in accordance with the ethical standards established by the Declaration of Helsinki, and was approved by the Ethics Committee of the Institut de Recherche en Sciences Psychologiques of the Université catholique de Louvain.

Stimuli, task and procedure

A list of 2-digit ± 1-digit problems (Masson & Pesenti, 2014; in press) was used. The first operand (O1) was comprised between 22 and 89. Three ranges of second operand (O2) were used: small (2, 3), medium (4, 5, and 6) and large (7, 8) in order to investigate whether larger mental moves would rely more on attentional mechanism than smaller mental moves. We controlled that the same number of carry and non-carry problems was presented for addition and subtraction. This resulted in a total of 144 different problems, with 12 problems per condition (e.g., Addition/Carry/LargeO2). The mean results of the problems of each condition were equilibrated (range: 23-89; mean for addition: 58 ± 16; subtraction: 57 ± 18) such that, when conducting an analysis of variance (ANOVA) on the magnitude of the results with OPERATION (Addition; Subtraction), O2 RANGE (Small; Medium; Large), and TYPE (Carry; Non-Carry) as within-subject variables, no main effect or interaction reached significance (all *p*-values > 0.1), thus excluding the possibility that the magnitude of the problems and/or results *per se* would induce different shifts of spatial attention across operation and problem types.

OKS consisted of black and white vertical stripes (width: 2 cm; height: 15 cm) presented on a black screen and moving at a speed of 3.7°/sec to the right or to the left direction. In the control condition, stripes changed colour from black to white or white to black every 1000 ms in a way that did not induce any OKN.

Participants sat at a distance of 60 cm from the eye tracker camera and head movements were prevented by using a chin and forehead stabilizer. They were submitted to the three conditions of OKS (i.e., leftward; rightward; control) in three separate sessions held on three different days; the order of the sessions was counter-balanced across participants. A session lasted approximately 45 minutes and began with a block of OKS without arithmetical problems in order to habituate the participants to the OKS procedure. The participants were then instructed to answer aloud to the arithmetic problems that were presented and to fixate the centre of the screen while the left, right or control OKS (as a function of the condition) was displayed during 6 blocks of 24 problems. At the beginning of each block, a standard 9-point protocol was used to calibrate the participant's eye-gaze position to a display screen using standard Eye-Link software. Blink events were subtracted from the original gaze stream by the software. This allowed the computation of the actual gaze position on the screen and the measurement of the distance and velocity of eye movements.

Apparatus

A computer screen (LCD; resolution 1080x1920; refresh rate 60 Hz) was placed 70 cm away from participants and was used to display the visual stimuli. Stimulus presentation and data collection were controlled by a laptop using E-Prime software (Schneider, Eschman, & Zuccolotto, 2000). The problems were presented through headphones and an interfaced microphone recorded the latencies of the verbal responses while accuracy was assessed online by the experimenter. We also recorded participants' eye movements to control for overt shifts of attention by using an Eyelink 1000 desktop-mounted eye tracker (SR Research, Canada; sampling rate of 1000 Hz; average accuracy range 0.25° to 0.5°, gaze tracking range of 32° horizontally and 25° vertically).

Results

Gaze pattern analysis

Separate analyses were made for saccades and slow pursuit in order to assess whether OKS induced an OKN in the expected direction (see Fig. 1). The starting and ending positions of each saccade made within a block were defined. We used a velocity threshold so that eye movements faster than 22°/second were considered as saccades. Saccade deviation was then calculated by subtracting the starting position of the saccade from the ending position of the saccade. The starting and ending positions of the slow pursuit were inferred from the ending position of the current saccade and the starting position of the next saccade. Negative values indicate a leftward deviation and positive values a rightward deviation. We then averaged the mean deviation for saccades and slow pursuit within each block, for each participant. Participants made a slow pursuit movement in the direction of the OKS (rightward; 48.32±15.03 pixels; leftward: -52.66±9.57 pixels). Pursuits during rightward OKS were significantly different from pursuits recorded during the control condition (-1.83±2.65 pixels; $t(19)=15.498$, $p<.001$) and during leftward OKS ($t(19)=20.558$, $p<.001$). Moreover, pursuits consecutive to leftward OKS were also different from those recorded during the control condition (*t*(19)=24.719, *p*<.001). Pursuits in the OKS conditions were followed by fast saccades in the opposite direction (rightward: -50.78±3.66 pixels; leftward: 56.44±2.38 pixels). Saccades occurring during rightward OKS were significantly different from those occurring during leftward OKS (*t*(19)=19.516, *p*<.001). Finally, the saccades recorded during the control condition (2.44±.69 pixels) were different from both those recorded during rightward OKS (*t*(19)=15.019, *p*<.001) and leftward OKS (*t*(19)=22.452, *p*<.001).

INSERT FIG.1 ABOUT HERE

Arithmetic Performance

Error Rates (ERs)

Overall, the participants made 343 errors out of 8640 observations (mean ER = 6.09±3.97 %), which clearly depart from chance level (*t*(19)=49.467, *p*<.001). We conducted a repeated measure ANOVA on the ERs with OPERATION (Addition; Subtraction), O2 RANGE (Small; Medium; Large) and TYPE (Carry; Non-Carry) as factors. This ANOVA revealed a main effect of OPERATION (*F*(1,19)=26.538, *p*<.001; η^2_p=.583) indicating that participants made more errors for subtraction (7.36±4.61 %) than for addition (4.81±3.56 %) problems. There was also a main effect of O2 RANGE (*F*(2,38)=23.621, *p*<.001; η^2_p=.554) showing that participants were better at solving small o2 problems (3.16±2.62 %) than medium o2 problems (6.18±4.27 %; *t*(19)=5.062, *p*<.001, *d*=1.4), which were themselves better solved than large o2 problems (8.92±6.02 %; $t(19)=3.311$, $p=.04$, $d=.826$). A main effect of TYPE was also found ($F(1,19)=36.435$, $p<.001$; $\eta^2_p=.657$), participants being better at solving non-carry (2.15±1.29 %) than carry (10.02±6.84 %) problems. Finally, there was a significant interaction between O2 RANGE and TYPE ($F(2,38)=19.426$, $p<.001$; $\eta^2_p=.506$). Participants made more errors when a carry or a borrow was needed for large o2 problems (Carry: 16.6±12.01 %; Non-Carry: 1.25±1.49 %; $t(19)=5.639$, $p<.001$, $d=4.11$) and for medium o2 problems (Carry: 9.17±7.12 %; Non-Carry: 3.19±2.07 %; $t(19)=4.404$, $p<.001$; $d=1.48$), but this difference was less important for small o2 problems (Carry: 4.31±3.6 %; Non-Carry: 2.01±2.45; $t(19)=3.176$, $p=.005$, $d=.749$). There was also a significant interaction between OPERATION and TYPE ($F(1,19)=11.431$, $p=.003$, $\eta^2_p=.376$): addition problems (7.92±6.04 %) were solved more accurately than subtraction problems (12.13±8.04 %) when carrying was involved ($t(19)=4.89$, $p<.001$, $d=1.264$) but not when carrying was not involved (Addition: 1.71±1.54 %; Subtraction: 2.59±1.82 %; $t(19)=1.825$, $p=.084$, $d=.41$). No other main effect or interaction reached significance (all *p*-values >.05).

Response latencies (RLs)

Trials where the answer to the arithmetic problem was incorrect (6.09 %), or where the microphone failed to trigger (1.78 %) were removed from the RLs analyses.

A repeated-measure ANOVA on the median RLs of correctly solved problems with OPERATION (Addition; Subtraction), O2 RANGE (Small; Medium; Large) and TYPE (Carry; Non-Carry) as factors revealed a main effect of OPERATION ($F(1,19)=52.621$, $p<.001$, $\eta^2=.735$), with addition (1458±304 ms) being solved faster than subtraction (1598±353 ms) problems. A main effect of O2 RANGE ($F(2,38)=59.403$, $p<.001$,

η^2_p=.758) showed that small problems (1392±286 ms) were solved faster than medium problems (1528±358 ms; $t(19)=5.226$, $p<.001$, $d=.473$), which were solved faster than large ones (1664±353ms; $t(19)=7.595$, $p<.001$, $d=.596$). There was also a significant main effect of TYPE ($F(1,19)=75.134$, $p<.001$, $\eta^2_p=.798$), participants being slower to respond to carry problems (1812±456 ms) than to non-carry problems (1244±214 ms). There was a significant interaction between OPERATION and TYPE ($F(1,19)=16.793$, $p=.001$, $\eta^2_p=.469$). Paired sample *t*-tests revealed that there was a larger difference between operations for carry (Addition: 1698±419 ms; Subtraction: 1926±509 ms; $t(19)=6.017$, $p<.001$, $d=1.588$) than for non-carry problems (Addition: 1230±215 ms; Subtraction: 1271±220 ms; $t(19)=3.07$, $p=.006$, $d=.695$). A significant interaction between TYPE and O2 RANGE ($F(2,38)=86.209$, $p<.001$, $\eta^2_p=.819$) revealed that carry problems with large o2 (2102±532 ms) were solved more slowly than those with medium o2 (1828±510 ms; $t(19)=6.865$, $p<.001$, $d=.61$), and that medium problems were solved more slowly than small problems (1506±367 ms; $t(19)=7.102$, $p<.001$, $d=1.204$). For non-carry problems, participants responded equally fast to all ranges of problems (all *p*-values >.1). No other main effect or interaction reached significance (all *p*-values >.1).

Effect of OKS

ERs

Participants made 6.49 ± 4.78 % of errors in the control condition, 5.9 ± 3.49 % in the Rightward condition, and 5.86 ± 4.85 % in the Leftward condition. Overall, when comparing ERs, there was no significant difference between condition of OKS on the performance of the participants ($F(2,38)=.44$, $p=.647$, $\eta^2_p=.024$). For each condition, we calculated the difference between the ERs in the leftward/rightward condition and the control condition (i.e., dERs). Negative and positive dERs mean that participants were more or less accurate respectively, in the OKS conditions than in the control condition. We then conducted a repeated-measures ANOVA on the dERs with OKS CONDITION (Leftward; Rightward), OPERATION (Addition; Subtraction), O2 RANGE (Small; Medium; Large) and TYPE (Carry; Non-carry) as factors. This analysis revealed a main effect of OPERATION ($F(1,19)=9.548$, $p=.006$, $\eta^2_p=.334$) indicating that dERs were higher for additions (0.764±1.51 %) than for subtractions (-1.98±3.64 %). No other main effect or interaction reached significance (all *p*-values >.05).

INSERT FIG.2 ABOUT HERE

RLs

Overall, the mean RLs were 1525 ± 289 ms in the control condition, 1475 ± 245 ms in the Rightward condition, and 1547 ± 352 ms in the Leftward condition. No significant main effect of the OKS condition was observed for the overall performance of the participants ($F(2,38)=.543$, $p=.585$, $\eta^2_p=.028$ For each problem, we calculated the difference between the median RLs in the leftward/rightward condition and the control condition (i.e., dRLs), for each participant. Negative dRLs mean that participants were faster in the leftward/rightward condition than in the control condition. We then conducted a repeated-measures ANOVA on the median dRLs with OKS CONDITION (Leftward; Rightward), OPERATION (Addition; Subtraction), O2 RANGE (Small; Medium; Large) and TYPE (Carry; Non-carry) as factors. that revealed a significant three-way interaction between OPERATION, TYPE and OKS CONDITION (F(1,19)=6.452, p=.02, η^2_p=.254). Separate ANOVAs for carry and non-carry problems were then carried out. For carry problems, there was a significant interaction between OPERATION and CONDITION (F(1,19)=8.429, p=.009, η^2_p=.307; see Fig. 2). For additions, the dRLs with rightward OKS (-111±184 ms) was significantly different from the dRLs with leftward OKS (28±238 ms; t(19)=2.928, p=.009, d=.671), while no such difference was found between leftward (12±281ms) and rightward OKS (-25±195 ms; t(19)=.703, p=.49; d=.16) for subtractions. The dRLs of the carry problems were compared to zero in order to evaluate if there was a significant RL gain or cost of the OKS in comparison to the control condition. dRLs significantly differed from zero only in the rightward condition for additions (t(19)=2.707, p=.014, d=.603) indicating that participants were faster for solving addition problems during a rightward OKS than during the control condition. None of the other comparisons reached significance (all p-values >.5). The interaction between OPERATION and CONDITION was not significant for non-carry problems (F(1,19)=.058, ns; η^2_p=.003). No other main effect or interaction reached significance (all p-values >.1).

Discussion

A growing body of evidence suggests that the mental manipulation of numbers goes along with spatial attentional shifts (e.g., Casarotti et al., 2007; Fischer et al., 2003; Masson & Pesenti, 2014) and/or eye movements (e.g., Fischer et al., 2004; Loetscher et al., 2010; Knops et al., 2009). These findings suggest that attention orientation underlies the mental manipulation of numbers on a visuospatial medium.

Accordingly, solving subtraction and addition problems has been associated to leftward or rightward shifts of attention in several behavioural (Masson & Pesenti, 2014; in press; Mathieu et al., 2016; Werner & Raab, 2014) and neuroimaging (Knops et al., 2009a) studies. Interestingly, it has also been shown that horizontal eye movements are related to numerical processing (e.g., Grade et al., 2013; Loetscher et al., 2010; Ranzini et al., 2015; 2016) and in mental arithmetic (Knops et al., 2009; Werner & Raab, 2014). Considering mental arithmetic, it is still debated whether horizontal eye movements are part of the solving procedure for accessing the answer of the problem (Knops et al., 2009; Hartmann, Mast, & Fischer, 2015). This study aimed at investigating the impact of horizontal eye movements on calculation by inducing leftward or rightward OKN by means of leftward and rightward OKS while solving additions or subtractions.

Analysis of participants' eye movements first showed that OKS presented while the participants were calculating provoked an OKN in the expected direction, and that the control condition did not induce any gaze shift in any particular direction. Beneficial effects of OKS on neglect were reported with stimuli moving at a low velocity (i.e., less than 10°/second; Mattingley et al., 1994). The OKN elicited by OKS is thus supposed to induce shifts of spatial attention in the direction of the pursuit. For instance, in left neglect patients, leftward OKS reduced the rightward bias in physical line bisection and improved the detection of targets in the left hemispace in cancellation tasks (Kerkhoff et al., 2006). However, in healthy participants, rightward OKS was the only condition modifying the bisection point in haptic line bisection while leftward OKS had no effect (Gallace, Auvray, & Spence, 2007), suggesting that rightward OKS is more effective than leftward OKS.

It is also worth noting that the more difficult the problems were, the longer the participants took to solve them, and the higher the error rate was. Subtraction problems are usually more difficult than additions, and the magnitude of the operands as well as the need to manage carrying and borrowing are known to make the solving more difficult (Ashcraft, 1992; Campbell, 2005). The findings of the present study are thus in line with these classical effects and with our previous studies that used the same lists of problems (Masson & Pesenti, 2014; in press), showing that our sample of participants did perform the arithmetic task as expected.

Considering now the impact of the direction of OKS, our results show that when participants are submitted to rightward OKS, they are faster to solve addition problems that necessitate carrying in comparison to leftward OKS or to the control condition in which no OKN was induced. The present study extends previous findings of attentional shifts induced by arithmetic problem solving (Knops et al., 2009; Masson & Pesenti, 2014; Werner & Raab, 2014) by documenting the reverse effect, namely that shifting overt attention affects the solving procedure. Our results show thus that attention orientation mechanisms are actually functionally involved during arithmetic problem solving and are not just irrelevant by-products of it. Importantly, these results are in line with previous studies on healthy participants reporting that lateralized distractors (Masson & Pesenti, in press), lateralized presentation of the second operands (Mathieu et al., 2016) or horizontal hand movements (Wiemers et al., 2014) or of the entire body in the horizontal (Anelli et al., 2014) and vertical planes (Lugli et al., 2013) have an impact on mental arithmetic solving. With the present study, we extend these results by showing an impact of the manipulation of exogenous spatial attention through reflexive eye movements on participants' performance in solving arithmetical problems, by facilitating addition solving when eyes are forced to move to the right.

One might suggest that observing a facilitation effect only for problems involving a carrying procedure implies that the recruitment of overt attention might only be fundamental, when participants have to solve difficult problems that require more cognitive resources. However, previous studies showed that solving small arithmetical problems induced attentional shifts (Masson & Pesenti, 2014; Mathieu et al., 2016) or that problems that do not require a carry procedure rely on attentional mechanisms (Masson & Pesenti, in press). Future studies should investigate this issue.

No such facilitation was found on subtraction solving while inducing leftward OKN. It is worth noting that neuroimaging data have also shown such asymmetrical results, as solving additions was related to activations of the posterior part of the superior parietal lobule (PSPL) elicited by rightward horizontal eye movements, while no such link was observed between the activations induced by solving subtractions and by leftward eye movements (Knops et al., 2009b). It is possible that leftward OKS failed to bias attention to the left side of space despite succeeding in inducing leftward OKN. An absence of leftward attentional bias in the leftward OKS condition might explain the absence of facilitation effect on subtraction solving. Previous studies documented that healthy participants showed a natural tendency to orient attention to the left (i.e., pseudoneglect; e.g., Bowers & Heilman, 1980; Jewell & McCourt, 2000; Nicholls et al., 1999) and that sensorimotor techniques were often unsuccessful to accentuate this leftward bias (for OKS see Gallace et al., 2007; for prismatic adaptation see Berberovic & Mattingley, 2003; Colent, Pisella, Bernieri, Rode, & Rossetti, 2000; Michel et al., 2003). Thus, leftward OKS might not be a suitable technique to induce a modulation of participants' performance on subtraction solving because it does not bias attention orientation to the left in healthy participants. Moreover, our asymmetrical results fit with other studies that investigated the impact of orienting attention with OKS or prismatic adaptation on numerical processing. After wearing leftward shifting prisms supposed to orient attention to the right, healthy participants who were submitted to a numerical interval bisection task deviated their responses towards larger numbers, while rightward shifting prisms supposed to orient attention to the left had no effect on participants' responses (Loftus, Nicholls, Mattingley, & Bradhsaw, 2008). Similarly, a recent study showed that rightward OKS improved participants' performance to process large numbers in numerical comparison to a standard task whereas no such facilitation was reported for small numbers while presenting leftward OKS (Ranzini et al., 2015).

The absence of impact of OKS on subtraction solving could also be explained by the fact that subtraction solving might require mixed strategies and might thus rely less on leftward attentional shifts. In one of our previous studies (Masson & Pesenti, 2014), the size of the attentional shifts appeared smaller when using 2-digit problems (i.e., the same list as in the present study) in comparison to arithmetical facts. It is possible that the need to apply several computation steps when solving a subtraction might, in fact, weaken rather than strengthen the recruitment of visuo-spatial attentional mechanisms, and thus reduce the impact of leftward OKS. One possible computation step might be the occasional recruitment of strategies based on complementary additions (e.g., 44-7=? solved as 44=7+3+34; Campbell, 2008; Geary, Frensch, & Wiley, 1993; LeFevre, DeStefano, Penner-Wilger, & Daley, 2006), which could have diminished the facilitating effect of leftward OKS on subtraction solving since both additions and at least some subtractions would be solved with additive procedures. Future studies should investigate this suggestion by controlling the solving strategies used by participants and by contrasting participants that used complementary additions strategies with those who did not. However, it is worth noting that some other previous studies reported attentional shifts while solving both additions and subtractions (e.g., Masson & Pesenti, 2015; Mathieu et al., 2016; Wiemers et al., 2014). Considering these symmetric effect in previous studies, strategies, it might be more likely that the absence of facilitation effect for subtraction during leftward OKN in the present study can be attributed to a failure to bias attention toward the left side with OKS.

Finally, our results show that externally-induced eye movements are linked to the solving procedure for accessing the mental representation of the response of the problem on a mental continuum oriented from left to right, and support the idea that attentional shifts consecutive to mental arithmetic reported in previous studies (Knops et al., 2009; Masson & Pesenti, 2014; Werner & Raab, 2014) are more than epiphenomena. We previously suggested that arithmetic solving may require shifting attention between the representations of two numerical magnitudes (Dormal et al., 2014; Masson & Pesenti, in press). First, it would be needed to represent mentally a spatial numerical continuum centred on the first operand and the approximate location of the result. Second, according to the operation, an internal attentional shift is made towards the location of the response that is located relative to the first operand on the right side for an addition and on the left side for a subtraction. This mechanism would be recruited similarly when solving arithmetic problems and when performing numerical comparison by mapping numbers onto a mental continuum centred on the standard of comparison (Masson et al., 2013; in press; Vuilleumier et al., 2004). Therefore, attention shifts may be functionally involved whenever a numerical magnitude has to be represented mentally relative to another.

Compliance with Ethical Standards

This study was supported by grants ADi/DB/1058.2011 from the Fonds Spéciaux de Recherche of the Université catholique de Louvain (Belgium) and 1.A.057.12 from the National Fund for Scientific Research (Belgium). N.M. is a research fellow; V.D is a postdoctoral researcher and M.P. is a research associate at the National Fund for Scientific Research (Belgium).

All procedures performed in this study were in accordance with the ethical standards of the Ethics Committee of the Institut de Recherche en Sciences Psychologiques of the Université catholique de Louvain and with the 1964 Helsinki declaration and its later amendments.

Informed consent was obtained from all individual participants included in the study.

All authors declare that they have no conflict of interest.

Bibliography

Anelli, F., Lugli, L., Baroni, G., Borghi, A. M., & Nicoletti, R. (2014). Walking boosts your performance in making additions and subtractions. *Frontiers in Psychology*, 5. 10.3389/fpsyg.2014.01459

Ashcraft, M. H. (1992). Cognitive arithmetic: a review of data and theory. *Cognition*, *44*, 75-106.

Berberovic, N., & Mattingley, J. B. (2003). Effects of prismatic adaptation on judgements of spatial extent in peripersonal and extrapersonal space. *Neuropsychologia*, *41*(4), 493-503.

Binder, J., Marshall, R., Lazar, R., Benjamin, J., & Morh, J.P. (1992). Distinct syndromes of hemineglect. *Archives of Neurology*, *49* (11), 1187-1194.

Bisiach, E., & Luzzatti, C. (1978). Unilateral neglect of representational space. *Cortex, 14*(1), 129-133.

Bisiach, E., Luzzatti, C., & Perani, D. (1979). Unilateral neglect, representational schema and consciousness. *Brain*, *102*(3), 609-618.

Bonato, M., Priftis, K., Marenzi, R., & Zorzi, M. (2009). Normal and impaired reflexive orienting of attention after central nonpredictive cues. *Journal of Cognitive Neuroscience, 21* (4), 745-759.

Bowers, D., & Heilman, K. M. (1980). Pseudoneglect: effects of hemispace on a tactile line bisection task. *Neuropsychologia*, *18*(4), 491-498.

Brandt, S. A., & Stark, L. W. (1997). Spontaneous eye movements during visual imagery reflect the content of the visual scene. *Journal of Cognitive Neuroscience, 9*(1), 27-38.

Campbell, J. I. D. (2005). *Handbook of Mathematical Cognition*. New York: Psychology Press.

Campbell, J. I. D. (2008). Subtraction by addition. *Memory & Cognition, 36*(6), 1094-1102.

Cappelletti, M., Freeman, E. D., & Cipolotti, L. (2007). The middle house or the middle floor: bisecting horizontal and vertical mental number lines in neglect. *Neuropsychologia*, *45*(13), 2989–3000. doi:10.1016/j.neuropsychologia.2007.05.014

Casarotti, M., Michielin, M., Zorzi, M., & Umiltà, C. (2007). Temporal order judgment reveals how number magnitude affects visuospatial attention. *Cognition*, *102*, 101-117.

Colent, C., Pisella, L., Bernieri, C., Rode, G., & Rossetti, Y. (2000). Cognitive bias induced by visuo-motor adaptation to prisms: a simulation of unilateral neglect in normal individuals?. *Neuroreport*, *11*(9), 1899-1902.

de Vito, S., Buonocore, A., Bonnefon, J. F., & Della Sala, S. (2014). Eye movements disrupt spatial but not visual mental imagery. *Cognitive Processing*, *15*(4), 543-549.

Dehaene, S., (1992). Varieties of numerical abilities, *Cognition, 4*, 1-42.

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

Fischer, M. H., Castel, A. D., Dodd, M. D., & Pratt, J. (2003). Perceiving numbers causes shifts of spatial attention. *Nature Neuroscience, 6* (6), 555-556.

Fischer, M. H., Warlop, N., Hill, R. L., & Fias, W. (2004). Oculomotor bias induced by number perception. *Experimental Psychology, 51*(2), 91-97.

Gallace, A., Auvray, M., & Spence, C. (2007). The modulation of haptic line bisection by a visual illusion and optokinetic stimulation. *Perception, 36*(7), 1003-1018. doi:10.1068/p5457.

Geary, D. C., Frensch, P. A., & Wiley, J. G. (1993). Simple and complex mental subtraction: strategy choice and speed-of-processing differences in younger and older adults. *Psychology and aging*, *8*(2), 242.

Grade, S., Lefèvre, N., & Pesenti, M. (2013). Influence of gaze observation on random number generation. *Experimental Psychology, 60*, 122-130. doi: 10.1027/1618-3169/a000178.

Guariglia, C., Palermo, L., Piccardi, L., Iaria, G., & Incoccia, C. (2013). Neglecting the left side of a city square but not the left side of its clock: prevalence and characteristics of representational neglect. *PloS one, 8*(7), e67390.

Halligan, P. W., Fink, G. R., Marshall, J. C., & Vallar, G. (2003). Spatial cognition: evidence from visual neglect. *Trends in Cognitive Sciences*, *7*(3), 125-133.

Hartmann, M. (2015). Numbers in the eye of the beholder: What do eye movements reveal about numerical cognition?. *Cognitive processing, 16*(1), 245-248.

Hartmann, M., Mast, F.W., & Fischer, M.H. (2015). Spatial biases during mental arithmetic: evidence from eye movements on blank screen. *Frontiers in Psychology, 6*:12. Doi:10.3389/fpsyg.2015.00012

Hartmann, M., Mast., F. W., & Fischer, M. H. (in press). Counting is a spatial process: evidence from eye movements. *Psychological Research*. Doi: 10.1007/s00426-015-0722-5

Hebb, D. O. (1968). Concerning imagery. *Psychological Review*, *75*(6), 466.

Hoeckner, S. H., Moeller, K., Zauner, H., Wood, G., Haider, C., Gabner, A., & Nuerk, H. C. (2008). Impairments of the mental line for two-digits numbers in neglect. *Cortex*, *44* (4), 429-438.

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews. Neuroscience*, 6, 435-448. doi:10.1038/nrn1684

Jewell, G., & McCourt, M. E. (2000). Pseudoneglect: a review and meta-analysis of performance factors in line bisection tasks. *Neuropsychologia*,*38*(1), 93-110.

Johansson, R., Holsanova, J., & Holmqvist, K. (2006). Pictures and spoken descriptions elicit similar eye movements during mental imagery, both in light and in complete darkness. *Cognitive Science*, *30*(6), 1053-1079.

Johansson, R., & Johansson, M. (2014). Look here, eye movements play a functional role in memory retrieval. *Psychological Science*, *25*(1), 236-242.

Kerkhoff G. (2003). Modulation and rehabilitation of spatial neglect by sensory stimulation. In C. Prablanc, D. Pélisson, & Y. Rossetti (Eds), *Neural Control of Space Coding and Action Production*. Amsterdam: Elsevier, 257-271.

Kerkhoff, G., Keller, I., Ritter, V. Marquardt. C. (2006). Repetitive optokinetic stimulation induces lasting recovery from visual neglect. *Restorative Neurology and Neuroscience, 24*(4), 357-370.

Knops, A., Dehaene, S., Berteletti, I., & Zorzi, M. (2014). Can approximate mental calculation account for operational momentum in addition and subtraction? *Quarterly Journal of Experimental Psychology, 67*(8), 1541-1556.

Knops, A., Thirion, B., Hubbard, E. M., Michel, V., & Dehaene, S. (2009a). Recruitment of an area involved in eye movements during mental arithmetic. *Science, 324*, 1583-1585.

Knops, A., Viarouge, A., & Dehaene, S. (2009b). Dynamic representations underlying symbolic and nonsymbolic calculation: Evidence from the operational momentum effect. *Attention, Perception, & Psychophysics, 71* (4), 803-821.

Knops, A., Zitzmann, S. & McCrink, K. (2013). Examining the presence and determinants of operational momentum in childhood. *Frontiers in Psychology*, 4, 325. doi: 10.3389/fpsyg.2013.00325.

Laeng, B., & Teodorescu, D. S. (2002). Eye scanpaths during visual imagery reenact those of perception of the same visual scene. *Cognitive Science*,*26*(2), 207-231.

LeFevre, J. A., DeStefano, D., Penner-Wilger, M., & Daley, K. E. (2006). Selection of procedures in mental subtraction. *Canadian Journal of Experimental Psychology, 60*(3), 209.

Lindemann, O., & Tira, M. (2011). Operational momentum in numerosity production judgments of multi-digit number problems. *Journal of Psychology, 219* (1), 50-57.

Loetscher, T., Bockisch, C. J., Nicholls, M. E., & Brugger, P. (2010). Eye position predicts what number you have in mind. *Current Biology*, *20*(6), R264-R265.

Loftus, A. M., Nicholls, M. E. R., Mattingley, J. B., & Bradshaw, J. L. (2008). Left to right: Representational biases for numbers and the effect of visuomotor adaptation. *Cognition, 107*(3), 1048–1058. doi:10.1016/j.cognition.2007.09.007

Lugli, L., Baroni, G., Anelli, F., Borghi, A. M., & Nicoletti, R. (2013). Counting is easier while experiencing a congruent motion*. PloS one, 8*(5), e64500.

Marghetis, T., Nunez, R., & Bergen, B. (2014). Hand movements during exact arithmetic reveal systematic, dynamic spatial processing. *The Quarterly Journal of Experimental Psychology, 67* (8), 1579-1596.

Marshall, J. C. & Halligan, P. W. (1989). When right goes left: an investigation of line bisection in a case of visual neglect. *Cortex*, 25 (3), 503-515

Masson, N., & Pesenti, M. (2014). Attentional bias induced by solving simple and complex addition and subtraction problems. *The Quarterly Journal of Experimental Psychology, 67* (8)*,* 1514-1526.

Masson, N., & Pesenti, M. (in press). Interference of lateralized distractors on arithmetic problem solving: a functional role for attention shifts in mental calculation. *Psychological Research*. doi: 10.1007/s00426-015-0668-7

Masson, N., Pesenti, M., & Dormal, V. (2013). Spatial bias in symbolic and non-symbolic numerical comparison in neglect. *Neuropsychologia*, 51(10), 1925–32. doi:10.1016/j.neuropsychologia.2013.06.004

Masson, N., Pesenti, M. & Dormal, V. (in press), Duration and numerical estimation in right brain-damaged patients with and without neglect: Lack of support for a mental time line. *British Journal of Psychology*. doi: 10.1111/bjop.12155

Mathieu, R., Gourjon, A., Couderc, A., Thevenot, C., & Prado, J. (2016). Running the number line: Rapid shifts of attention in single-digit arithmetic. *Cognition*, *146*, 229-239.

Mattingley, J. B., Bradshaw, J. L., & Bradshaw, J. A. (1994). Horizontal visual motion modulates focal attention in left unilateral spatial neglect. *Journal of Neurology, Neurosurgery & Psychiatry, 57*(10), 1228-1235.

McCrink, K., Dehaene, S., & Dehaene-Lambertz, G. (2007). Moving along the number line: operational momentum in nonsymbolic arithmetic. *Perception and Psychophysics, 69* (8), 1324-1333.

McCrink, K., & Wynn, K. (2009). Operational momentum in large number addition and subtraction by 9-month-olds. *Journal of Experimental Child Psychology, 103* (4), 400-408.

Michel, C., Pisella, L., Halligan, P. W., Luauté, J., Rode, G., Boisson, D., & Rossetti, Y. (2003). Simulating unilateral neglect in normals using prism adaptation: implications for theory. *Neuropsychologia*, *41*(1), 25-39.

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

Nicholls, M. E., Bradshaw, J. L., & Mattingley, J. B. (1999). Free-viewing perceptual asymmetries for the judgement of brightness, numerosity and size. *Neuropsychologia*, *37*(3), 307-314.

Ogden, J. A. (1985). Anterior-posterior interhemispheric differences in the loci of lesions producing visual hemineglect. *Brain and cognition*, *4*(1), 59-75.

Pizzamiglio, L., Frasca, R., Guariglia, C., Incoccia, C., & Antonucci, G. (1990). Effect of optokinetic stimulation in patients with visual neglect. *Cortex*, *26*(4), 535-541.

Priftis, K., Pitteri, M., Meneghello, F., Umiltà, C., & Zorzi, M. (2012). Optokinetic stimulation modulates neglect for the number space: evidence from mental number interval bisection. *Frontiers in Human Neuroscience*, *6,* 23. doi: 10.3389/fnhum.2012.00023

Ranzini, M., Lisi, M., Blini, E., Pitteri, M., Treccani, B., Priftis, K., & Zorzi, M. (2015). Larger, smaller, odd or even? Task-specific effects of optokinetic stimulation on the mental number space. *Journal of Cognitive Psychology*, *27*(4), 459-470.

Ranzini, M., Lisi, M., & Zorzi, M. (2016). Voluntary eye movements direct attention on the mental number space. *Psychological Research*, *80*(3), 389-398. doi: 10.1007/s00426-015-0741-2

Rode, G., Rossetti, Y., & Boisson, D. (2001). Prism adaptation improves representational neglect. *Neuropsychologia*, *39*(11), 1250-1254.

Ruiz Fernandez, S., Rahona, J. J., Hervas, G., Vazquez, C., & Ulrich, R. (2011). Number magnitude determine gaze direction. *Cortex, 47*, 617-620.

Salillas, E., Granà, A., Juncadella, M., Rico, I., & Semenza, C. (2009). Leftward motion restores number space in neglect. *Cortex*, *45* (6), 730-737.

Salvato, G., Sedda, A., & Bottini, G. (2014). In search of the disappeared half of it: 35 years of studies on representational neglect. *Neuropsychology*, *28*(5), 706.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime user's guide*. Pittsburgh: Psychology Software Tools, Inc. doi:10.1186/1756-0381-3-1

Stone, S. P., Halligan, P. W., & Greenwood, R. J. (1993). The incidence of neglect phenomena and related disorders in patients with an acute right or left hemisphere stroke. *Age and Ageing*, *22*(1), 46–52. doi:10.1093/ageing/22.1.46

Thimm, M., Fink, G. R., Küst, J., Karbe, H., Willmes, K., & Sturm, W. (2009). Recovery from hemineglect: differential neurobiological effects of optokinetic stimulation and alertness training. *Cortex, 45*(7), 850-862.

van Dijck, J.-P., Gevers, W., Lafosse, C., & Fias, W. (2012). The heterogeneous nature of number-space interactions. *Frontiers in Human Neuroscience*, 5, 182. doi:10.3389/fnhum.2011.00182

Vuilleumier, P., Ortigue, S., & Brugger, P. (2004). The number space and neglect. *Cortex, 40* (2), 399-410. doi:10.1016/S0010-9452(08)70134-5

Walsh, V. (2003). A theory of magnitude: common cortical metrics of time, space, and quantity. *Trends in Cognitive Science, 7* (11), 483-488.

Werner, K., & Raab, M. (2014). Moving your eyes to solution: Effects of movement on the perception of problem-solving task. *The Quarterly Journal of Experimental Psychology*, *67* (8), 1571-1578.

Wiemers, M. Bekkering, H., & Lindemann, O. (2014). Spatial interferences in mental arithmetic: Evidence from the motion-arithmetic compatibility effect. *The Quarterly Journal of Experimental Psychology, 67* (8), 1557-1570.

Yu, X., Liu, J., Li, D., Liu, H., Cui, J., & Zhou, X. (2016). Dynamic mental number line in simple arithmetic. *Psychological Research*, *80*(3), 410-421. doi: 10.1007/s00426-015-0730-5

Zorzi, M., Bonato, M., Treccani, B., Scalambrin, G., Marenzi, R., & Priftis, K. (2012). Neglect impairs explicit processing of the mental number line. *Frontiers in Human Neuroscience*, 6, 125. doi: 10.3389/fnhum.2012.00125

Zorzi, M., Priftis, K., & Umiltà, C. (2002). Brain damage: neglect disrupts the mental number line. *Nature*, 417(6885), 138–139. doi:10.1038/417138a

Figure Captions:

Fig. 1 Mean horizontal gaze deviation (±S.E.) during pursuits and saccades as a function of the stimulation condition.

Fig. 2 Mean dRLS (±S.E) for leftward and rightward OKS as a function of Operation (addition *vs.* subtraction) for Carry problems. Positive/negative values indicate that participants are slower/faster in the OKS conditions than in the control condition. Asterisk indicates that addition solving was significantly accelerated by Rightward OKS in comparison to Control condition.