Title

Effects of attentional shifts along the vertical axis on number processing: an eye-tracking study with optokinetic stimulation

Authors

Arianna Felisatti[1*], Mariagrazia Ranzini[2*], Elvio Blini[3], Matteo Lisi[4], & Marco Zorzi[3,5]

These authors contributed equally to this work and are listed in alphabetical order

Affiliation

1. Department of Psychology, University of Potsdam, Germany
2. Department of Neuroscience, University of Padua, Italy
3. Department of General Psychology, University of Padua, Italy
4. Department of Psychology, University of Essex, UK
5. IRCCS San Camillo Hospital, Venice-Lido, Italy

Corresponding Author

Prof. Marco Zorzi

Department of General Psychology – University of Padua

Via Venezia 8

35131 Padova (Italy)

Email: marco.zorzi@unipd.it

Word Count: 6415 (excluding Title, Tables titles, Abstract, Figures legends and References)

Tables: 3

Figures: 4

Abstract (Word count = 252)

Previous studies suggest that associations between numbers and space are mediated by shifts of visuospatial attention along the horizontal axis. In this study, we investigated the effect of vertical shifts of overt attention, induced by optokinetic stimulation (OKS) and monitored through eye-tracking, in two tasks requiring explicit (number comparison) or implicit (parity judgment) processing of number magnitude. Participants were exposed to black-and-white stripes (OKS) that moved vertically (upward or downward) or remained static (control condition). During the OKS, participants were asked to verbally classify auditory one-digit numbers as larger/smaller than 5 (comparison task; Exp. 1) or as odd/even (parity task; Exp. 2). OKS modulated response times in both experiments. In Exp.1, downward attentional displacement increased the Magnitude effect (slower responses for large numbers) and reduced the Distance effect (slower responses for numbers close to the reference). In Exp.2, we observed a parity by magnitude interaction that was amplified by downward OKS. Moreover, eye tracking analyses revealed an influence of number processing on eye movements both in Exp. 1, with eye gaze shifting downwards during the processing of numbers 1-2 as compared to 8-9; and in Exp. 2, with leftward shifts after large even numbers (6,8) and rightward shifts after large odd numbers (7,9). These results provide evidence of bidirectional links between number and space and extend them to the vertical dimension. Moreover, they document the influence of visuo-spatial attention on processing of numerical magnitude, numerical distance and parity. Together, our findings are in line with grounded and embodied accounts of numerical cognition.

Keywords

Numerical cognition; Optokinetic stimulation; Number-space association; Spatial cognition; Visuospatial attention; Grounded cognition.

Introduction

About thirty years ago, Dehaene, Bossini and Giraux (1993) showed that participants executing parity judgments responded faster with their left hand to small numbers and with the right hand to larger numbers. This effect is known as SNARC (Spatial Numerical Association of Response Codes; for reviews, see Wood, Willmes, Nuerk, & Fischer, 2008; Toomarian, & Hubbard, 2018) and it has been taken as evidence for the human natural tendency to spatialize numbers and numerical magnitudes. The SNARC effect is considered to reflect an analogue, left-to-right oriented internal representation for number magnitudes, i.e. a mental number line (MNL; Restle, 1970), though this interpretation has been debated and alternative accounts have been proposed, based on working memory (Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006) or polarity correspondence (Proctor & Cho, 2006).

The different facets of number-space associations have been recently integrated into a theoretical framework proposing that the mental representation of numbers is built upon *grounded* (universal), *embodied* (learning-related) and *situated* (task-dependent) aspects (Fischer, 2012). This framework is in line with the idea that conceptual knowledge develops from sensorimotor experiences (see Barsalou, 2008; Matheson, & Barsalou, 2018). According to this view, the development of a spatial representation of numbers, as well as its deployment in everyday cognition, is influenced by a variety of factors that include: i) physical properties of the world (e.g., Sixtus, Lonnemann, Fischer, & Werner, 2019; Blini, Pitteri, & Zorzi, 2019); ii) biological constraints (e.g., Myachykov, Scheepers, Fischer, & Kessler, 2014; Rugani, Vallortigara, Priftis, & Regolin, 2015; Felisatti, Laubrock, Shaki, & Fischer, 2020); iii) overlearned cultural habits, such as reading and writing or finger counting direction (e.g., Dehaene et al., 1993, Exp. 7; Fischer & Brugger, 2011, Göbel, Shaki, & Fischer, 2011); iv) context-dependent factors (e.g., Bächtold, Baumüller, & Brugger, 1998; Fischer, Mills, & Shaki, 2010; Pinto, Pellegrino, Marson, Lasaponara, Cestari, & Doricchi; 2019; Wasner, Moeller, Fischer, & Nuerk, 2014). Importantly, in this context spatial attention appears an ideal process potentially capable of bridging all these heterogeneous factors, as it subserves a variety of sensorimotor processes (Hubbard, Piazza, Pinel, & Dehaene, 2005, for review). Below, we focus on previous studies that specifically related number processing to visuospatial attention.

Horizontal number-space associations and visuospatial attention

Early behavioural studies reported that the detection of left or right visual targets is facilitated when cued by small or large numbers, respectively. A phenomenon which has been termed “attentional SNARC effect” (Att-SNARC: Fischer, Castel, Dodd, & Pratt, 2003). The automaticity of this effect is, to date, strongly debated (e.g., Fattorini, Pinto, Rotondaro, & Doricchi, 2015; Galfano, Rusconi, & Umiltà, 2006; see Colling, Szűcs, De Marco, Cipora, Ulrich, Nuerk, .., & Henare, 2020, for a recent failed many-labs attempt to replicate the Att-SNARC). Nonetheless, visuospatial attention shifts triggered by number processing have been highlighted with a variety of experimental settings, such as in temporal order judgment (Casarotti, Michielin, Zorzi, & Umiltà, 2007), line bisection (De Hevia, Girelli, Vallar, 2006) or greyscale tasks (Nicholls, Loftus, & Gevers, 2008), and by electrophysiological and neuroimaging studies (Goffaux, Martin, Dormal, Goebel, & Schiltz, 2012; Pinto, Fattorini, Lasaponara, D'Onofrio, Fortunato, & Doricchi, 2018; Ranzini, Dehaene, Piazza, & Hubbard, 2009; Salillas, El Yagoubi, & Semenza, 2008).

Neuropsychological studies have found impaired number-space associations in patients with unilateral spatial neglect, a syndrome characterized by attentional deficits in the contralesional side of space following brain-damage (e.g., Aiello, Jacquin-Courtois, Merola, Ottaviani, Tomaiuolo, Bueti,.., & Doricchi, 2012; Masson, Pesenti, & Dormal, 2013; Van Dijck, Gevers, Lafosse, & Fias, 2012; Zorzi, Priftis, & Umiltà, 2002; Zorzi, Bonato, Treccani, Scalambrin, Marenzi, & Priftis, 2012; see Umiltà, Priftis, & Zorzi, 2009, for a review of earlier studies). Impairment in accessing the spatial representation of numbers in neglect patients indicates that number and space are causally linked by visuospatial attention, and it suggests that cognitive and neural mechanisms might be shared between the two domains. Neuroimaging studies, indeed, highlight the involvement of common parietal regions in number and visuospatial attention processes (e.g., Göbel, Calabria, Farnè, & Rossetti, 2006; Rusconi, Bueti, Walsh, & Butterworth, 2011; Knops, Thirion, Hubbard, Michel, & Dehaene, 2009; Simon, Mangin, Cohen, Le Bihan, & Dehaene, 2002).

However, up to now, a limited number of behavioural studies have systematically investigated the effects of manipulating the orienting of attention on number processing. For instance, Stoianov, Kramer, Umiltà and Zorzi (2008) manipulated the orienting of attention by presenting participants with left or right irrelevant spatial cues during a number task. They observed that responses to small or large numbers were facilitated by left or right spatial cues, respectively (SNIPS: Spatio-Numerical Interaction between Perception and Semantics; see also Kramer, Stoianov, Umiltà, & Zorzi, 2011). Other studies have used different techniques to manipulate the orienting of attention during number tasks, such as prismatic adaptation (e.g., Rossetti, Jacquin-Courtois, Rode, Ota, Michel, & Boisson, 2004), gaze cues (Grade, Lefèvre, & Pesenti, 2013), eye pursuit (Ranzini, Carbè, & Gevers, 2017; Ranzini, Lisi, & Zorzi, 2016), or optokinetic stimulation (Blini, Pitteri, & Zorzi, 2019; Ranzini et al., 2015). The majority of these experiments showed that inducing attentional shifts biases the concurrent processing of numerical magnitude. Overall these studies, exploiting a systematic manipulation of the orienting of attention, suggest the existence of bidirectional links between number and space. These bidirectional links, together with the neuropsychological evidence from studies on neglect patients (e.g., Zorzi et al. 2002), provide evidence for a functional role of visuospatial attention in number processes.

Vertical number-space associations and visuospatial attention

Number-space associations along the vertical axis are much less investigated than the ones along the horizontal axis. Among studies comparing SNARC effects across different axes, some have reported stronger vertical compared to horizontal number-space associations (Sixtus, Lonnemann, Fischer & Werner, 2019; Winter & Matlock, 2013); others have provided inconsistent results: vertical SNARC during parity judgments but not during magnitude comparison (Ito & Hatta, 2004), vertical SNARC only in an experimental setting where the horizontal spatial representation was inhibited (Wiemers, Bekkering, & Lindemann, 2017), or even a reversed vertical SNARC with combined hand and foot response effectors (Hartmann, Gashaj, Stahnke, & Mast, 2014). In a recent pre-registered study with a within-subject design, Aleotti, Di Girolamo, Massaccesi, and Priftis (2020) compared horizontal, vertical and sagittal SNARC effect, and found that SNARC was present in each condition with equal strength and equal costs (in terms of response latencies); nonetheless, the results suggested independence of number space-associations among the three axes. Further evidence on the vertical SNARC effect comes from neuropsychological studies: Indeed, neglect patients, when asked to place numerical values onto a vertical number line, overestimated the position of the lower middle range close to the middle point (i.e., 50; Mihulowicz, Klein, Nuerk, Willmes, & Karnath, 2015). Together, these findings suggest that previous inconsistent reports on the vertical SNARC effect might be explained by the use of heterogeneous paradigms (e.g., combination of Simon and SNARC effect: Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006; saccadic response modality: Hesse & Bremmer, 2017). A vertical spatial mapping for numbers has also been described in association to words conveying spatial information (Lachmair, Dudschig, de la Vega, & Kaup, 2014): When participants were presented with sentences expressing numbers in concrete situations (e.g., "*On New Year's Eve he drank 4 beers*": Pecher & Boot, 2011), and when magnitude stimuli consisted of sentences expressing magnitude information in verbal format (e.g., "*More runs were being scored in this game*": Sell & Kaschak, 2012).

Studies that explicitly investigated the effect of orienting attention along the vertical axis on number processing are sparse. Some experiments focused on the effect of body position or gaze position on random number generation, and reported that participants produced more small numbers when body or gaze were oriented downward as compared to upward (e.g., Hartmann, Grabherr, & Mast, 2012; Winter & Matlock, 2013). Similarly, Götz and colleagues (Götz, Böckler, & Eder, 2019) showed that observing a head oriented downward induced generation of smaller numbers as compared to a head oriented upward. Effects of body movement or gaze direction along the vertical axis extend also to mental arithmetic, showing that downward/upward movements affect the performance of addition/subtraction, respectively (Blini, Pitteri, & Zorzi, 2019; Lugli, Baroni, Anelli, Borghi, & Nicoletti, 2013; Wiemers, Bekkering, & Lindemann, 2014; but see Liu, Verguts, Li, Ling, & Chen, 2017). However, with the exception of few studies (e.g., Blini et al., 2019), the heterogeneity of paradigms - not primarily conceived to investigate the effects of visuospatial attention - prevents from drawing a clear-cut description of the effects of attentional orienting along the vertical axis on number processing. The aim of the present study was specifically to fill this gap.

The present study

In this study, we investigated the effects of vertical optokinetic stimulation (OKS) on number processing. OKS is a visuo-motor technique which allows one to manipulate attentional orienting through eye movements (for the reliance of attentional orienting on eye movements mechanisms, see the premotor theory of attention: Casarotti, Lisi, Umiltà, & Zorzi, 2012; Rizzolatti, Riggio, Dascola, & Umiltà, 1987). It consists of observing a visual stimulus (e.g., black and white stripes) which moves coherently towards a specific direction, thereby inducing a specific pattern of ocular movements, known as optokinetic nystagmus (OKN). The latter consists of an alternation of pursuit (slow eye movement phase) in the direction of the stimulation, and saccades (fast eye movement phase) in the opposite direction. During OKS, attention is driven toward the direction of the stimulation (e.g., Kerkhoff, 2003). OKS has already proved useful in order to investigate the effects of attentional orienting on number processing, specifically on neglect-related number impairment following brain damage (Priftis, Pitteri, Meneghello, Umiltà, & Zorzi, 2012, see also Salillas et al., 2009), on number magnitude processing and mental arithmetic (Blini et al., 2019; Ranzini et al., 2015). In a previous study we observed that shifts of attention along the horizontal axis, induced by leftward vs. righward OKS, modulated the processing of numerical magnitude (Ranzini et al., 2015). Specifically, we found that rightward OKS affected number processing in the number comparison task but not in the parity judgment task. The stronger impact of OKS on number comparison was interpreted according to the hypothesis that explicit magnitude processing relies on visuospatial mechanisms to a greater extent than implicit magnitude processing (e.g., Herrera, Macizo, & Semenza, 2008; Priftis, Zorzi, Meneghello, Marenzi, & Umiltà, 2006; Van Dijck, Gevers, Fias, 2009; Zorzi et al., 2012).

In the present study, participants performed two tasks requiring explicit (number comparison, Exp.1) or implicit (parity judgment, Exp.2) magnitude processing, and were concurrently exposed to three different OKS conditions: upward, downward, or static (control condition). In line with previous studies on the role of visuospatial attention in numerical cognition (Ranzini et al., 2015; Blini et al., 2019), we expected to find effects of OKS on number processing as a function of numerical magnitude (e.g., Ranzini et al., 2015; Ranzini et al. 2016). Based on recent findings about associations between small/large numbers and bottom/top space, respectively (e.g., Aleotti et al., 2020), we predicted faster responses for smaller digits during downward OKS, and for larger digits during upward OKS. Additionally, we investigated the effect of number processing on ocular movements during OKN to confirm the presence of bidirectional links between number and space, given the relevance of eye movements investigation in numerical tasks (e.g., Hartmann, Mast, & Fischer, 2015).

Method

Participants. Twenty-four healthy, right-handers adults (mean age = 24 years old, 17 females) took part in Experiment 1, and twenty-four healthy, right-handers adults (mean age = 23 years old, 18 females) took part in Experiment 2. The sample size was established in consistency with previous studies (Ranzini et al., 2015; Blini et al., 2019). All participants had normal or correct to normal vision. The study conformed with the Code of Ethics of the World Medical Associations (Declaration of Helsinki) and was approved by the Psychological Science Ethics Committee of the University of Padua.

Materials and procedure. In Experiment 1, participants were asked to classify the target number as larger or smaller than 5 (number comparison). In Experiment 2, participants were asked to verbally classify the target number as odd or even (parity judgments). Digits from 1 to 9 (w/o 5) were acoustically presented, and the participant was required to verbally respond as fast as possible by pronouncing two meaningless verbal labels ("BI" or "BO") mapped (by instructions) to the task-relevant classes (this ensured that the two labels triggered the voice-key with comparable latency; for similar procedures, see: Di Bono, Casarotti et al., 2012; Ranzini et al., 2015; Stoianov et al., 2008). Response contingencies were additionally counterbalanced between subjects. Materials and procedure were exactly the same as in Ranzini et al. (2015), except for the direction of OKS. A schematic representation of the paradigm is given in Figure 1a. In both experiments, the participants observed black-and-white stripes (OKS) during the numerical task. OKS consisted of white horizontal stripes (width: ~ 25°, height: ~ 1.4°, inter-stripe distance: ~ 1.4°) presented against a black background. OKS stripes could be static or move vertically (downward or upward), at a constant speed of 8.4 cm/s (~ 12°/s). Dynamic OKS induced optokinetic nystagmus (OKN), characterized by overt shifts of attention in the direction of the movement (Figure 1b and 1c). In both experiments, any condition consisted of 4 blocks, each starting with 8 practice trials followed by 28 experimental trials. The static condition was always the first administered. The order of the other conditions was counterbalanced between participants. The numerical tasks and the OKS stimuli were controlled by E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA) on two independent personal computers. Ocular movements were recorded via a Tobii T120 screen-based eye-tracker (Tobii Technology, Sweden). The Tobii was also used to present OKS bars through its embedded 17-inch TFT monitor using a screen resolution of 1024 x 768 pixels. Eye movements were recorded at 120 hz. Vocal RTs were collected using a microphone connected to a voice-key.

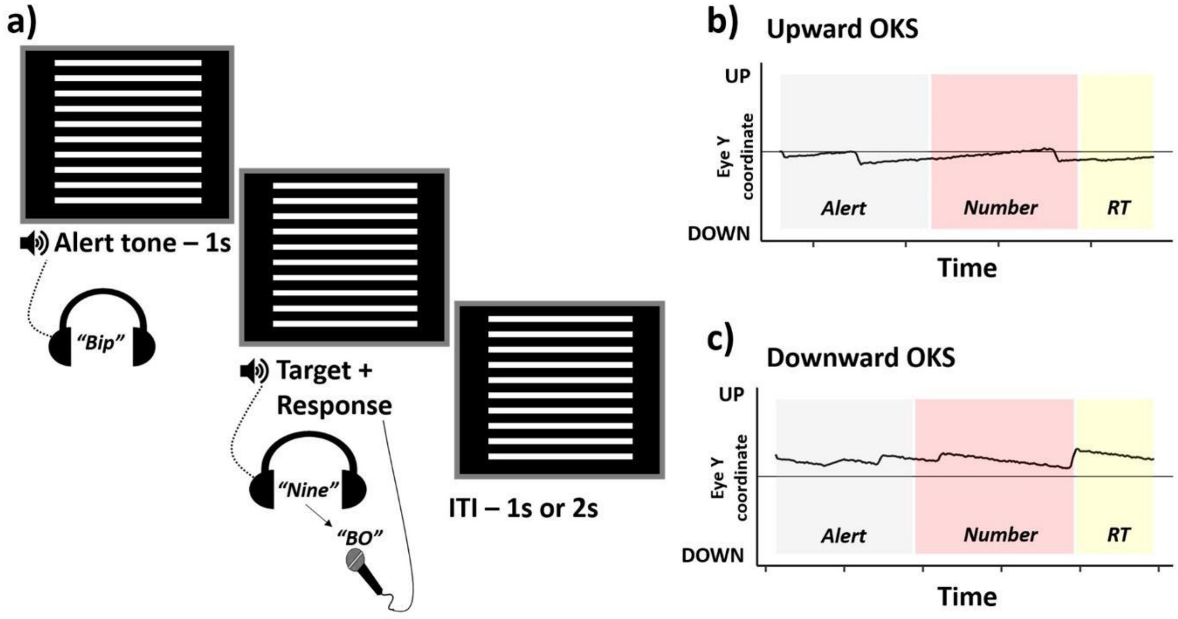

Figure 1. Panel a shows a schematic representation of the experimental procedure. After a brief alert tone, a one-digit number (range 1-9, excluding 5) was presented acoustically via stereo headphones. Participants responded using two meaningless verbal labels ("BI" or "BO") to indicate the digit's magnitude (smaller vs. larger than 5; Experiment 1) or parity (odd vs. even; Experiment 2). OKS, or the static condition, was concurrently presented during all trials. Panels b and c represent the time points of eye position along the vertical axis during OKS. OKS triggers the optokinetic nystagmus (OKN), characterized by pursuit in the direction of OKS and saccades in the opposite direction, and induces overt shifts of attention in the direction of the stripes' movement. The presence of OKN was ensured online by the experimenter, who monitored the graphic representation of the participants' ocular movements on the experimenter's screen throughout the entire session.

Data preprocessing and analyses. Trials with erroneous responses were excluded from the analyses (1% in Experiment 1 and 1% in Experiment 2). Additional trials with microphone errors (anticipations, i.e. response times < 100ms, or missed detection of the response) were excluded from the analyses (2% in Experiment 1 and 2% in Experiment 2). Finally, the response times outside 2.5 SD from the mean for each participant and OKS condition were discarded (2% in Experiment 1 and 2% in Experiment 2). To further check for possible biases on RTs induced by abnormal ocular movements, and to evaluate the robustness of our findings, we also repeated the analyses after excluding trials in which ocular movement data were recorded in less than two thirds of the relevant time period (see below).

Ocular movements analyses consisted in the analysis of gaze shifts (GS) along the X and Y axes, separately. A GS corresponds to the difference between gaze positions in subsequent time points. Specifically, for each trial, the sum of GS (in pixels) along the X and Y axes was computed throughout the time period from the onset of the target number to the onset of the response. Positive values of GS corresponded to rightward or upward shifts, and negative values corresponded to leftward or downward shifts. Trials in which eye-tracker data were available for less than two thirds of time during the relevant time window - which may be due to eye tracker errors, to gaze falling outside of the screen, or to the presence of eye blinks - were excluded (14% in Experiment 1 and 11% Experiment 2). Data from three participants in Experiment 1 and from three participants in Experiment 2 were excluded from the ocular movements analyses because they presented a large number of invalid trials in one or more experimental conditions (>75%). Mean GS were computed on a minimum of 8 trials per subject and condition in Experiment 1, and on a minimum of 12 trials (main analysis) per subject and condition in Experiment 2. On average, the mean gaze position along the horizontal axis was 16 px on the left of the screen centre (SD=6.22) in Experiment 1 and 21 px on the left of the screen centre (SD=5.15) in Experiment 2, and the mean gaze position along the vertical axis was 25 px on the bottom of the screen centre (SD=8.41) in Experiment 1 and 15 px on the bottom of the screen centre (SD=5.03) in Experiment 2: these data ensure that participants were overall actively trying to maintain the gaze position around the centre of the screen during OKS stimulation, as required by the instructions.

We used the open source software R (The R Core Team, 2021) for data analysis. Specifically, response times (RTs) and sum of GS along the X and the Y axes were analysed by means of mixed-effects multiple regression models (Baayen, Davidson, & Bates, 2008). The lme4 package (Bates, Maechler, Bolker, & Walker, 2014) and the emmeans package (Lenth & Lenth 2018) were used to fit the models and to compute the results of follow-up comparisons, respectively. The effects of OKS (static, downward, upward), Number Magnitude (small, large), and Distance from number 5 (Experiment 1: close, far) or Parity (Experiment 2: odd, even), as well as their interactions, were analysed, and entered in the models as factors.

First, we defined the best random effects matrix with a forward procedure: we started from the null model, which only included the variable Subject as random intercept, and then systematically added random slopes; random slopes for the two- or three-way interactions were also tested, but only if the corresponding lower-level slopes were previously selected and retained in the model. Random slopes were entered in the models in the following order: the experimental variable of interest as first (OKS), the numerical variable explicitly processed in the task (Exp.1: Magnitude; Exp.2: Parity), and finally the numerical variable implicitly processed (Exp1.: Distance; Exp.2: Magnitude). Each model was compared with the next, and the model with the lower deviance following a significant likelihood ratio test (LRT) was retained. For a more detailed description of this pipeline, see Blini et al., (Blini, Tilikete, Farne’, & Hadj-Bouziane, 2018). In this phase, models presenting fitting problems (e.g., failure in convergence) were systematically excluded, as to avoid overfitting. Once selected the random effects, we assessed the fixed effects, for each experiment (number comparison, parity judgment) and dependent variables (RTs; RTs excluding trials and participants on the bases of a more stringent threshold for ocular movements correction; GS along the X axis; GS along the Y axis). P-values for the main effects and interactions were obtained using Type II LRT; follow-up t-tests were based on estimated marginal means (Lenth & Lenth, 2018), and Tukey correction was applied to p values when warranted by the multiplicity of the performed comparisons.

Results

Experiment 1 - Magnitude Comparison

Response times. The final model resulting from the selection procedure described above included OKS and Number Magnitude as random slopes. The effect of Magnitude was significant ($X^2_{(1)}$ = 6.5, p=.011), indicating faster responses for small (M=964ms, SEM=28) than large numbers (M=980ms, SEM=28). The effect of Distance was also significant, ($X^2_{(1)}$ = 432.5, p<.0001), indicating faster responses for far (M=948ms, SEM=28) than for close numbers (M=996ms, SEM=27). Magnitude interacted with Distance ($X^2_{(1)}$ = 20.6, p<.0001), as displayed in Figure 3a. This interaction resulted in an asymmetric distance effect, characterized by faster responses for small-close numbers as compared to large-close ones (small-close: M=983, SEM=28; large-close: M=1009, SEM=27; (|z| = 4.04, p=.0001). On the contrary, no difference was found between RTs for small-far and large-far numbers (small-far: M=945, SEM=29; large-far: M=950, SEM=28; p>.05). As predicted, Magnitude interacted with OKS ($X^2_{(2)}$ = 6.8, p=.033), as displayed in Figure 2b. The Magnitude effect was significant in the downward OKS condition (|z| = 2.59, p=.010) and in the static OKS condition (|z| = 3.13, p=.002), but not in the upward one (|z| =1.03, p>.05). Follow-up comparisons contrasting the OKS conditions within each Magnitude condition revealed that small digits were processed slower in the upward OKS condition as compared to the static one (|z| = 2.54, p=.030). Interestingly, the distance effect also interacted with OKS ($X^2_{(2)}$ = 6.2, p=.044). Additional planned comparisons revealed that the distance effect was significant in each OKS condition (all |z| > 10.00, all p<.0001), however visibly smaller in the downward condition and larger in the upward one (|z|= 2.50, p= 0.013; Figure 3c). Table 1 lists the mean RTs and SEM for each condition resulting from the combination of Distance and OKS. No other main effects or interactions reached significance (p>.05). This pattern of results was unchanged when excluding data based on missing eye-tracking recording (see the Data preprocessing and Analyses subsection for details), except for the interaction between Magnitude and OKS which was no longer significant (p=.11).

To deeper investigate the effect of OKS on numerical distance, we performed an exploratory analysis. Specifically, we computed differential RTs (dRTs; the difference of RTs in the upward OKS condition minus RTs in the downward OKS condition) for each number distance (distances 1-4) and participants. In this way, positive values correspond to faster RTs during downward OKS, while negative values correspond to faster RTs during upward OKS. For each participant, we computed a linear regression on dRTs including Distance as predictor in order to measure at a fine-grained level the impact of OKS on number comparison: the more negative the slope, the larger the impact of OKS as a function of number distance. We compared the slopes for Distance against 0, confirming the presence of a Distance by OKS effect (slope= -6.14; t(23)=-2.8, p=.006, one tailed, d=-1.16, 95% CI [-2.03, -0.27]). The impact of OKS condition decreased with increasing numerical distance, as shown in Figure 2c. The number of participants presenting the effect in the mean direction (negative slope, N=17) was more than twice the number of participants presenting the effect in the opposite direction (positive slope, N=7; Figure 2d). The same analysis on the individual intercepts did not reveal a significant effect (t-test vs. 0: p>.05).

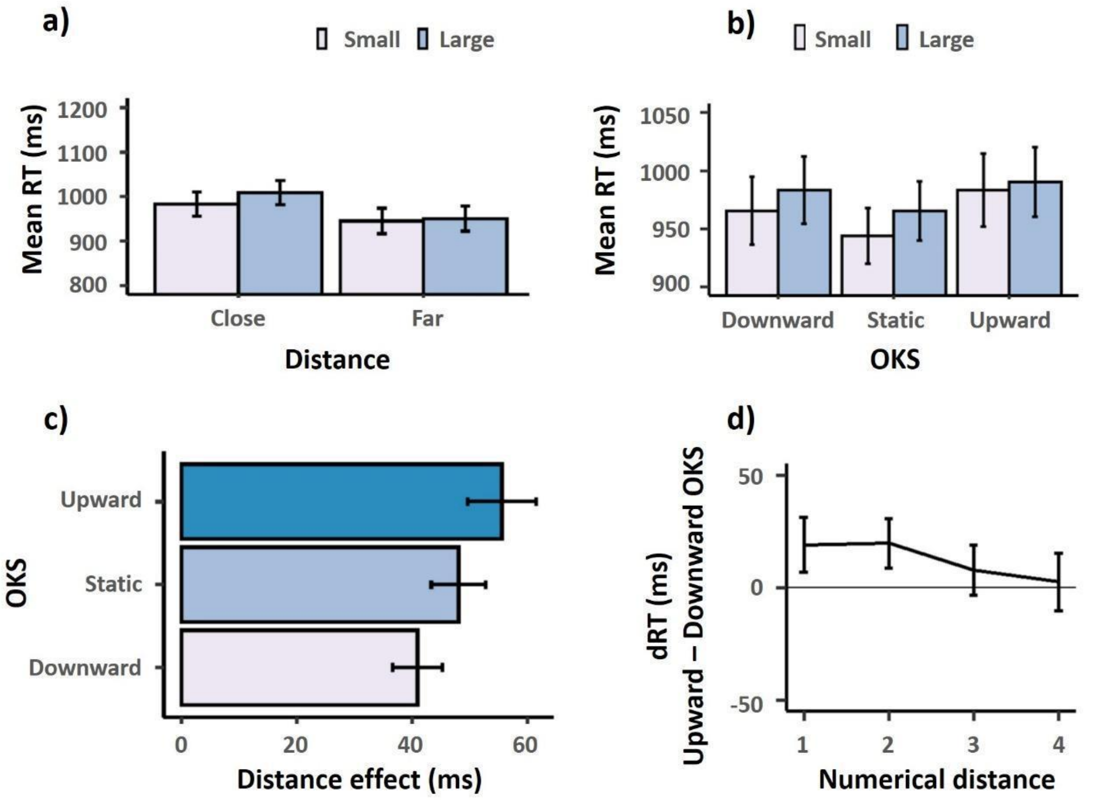

Figure 2. Panel a: Mean response times as a function of Number Magnitude and Distance. **Panel b:** Interaction between Number Magnitude and OKS. **Panel c:** The interaction between Number Magnitude and Distance (*Close numerical distance – Far numerical distance)* is plotted for each OKS condition. **Panel d:** within-subject differences in reaction times between upward and downward OKS conditions as a function of Distance. In panels a-c error bars represent SEM.

Table 1

OKS	Distance	Mean (ms)	SEM
Upward	Close	1015	30
	Far	959	31
Static	Close	979	24
	Far	931	25
Downward	Close	995	28
	Far	954	30

Table 1. M and SEM for each condition resulting from the combination of Distance and OKS in Experiment 2.

Ocular Movements along the X axis**.** The final model included Numerical Magnitude and OKS as random slopes. No significant main effects or interactions were found (all p>.05); Among these, the main effect of Magnitude approached significance (p=.08), with small digits shifting ocular movements toward the left (-1.49px (-0.0748°), SEM=1.26) and large digits shifting ocular movements toward the right (3.65px (0.1834°), SEM=2.67).

Ocular Movements along the Y axis**.** The final model included OKS as a random slope. The Magnitude effect was significant ($X^2_{(1)}$ = 6.85, p=.009) indicating larger GS in the downward direction for small numbers (M=-9px (0.45°), SEM=6) as compared to large numbers (M=-3 px (0.15°), SEM=6). The interaction between Magnitude and OKS was also significant, ($X^2_{(2)}$ = 6.13, p=.047), indicating that the effect of magnitude was significant only during downward OKS (|z| = 3.28, p=.001); nonetheless, the direction of the effect was the same in the upward condition.

To further investigate the effect of Number Magnitude on vertical gaze shifts, we performed an additional exploratory analysis. Specifically, we computed for each participant a linear regression on mean GS including Number as predictor (1-9 w/o 5): the more positive the slope, the larger the impact of Number Magnitude. We compared the slopes for Number against 0, confirming the presence of a Magnitude effect (slope= 1.52; t(20)=2.9, p=.005, one tailed, d=1.27, 95% CI [0.30, 2.22]): increasing numerical magnitude was associated to decreasing GS shift (Figure 3). The number of participants presenting the effect in this direction (positive slope, N=15) was three times the number of participants presenting the effect in the opposite direction (negative slope, N=5). The same analysis on the individual intercepts did not reveal a significant effect (t-test vs. 0: p>.05).

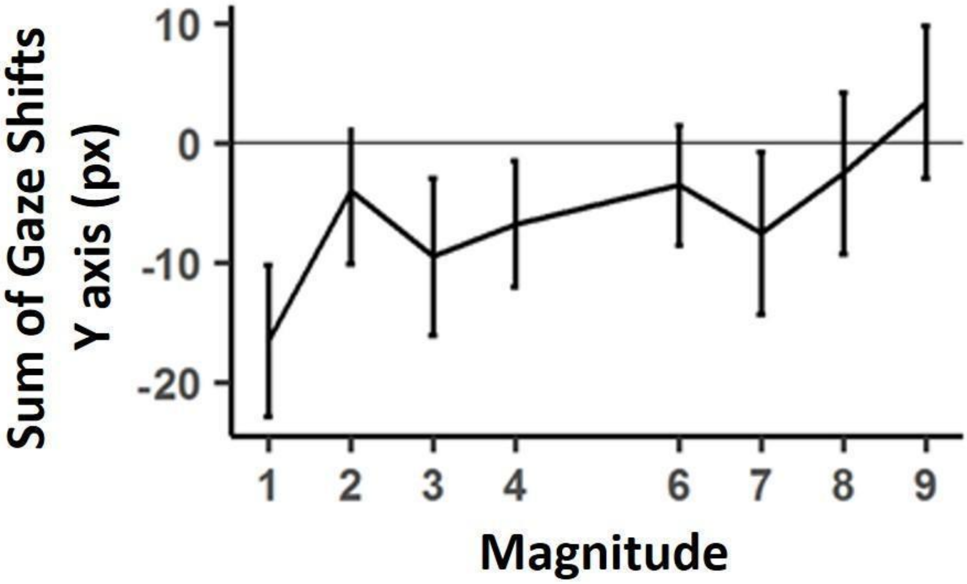

Figure 3. Mean sum of gaze shifts (GS) as a function of number magnitude. Error bars represent SEM. Positive values indicate gaze shifts upward while negative values indicate gaze shifts downward.

Results: Experiment 2 - Parity Judgment

Response times. The final model resulting from the selection procedure described above included OKS and Parity as random slopes. The Magnitude effect was significant ($X^2_{(1)}$ = 36.2, p<.0001) indicating faster responses for small (M=1029ms, SEM=35) than for large numbers (M=1048ms, SEM=34). The interaction between Magnitude and Parity was significant ($X^2_{(1)}$ = 88.4, p<.0001). Specifically, small odd digits were processed faster than large odd ones (|z| = 10.88, p<.0001), while the reverse pattern was true for even digits (|z| = 2.36, p=.018), as displayed in Figure 4a. Furthermore, the three-way interaction between Magnitude, Parity and OKS was significant ($X^2_{(2)}$ = 14.96, p=.0005). Table 2 lists the mean response RTs and SEM for each condition resulting from the combination of the three interacting factors. Additional follow-up comparisons revealed that RTs for small-odd and large-odd numbers were significantly different in each OKS condition (all |z| > 5.00, all p<.0001), while RTs for small-even and large-even numbers were significantly different only during downward OKS (|z| = 4.03, p=.0001). Another way to look at the triple interaction is to measure the size of the interaction between Magnitude and Parity in each OKS condition: as depicted in Figure 4b, the interaction between Parity and Magnitude was visibly larger in the downward condition with respect to both upward (|z| = 2.98, p=.0028) and static (|z| = 3.62, p=.0003) OKS, with no differences between the latter two (|z| = 0.66, p>.05). No other main effects or interactions reached significance (p>.05). The pattern of results remained unchanged even after exclusion of data related to abnormal gaze positions (see the Data preprocessing and Analyses subsections for details).

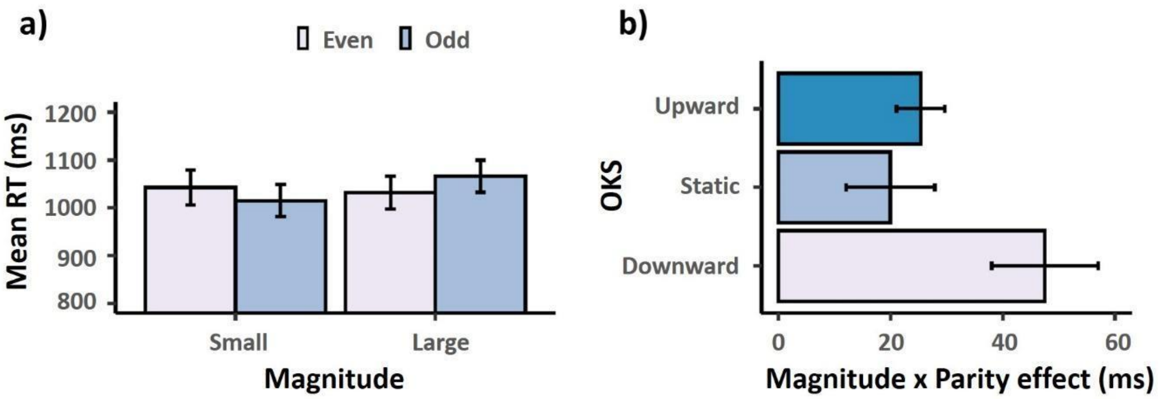

Figure 4. Panel a: Mean response times as a function of Parity and Number Magnitude. **Panel b:** The interaction between Number Magnitude and Parity *(Small Even – Small Odd) + (Large Odd – Large Even) / 2* plotted for each OKS condition.

Table 2

OKS	Magnitude	Parity	Mean (ms)	SEM
Upward	**Small**	**Odd**	**1007**	**34**
		Even	**1036**	**35**
	Large	**Odd**	**1053**	**32**
		Even	**1033**	**37**
Static	**Small**	**Odd**	**1015**	**34**
		Even	**1030**	**37**
	Large	**Odd**	**1056**	**33**
		Even	**1033**	**33**
Downward	**Small**	**Odd**	**1025**	**35**
		Even	**1059**	**40**
	Large	**Odd**	**1088**	**37**
		Even	**1028**	**35**

Table 2. M and SEM of RTs for each condition resulting from the combination of the three interacting factors in Experiment 1.

Ocular Movements along the X axis. The final model included OKS and Parity as random slopes. The Parity effect was significant ($X^2_{(1)}$ = 5.6, p=.018), indicating larger leftward shifts when processing even numbers (M=-4.87px (-0.24°), SEM=5.23) as compared to odd ones (M=-0.81px (-0.04°), SEM=3.79). Also, the interaction between Number Magnitude and Parity was significant ($X^2_{(1)}$ = 6.15, p=.013). Specifically, the Parity effect (odd vs. even digits) was present for large digits (even numbers: M=-6.20px (-0.31°), SEM=5.36; odd numbers: M=0.93px (0.04°), SEM=3.61; |z| = 3.43, p=.0006), but not for small ones (even numbers: M=-3.54px (-0.17°), SEM=5.13; odd numbers: M=-2.54px (-0.12°), SEM= 3.96; p>.05). Furthermore, the interaction between Number Magnitude and OKS was significant ($X^2_{(1)}$ = 8.00, p=.018: in the upward OKS condition, when compared to the static one, the magnitude effect was larger (small numbers being associated with leftward GS and large numbers with rightward GS; |z| = 2.77, p=.0055). However, this two-way interaction was further qualified by the three-way interaction between Number Magnitude, Parity and OKS ($X^2_{(2)}$ = 7.69, p=.021). Table 3 lists the mean GS and SEM for each condition resulting from the combination of the three interacting factors. Additional planned comparisons contrasting odd and even numbers within each Number Magnitude and OKS condition revealed a significant difference in the static OKS condition with large numbers (|z| = 4.04, p=.0001). No other main effects or interactions were significant (p>.05).

Table 3

OKS	Magnitude	Parity	Mean (px)	SEM
Upward	Small	Odd	-5.16 (-0.25°)	2.48
		Even	-5.03 (-0.25°)	2.94
	Large	Odd	0.332 (0.01°)	1.90
		Even	-2.06 (-0.10°)	3.16
Static	Small	Odd	2.25 (0.11°)	4.48
		Even	5.28 (0.26°)	5.66
	Large	Odd	5.88 (0.29°)	5.16
		Even	-6.34 (-0.31°)	6.30
Downward	Small	Odd	4.72 (0.23°)	4.54
		Even	-10.9 (-0.54°)	5.84
	Large	Odd	-3.42 (-0.17°)	2.82
		Even	-10.2 (-0.51°)	6.13

Table 3. M and SEM of GS along the X axis for each condition resulting from the combination of the three interacting factors in Experiment 1.

Ocular Movements along the Y axis. The final model included only the random intercept for participants. No significant main effects or interactions were found (all p>.05).

General discussion

In this study, we investigated the effects of overt attentional orienting along the vertical axis on explicit (Experiment 1: number comparison) and implicit (Experiment 2: parity judgment) processing of number magnitude. The attentional shifts were induced by OKS and monitored through eye-tracking. OKS consisted of horizontal lines endowed with a coherent movement, upward or downward. We hypothesized bidirectional links between attentional orienting and number processing in light of the scaffolding role of visuo-spatial attention in the high level processes involved in numerical cognition (Hartmann et al., 2012; Loetscher, Schwarz, Schubiger, & Brugger, 2008; Winter, Matlock, Shaki, & Fischer, 2015; Kramer et al., 2011; Gallagher, Arshad & Ferrè, 2019; Ranzini et al., 2015; Ranzini et al., 2016; Blini et al. 2013). We further hypothesized a stronger (if not selective) impact of OKS in tasks that involve explicit processing of numerical magnitude (number comparison, Exp.1), as opposed to tasks where numerical magnitude is implicitly activated (parity judgement, Exp. 2; see: Herrera et al., 2008; Van Dijck et al., 2009; Zorzi et al., 2012). Finally, we expected association of small numbers with the bottom part of space and large numbers with the top part of space, based on the grounding role of physical properties of the world in mapping numbers onto space (Lindemann & Fischer, 2015; Aleotti et al., 2020). Our results confirm and extend previous findings (Ranzini et al., 2015; Blini et al., 2019), showing that mechanisms of attentional orienting along the vertical axis are involved in number processing in both tasks. Below we discuss our main findings, organized by experiment.

Vertical displacement of attention and numerical distance in Number comparison

In the magnitude comparison task (Experiment 1), we found an influence of attentional orienting on number processing. First, we found that visuo-spatial attention influences the processing of numerical magnitude, in keeping with previous studies (Stoianov et al., 2008; Ranzini et al., 2015; Ranzini et al., 2016), and that this influence is also conveyed by stimulating the vertical dimension. Indeed, downward OKS led to facilitation for small numbers when compared to the upward OKS condition. This is in line with our starting hypothesis, based on previous studies on number-space mapping along the vertical axis (e.g., Aleotti et al., 2020). However, this first result should be taken with caution because, while it is the natural prediction stemming from a number of previous studies, it did not hold up in the supplementary analysis that excluded data related to abnormal gaze positions.

On the other hand, we also found, for the first time, that attentional shifts along the vertical axis modulated the processing of numerical distance. This effect was robust across analyses and indicates that downward OKS decreases the classic distance effect, namely the tendency to respond faster to numbers far vs. close to the reference. If we consider that the distance effect in number comparison is commonly interpreted as evidence of semantic processing of number magnitude (Moyer & Landauer, 1967), the impact of vertical OKS on this phenomenon is coherent with previous neuropsychological findings. Indeed, attentional deficit in patients with unilateral spatial neglect has been consistently associated with abnormal distance effect in number tasks. Specifically, previous studies observed that patients suffering from left neglect following right brain damage are selectively impaired in processing the number immediately preceding the reference number during number comparison: For instance, they are slower in responding to number 4 with respect to number 6, while comparing numbers against 5 (Salillas, Granà, Juncadella, Rico, & Semenza, 2009; Vuilleumier, Ortigue, & Brugger, 2004; Zorzi et al., 2012). Interestingly, this impairment is independent of numerical magnitude, varying as a function of the reference: Indeed, when asked to compare digits against 7, left neglect patients show difficulties in processing the number 6, while performance to the number 4 remains within a normal range. Perceiving leftward motion leads patients to restore a normal representation of number distances (Salillas et al., 2009), further confirming that visuospatial attentional orienting plays an important role in number processing.

Neuroimaging studies corroborate neuropsychological research showing the influence of orienting mechanisms in the mental representation of numerical distance. For instance, Göbel and colleagues (Göbel et al., 2006) applied repetitive transcranial magnetic stimulation (rTMS) on parietal areas involved in visuospatial search and observed a modulation of number comparison performance that has similarities with the pattern shown by neglect patients. Taken together, these findings indicate that numbers are not mapped onto an absolute spatial representation; instead, spatial orienting appears to be a mechanism which permits to navigate through a variable, task-dependent, mental number line.

Finally, the results from Experiment 1 further support the idea that number and space are linked bidirectionally, showing that number magnitude in turn influences attentional orienting along the vertical axis. Specifically, eye movements revealed association of small/large numbers with bottom/top space, respectively, suggesting attentional shifts in the direction predicted by the vertical SNARC effect (e.g., Aleotti et al., 2020; Ito & Hatta, 2004; Sixtus et al., 2019; Winter & Matlock, 2013). This is in line with our starting hypothesis, and fits with the *hierarchical view* of spatial-numerical associations (Fischer, 2012), according to which, grounded aspects (e.g., physical properties of the world) contribute to the development of a mental representation of numbers primarily along the vertical dimension (see Blini et al., 2019, for discussion).

Vertical displacement of attention and numerical magnitude in Parity judgement

In the parity judgment task (Experiment 2), we found an interaction between Number magnitude and Parity. Specifically, the Magnitude effect, i.e., faster responses for small than large numbers, emerged with odd numbers and not with even ones. Interestingly, although this trend was observed across all OKS conditions, the triple interaction with OKS direction (static/upward/downward) revealed that downward displacement of attention significantly amplified the interplay between Number magnitude and Parity. Influence of Parity on Number magnitude has been previously documented (Nuerk, Iversen, & Willmes, 2004; Krajcsi, Lengyel, & Laczkó, 2018). In contrast with our findings, Nuerk and colleagues (2004) reported longer RTs for small-odd rather than for small-even numbers and a stronger SNARC effect for odd numbers (i.e., associations between 1 and 3 with left response side and 7 and 9 with right response side). More recently, Krajcsi et al. (2018) found the opposite pattern, highlighting the heterogeneity of this interference.

It has been suggested that the parity judgement task relies more on a linguistic-conceptual representation of numbers rather than on a visuo-spatial one (e.g., Van Dijck et al., 2009). The *Markedness of Response Codes* (MARC; Willmes & Iversen, 1995; Nuerk et al., 2004; Cipora, Soltanlou, Reips, & Nuerk, 2019) effect is an example of the role of verbal processing in numerical cognition. The MARC effect consists of faster responses to odd/even numbers with left-/right-sided buttons, respectively. One likely explanation is provided by the *polarity correspondence account* (Proctor & Cho, 2006), postulating that opposite concepts such as odd/even and left/right are naturally marked as positive or negative, based on some relevant factors (e.g., frequency; see Cipora et al., 2019, for a recent discussion on the MARC effect). Specifically, even numbers and the right side of space are naturally labelled as positive, whereas odd numbers and the left side of space are labelled as negative. In the present study, the Parity by Number magnitude interaction might be explained in terms of polarity correspondence. Indeed, there is an overlap between the polarity of small and odd (negative) concepts on the one hand, and the polarity of large and even (positive) concepts on the other hand. This correspondence and the subsequent behavioral effects are largely implicit in nature, as magnitude is not a task-relevant dimension in parity judgments; it is also worth stressing that, in our experiment, there was no left/right dimension occurring in the response space, as participants performed the task by using meaningless verbal labels (as in Di Bono et al., 2012; Ranzini et al., 2015; Stoianov et al., 2008). Yet, OKS qualified the interaction between parity and magnitude so that responses became slower for even-small numbers (2,4) and for odd-large numbers (7,9) during downward OKS (see Table 1). Thus, this triple interaction might be triggered by mechanisms of (spatial) inhibition of the usual polarity mappings, or alternatively by mechanisms beyond the polarity correspondence account (see, e.g., Casasanto, 2009).

Finally, also the results from Experiment 2 support the idea that number and space are linked bidirectionally, showing that parity influences attentional orienting along the horizontal axis. Specifically, larger leftward eye movements after even numbers and rightward after odd numbers revealed the presence of the Parity effect with opposite direction to that implied by the MARC effect. The significant interaction between Parity and Number magnitude indicated that this pattern was reliable only for large numbers: “6” and “8” led to leftward gaze displacement, while “7” and “9” led to rightward shifts. The triple interaction between Parity, Number magnitude and OKS was also significant, however planned comparisons did not permit to unveil the nature of this effect. Future studies are necessary to clarify the reliability of the observed, previously unsuspected, bidirectional links between spatial orienting and number processes in the parity task, besides investigating the underlying mechanisms.

Embodied Cognition as unifying framework

Our results can be interpreted in light of the Embodied cognition framework (Barsalou 2008; Matheson & Barsalou, 2018; Fischer, 2012). According to this view, physical properties of the world (e.g., gravity law, direction of growing, etc.) together with embodied constraints (e.g., human visual system, human hand motor system, etc.) and sensorimotor experiences (e.g., reading and writing habits, use of the computer mouse, etc.) modulate the orienting of attention and sensorimotor processes, allowing the development over time of a strong association between numbers and space (e.g., Fischer, 2012).

It has been argued that the influence of vertical attentional orienting on number representation is stronger and deeper than the influence of horizontal orienting (e.g., Blini et al., 2019), being more grounded on physical properties of the world. Our findings, together with the results of previous studies (Ranzini et al., 2015; 2016), suggest the existence of qualitative – rather than quantitative – differences between vertical and horizontal mental number lines. Indeed, the different effects of OKS on number comparison and parity judgment confirm that these two tasks require - at least partially - different mechanisms (e.g., Herrera et al., 2008; Van Dijck et al., 2009), with number comparison tapping primarily on visuospatial processes and parity judgment on verbal mechanisms. Nonetheless, importantly, attentional orienting along the vertical axis operates on numbers - and it is triggered by numbers - in both tasks.

We suggest that both egocentric (in relation to the own body) and geocentric (in relation to the ground) reference frames contribute to the development of mental representation of numbers (Wiemers et al., 2017). An intriguing hypothesis to probe with future studies postulates that grounded factors (e.g., gravity law leading to vertical mapping) might characterize the impact of space on numbers, while in the case of numbers acting on space this link would be less systematic (e.g., Aleotti et al., 2020).

Conclusion

To conclude, we have shown the presence of bidirectional links between number and vertical space, extending the idea of a crucial role of attentional orienting on the vertical number-space (see also Blini et al., 2019). The present study highlights the suitability of the OKS technique to explore visuospatial attentional mechanisms in relation to cognitive processes. Importantly, both attention and eye movements are consistently embedded into body movements, impacting the processing of numerical information (e.g., eye movements: Loetscher, Bockisch, Nicholls, & Brugger, 2010; head movements: Götz et al., 2019; hand movements: Gianelli, Ranzini, Marzocchi, Micheli, & Borghi, 2012; Anobile, Arrighi, Togoli, & Burr, 2016; body movements: Lugli et al., 2013). The tight link between attentional orienting and gaze shifts (Rizzolatti et al., 1987) strengthen the relevance of theoretical approaches which consider the importance of sensorimotor experiences in cognitive processes (Barsalou, 2008).

Availability of data: Data are publicly available at https://osf.io/nc7jz/?view_only=91bb26db5fe94a7594bb3d1dcbc33f83

Authors' contributions: Marco Zorzi: Conceptualization, Supervision, Writing - Review & Editing; **Arianna Felisatti:** Methodology, Investigation, Data Curation, Formal analysis, Writing - Original Draft, Writing- Review & Editing, Project administration; **Mariagrazia Ranzini:** Data Curation, Formal analysis, Writing - Original Draft, Writing- Review & Editing; **Elvio Blini:** Methodology, Data Curation, Formal analysis, Writing- Review & Editing; **Matteo Lisi:** Software, Writing- Review & Editing.

Acknowledgements

This study was carried out within the scope of the research program Dipartimenti di Eccellenza (art.1, commi 314-337 legge 232/2016), which was supported by a grant from MIUR to the Department of General Psychology, University of Padua. MR is funded by the European Union's Horizon 2020 research and innovation program under Marie Skłodowska-Curie Grant 839394. The authors thank Leandro Cenesi for help in data collection.

References

Aiello, M., Jacquin-Courtois, S., Merola, S., Ottaviani, T., Tomaiuolo, F., Bueti, D., ... & Doricchi, F. (2012). No inherent left and right side in human ‘mental number line’: evidence from right brain damage. *Brain, 135(8)*, 2492-2505.

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

Anobile, G., Arrighi, R., Togoli, I., & Burr, D. C. (2016). A shared numerical representation for action and perception. Elife, 5, e16161.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of memory and language*, *59*(4), 390-412.

Bächtold, D., Baumüller, M., & Brugger, P. (1998). Stimulus-response compatibility in representational space. *Neuropsychologia, 36(8)*, 731-735.

Barsalou, L. W. (2008). Grounded cognition. *Annu. Rev. Psychol., 59*, 617-645.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. *arXiv preprint arXiv:1406.5823*.

Blini, E., Cattaneo, Z., & Vallar, G. (2013). Different effects of numerical magnitude on visual and proprioceptive reference frames. *Frontiers in Psychology*, *4*, 190.

Blini, E., Pitteri, M., & Zorzi, M. (2019). Spatial grounding of symbolic arithmetic: an investigation with optokinetic stimulation. *Psychological research, 83(1)*, 64-83.

Blini, E., Tilikete, C., Farnè, A., & Hadj-Bouziane, F. (2018). Probing the role of the vestibular system in motivation and reward-based attention. *Cortex*, *103*, 82-99.

Casarotti, M., Lisi, M., Umiltà, C., & Zorzi, M. (2012). Paying attention through eye movements: a computational investigation of the premotor theory of spatial attention. *Journal of Cognitive Neuroscience, 24(7)*, 1519-1531.

Casarotti, M., Michielin, M., Zorzi, M., & Umiltà, C. (2007). Temporal order judgment reveals how number magnitude affects visuospatial attention. *Cognition, 102(1)*, 101-117.

Casasanto, D. (2009). Embodiment of abstract concepts: good and bad in right-and left-handers. *Journal of Experimental Psychology: General*, *138*(3), 351.

Colling, L. J., Szűcs, D., De Marco, D., Cipora, K., Ulrich, R., Nuerk, H. C., ... & Henare, D. T. (2020). Registered Replication Report on Fischer, Castel, Dodd, and Pratt (2003). Advances in Methods and Practices in Psychological Science, 2515245920903079.

De Hevia, M. D., Girelli, L., & Vallar, G. (2006). Numbers and space: a cognitive illusion?. *Experimental brain research, 168(1-2)*, 254-264.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General, 122(3)*, 371.

Di Bono, M. G., Casarotti, M., Priftis, K., Gava, L., Umiltà, C., & Zorzi, M. (2012). Priming the mental time line. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(4), 838.

Fattorini, E., Pinto, M., Rotondaro, F., & Doricchi, F. (2015). Perceiving numbers does not cause automatic shifts of spatial attention. *Cortex, 73*, 298-316.

Felisatti, A., Laubrock, J., Shaki, S., & Fischer, M. H. (2020). A biological foundation for spatial–numerical associations: the brain's asymmetric frequency tuning. *Annals of the New York Academy of Sciences*, *1477*(1), 44-53.

Fischer, M. H. (2012). A hierarchical view of grounded, embodied, and situated numerical cognition. *Cognitive processing, 13(1)*, 161-164.

Fischer, M. H., & Brugger, P. (2011). When digits help digits: spatial–numerical associations point to finger counting as prime example of embodied cognition. *Frontiers in psychology, 2*, 260.

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

Fischer, M. H., Mills, R. A., & Shaki, S. (2010). How to cook a SNARC: Number placement in text rapidly changes spatial–numerical associations. *Brain and cognition, 72(3)*, 333-336.

Galfano, G., Rusconi, E., & Umiltà, C. (2006). Number magnitude orients attention, but not against one's will. *Psychonomic bulletin & review, 13(5)*, 869-874.

Gallagher, M., Arshad, I., & Ferrè, E. R. (2019). Gravity modulates behaviour control strategy. Experimental brain research, 237(4), 989-994.

Gevers, W., Lammertyn, J., Notebaert, W., Verguts, T., & Fias, W. (2006). Automatic response activation of implicit spatial information: Evidence from the SNARC effect. *Acta psychologica*, *122*(3), 221-233.

Gevers, W., Verguts, T., Reynvoet, B., Caessens, B., & Fias, W. (2006). Numbers and space: a computational model of the SNARC effect. *Journal of Experimental Psychology: Human Perception and Performance, 32(1)*, 32.

Gianelli, C., Ranzini, M., Marzocchi, M., Micheli, L. R., & Borghi, A. M. (2012). Influence of numerical magnitudes on the free choice of an object position. *Cognitive processing*, *13*(1), 185-188.

Göbel, S. M., Calabria, M., Farne, A., & Rossetti, Y. (2006). Parietal rTMS distorts the mental number line: simulating 'spatial'neglect in healthy subjects. *Neuropsychologia, 44(6)*, 860-868.

Göbel, S. M., Shaki, S., & Fischer, M. H. (2011). The cultural number line: a review of cultural and linguistic influences on the development of number processing. *Journal of Cross-Cultural Psychology, 42(4)*, 543-565.

Goffaux, V., Martin, R., Dormal, G., Goebel, R., & Schiltz, C. (2012). Attentional shifts induced by uninformative number symbols modulate neural activity in human occipital cortex. *Neuropsychologia, 50(14)*, 3419-3428.

Götz, F. J., Böckler, A., & Eder, A. B. (2019). Low numbers from a low head? Effects of observed head orientation on numerical cognition. *Psychological research*, 1-14.

Grade, S., Lefèvre, N., & Pesenti, M. (2013). Influence of gaze observation on random number generation. *Experimental Psychology*.

Hartmann, M., Gashaj, V., Stahnke, A., & Mast, F. W. (2014). There is more than "more is up": hand and foot responses reverse the vertical association of number magnitudes. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(4), 1401.

Hartmann, M., Grabherr, L., & Mast, F. W. (2012). Moving along the mental number line: Interactions between whole-body motion and numerical cognition. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(6), 1416.

Hartmann, M., Mast, F. W., & Fischer, M. H. (2015). Counting is a spatial process: Evidence from eye movements. *Psychological Research*. doi:10.1007/s00426-015-0722-5.

Herrera, A., Macizo, P., & Semenza, C. (2008). The role of working memory in the association between number magnitude and space. *Acta psychologica*, *128*(2), 225-237.

Hesse, P. N., & Bremmer, F. (2017). The SNARC effect in two dimensions: Evidence for a frontoparallel mental number plane. *Vision research*, *130*, 85-96.

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

Kerkhoff, G. (2003). Modulation and rehabilitation of spatial neglect by sensory stimulation. In *Progress in brain research (Vol. 142, pp. 257-271)*. Elsevier.

Knops, A., Thirion, B., Hubbard, E. M., Michel, V., & Dehaene, S. (2009). Recruitment of an area involved in eye movements during mental arithmetic. *Science, 324(5934)*, 1583-1585.

Krajcsi, A., Lengyel, G., & Laczkó, Á. (2018). Interference between number magnitude and parity. *Experimental Psychology*.

Kramer, P., Stoianov, I., Umiltà, C., & Zorzi, M. (2011). Interactions between perceptual and numerical space. *Psychonomic bulletin & review, 18(4)*, 722.

Ito, Y., & Hatta, T. (2004). Spatial structure of quantitative representation of numbers: Evidence from the SNARC effect. *Memory & Cognition*, *32*(4), 662-673.

Lachmair, M., Dudschig, C., de la Vega, I., & Kaup, B. (2014). Relating numeric cognition and language processing: Do numbers and words share a common representational platform?. *Acta psychologica, 148,* 107-114.

Laubrock, J., Cajar, A., & Engbert, R. (2013). Control of fixation duration during scene viewing by interaction of foveal and peripheral processing. *Journal of Vision*, *13*(12), 11-11.

Lenth, R., & Lenth, M. R. (2018). Package ‘lsmeans’. *The American Statistician*, *34*(4), 216-221.

Lindemann, O., & Fischer, M. H. (2015). Embodied number processing. *Journal of Cognitive Psychology*, *27*(4), 381-387.

Liu, D., Verguts, T., Li, M., Ling, Z., & Chen, Q. (2017). Dissociated spatial-arithmetic associations in horizontal and vertical dimensions. *Frontiers in psychology*, *8*, 1741.

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.

Loetscher, T., Schwarz, U., Schubiger, M., & Brugger, P. (2008). Head turns bias the brain's internal random generator. *Current Biology*, *18*(2), R60-R62.

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.

Masson, N., Pesenti, M., & Dormal, V. (2013). Spatial bias in symbolic and non-symbolic numerical comparison in neglect. *Neuropsychologia, 51(10)*, 1925-1932.

Matheson, H. E., & Barsalou, L. W. (2018). Embodiment and grounding in cognitive neuroscience. *Stevens' handbook of experimental psychology and cognitive neuroscience*, *3*, 1-27.

Mihulowicz, U., Klein, E., Nuerk, H. C., Willmes, K., & Karnath, H. O. (2015). Spatial displacement of numbers on a vertical number line in spatial neglect. *Frontiers in Human Neuroscience*, *9*, 240.

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature*, *215*(5109), 1519-1520.

Myachykov, A., Scheepers, C., Fischer, M. H., & Kessler, K. (2014). TEST: a tropic, embodied, and situated theory of cognition. *Topics in cognitive science, 6(3)*, 442-460.

Nicholls, M. E., Loftus, A. M., & Gevers, W. (2008). Look, no hands: A perceptual task shows that number magnitude induces shifts of attention. *Psychonomic bulletin & review, 15(2)*, 413-418.

Nuerk, H. C., Iversen, W., & Willmes, K. (2004). Notational modulation of the SNARC and the MARC (linguistic markedness of response codes) effect. *The Quarterly Journal of Experimental Psychology Section A*, *57*(5), 835-863.

Pecher, D., & Boot, I. (2011). Numbers in space: differences between concrete and abstract situations. Frontiers in Psychology, 2, 121.

Pinto, M., Fattorini, E., Lasaponara, S., D'Onofrio, M., Fortunato, G., & Doricchi, F. (2018). Visualising numerals: An ERPs study with the attentional SNARC task. *Cortex, 101*, 1-15.

Pinto, M., Pellegrino, M., Marson, F., Lasaponara, S., Cestari, V., & Doricchi, F. (2019). How to make “number lines” stable in the mind’s eye. *bioRxiv*, 714659.

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.

Priftis, K., Zorzi, M., Meneghello, F., Marenzi, R., & Umiltà, C. (2006). Explicit versus implicit processing of representational space in neglect: Dissociations in accessing the mental number line. *Journal of cognitive neuroscience*, *18*(4), 680-688.

Proctor, R. W., & Cho, Y. S. (2006). Polarity correspondence: a general principle for performance of speeded binary classification tasks. *Psychological bulletin, 132(3)*, 416.

Ranzini, M., Carbè, K., & Gevers, W. (2017). Contribution of visuospatial attention, short-term memory and executive functions to performance in number interval bisection. *Neuropsychologia, 99*, 225-235.

Ranzini, M., Dehaene, S., Piazza, M., & Hubbard, E. M. (2009). Neural mechanisms of attentional shifts due to irrelevant spatial and numerical cues. *Neuropsychologia, 47(12)*, 2615-2624.

Ranzini, M., Lisi, M., & Zorzi, M. (2016). Voluntary eye movements direct attention on the mental number space. *Psychological research, 80(3)*, 389-398.

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.

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Restle, F. (1970). Speed of adding and comparing numbers. *Journal of Experimental Psychology, 83(2p1)*, 274.

Rizzolatti, G., Riggio, L., Dascola, I., & Umiltá, C. (1987). Reorienting attention across the horizontal and vertical meridians: evidence in favor of a premotor theory of attention. *Neuropsychologia, 25(1)*, 31-40.

Rossetti, Y., Jacquin-Courtois, S., Rode, G., Ota, H., Michel, C., & Boisson, D. (2004). Does action make the link between number and space representation? Visuo-manual adaptation improves number bisection in unilateral neglect. *Psychological science, 15(6)*, 426-430.

Rugani, R., Vallortigara, G., Priftis, K., & Regolin, L. (2015). Number-space mapping in the newborn chick resembles humans' mental number line. *Science*, *347*(6221), 534-536.

Rusconi, E., Bueti, D., Walsh, V., & Butterworth, B. (2011). Contribution of frontal cortex to the spatial representation of number. *Cortex, 47(1)*, 2-13.

Salillas, E., El Yagoubi, R., & Semenza, C. (2008). Sensory and cognitive processes of shifts of spatial attention induced by numbers: an ERP study. *Cortex, 44(4)*, 406-413.

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

Sell, A. J., & Kaschak, M. P. (2012). The comprehension of sentences involving quantity information affects responses on the up–down axis. *Psychonomic bulletin & review, 19(4),* 708-714.

Simon, O., Mangin, J. F., Cohen, L., Le Bihan, D., & Dehaene, S. (2002). Topographical layout of hand, eye, calculation, and language-related areas in the human parietal lobe. Neuron, 33(3), 475-487.

Sixtus, E., Lonnemann, J., Fischer, M. H., & Werner, K. (2019). Mental number representations in 2D space. *Frontiers in psychology*, *10*, 172.

Stoianov, I., Kramer, P., Umiltà, C., & Zorzi, M. (2008). Visuospatial priming of the mental number line. *Cognition, 106(2)*, 770-779.

Toomarian, E. Y., & Hubbard, E. M. (2018). On the genesis of spatial-numerical associations: Evolutionary and cultural factors co-construct the mental number line. *Neuroscience & Biobehavioral Reviews*, *90*, 184-199.

Umiltà, C., Priftis, K., & Zorzi, M. (2009). The spatial representation of numbers: evidence from neglect and pseudoneglect. *Experimental Brain Research, 192(3)*, 561-569.

Van Dijck, J. P., Gevers, W., & Fias, W. (2009). Numbers are associated with different types of spatial information depending on the task. Cognition, 113(2), 248-253.

Van Dijck, J. P., Gevers, W., Lafosse, C., & Fias, W. (2012). The heterogeneous nature of number–space interactions. *Frontiers in human neuroscience, 5*, 182.

Vuilleumier, P., Ortigue, S., & Brugger, P. (2004). The number space and neglect. *Cortex*, *40*(2), 399-410.

Wasner, M., Moeller, K., Fischer, M. H., & Nuerk, H. C. (2014). Aspects of situated cognition in embodied numerosity: the case of finger counting. *Cognitive Processing, 15(3)*, 317-328.

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

Wiemers, M., Bekkering, H., & Lindemann, O. (2017). Is more always up? Evidence for a preference of hand-based associations over vertical number mappings. *Journal of Cognitive Psychology*, *29*(5), 642-652.

Willmes, K., & Iversen, W. (1995). On the internal representation of number parity. Paper presented at the Spring Annual General Meeting of the British Neuropsychological Society. London.

Winter, B., & Matlock, T. (2013). More is up… and right: Random number generation along two axes. In *Proceedings of the Annual Meeting of the Cognitive Science Society* (Vol. 35, No. 35).

Winter, B., Matlock, T., Shaki, S., & Fischer, M. H. (2015). Mental number space in three dimensions. *Neuroscience & Biobehavioral Reviews, 57*, 209-219.

Wood, G., Willmes, K., Nuerk, H. C., & Fischer, M. H. (2008). On the cognitive link between space and number: a meta-analysis of the SNARC effect. *Psychology Science*.

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.

Zorzi, M., Priftis, K., & Umiltà, C. (2002). Neglect disrupts the mental number line. *Nature, 417(6885)*, 138-139.