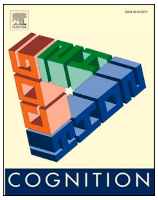
Cognition 221 (2022) 104991

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit



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

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ARTICLE INFO

Keywords:
Numerical cognition
Optokinetic stimulation
Number-space association
Spatial cognition
Visuospatial attention
Grounded cognition

ABSTRACT

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, upward attentional displacement decreased the Magnitude effect (slower responses for large numbers) and increased the Distance effect (slower responses for numbers close to the reference). In Exp.2, we observed a complex interaction between parity, magnitude, and OKS, indicating that downward attentional displacement slowed down responses for large odd numbers. 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 small numbers as compared to large ones; 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.

1. 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 spatial-numerical associations (SNAs) can be interpreted in the perspective of the *Embodied Cognition* approach (Barsalou, 2008), which gives the body and bodily processes a central role in cognition. According to embodied cognition theories, sensory and motor experiences form body representations, whose activation allows the construction of knowledge; high-level cognitive processes, such as those involved in numerical cognition, would result from the involvement of low-level processes such as the basic sensorimotor transformations involved in perception and action. Within this framework, SNAs can be hierarchically organized according to their dependency upon *grounded* (universal), *embodied* (learning-related), or

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https://doi.org/10.1016/j.cognition.2021.104991
Received 8 March 2021; Received in revised form 6 November 2021; Accepted 10 December 2021

situated (task-dependent) aspects (Fischer, 2012).

The *grounded* aspects derive from physical properties of the world (e.g., Blini, Pitteri, & Zorzi, 2019; Sixtus, Lonnemann, Fischer, & Werner, 2019) and biological constraints (e.g., Felisatti, Laubrock, Shaki, & Fischer, 2020; Myachykov, Scheepers, Fischer, & Kessler, 2014; Rugani, Vallortigara, Priftis, & Regolin, 2015). This would lead to SNAs that are universal and more resistant to change. The *embodied* aspects develop from the interaction with the environment and refer to sensory and motor constraints imposed by the human body (e.g., Schmidt et al., 2021), as well as to 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). The *situated* aspects concern the body and the environment conditions in which it is located (e.g., Belli, Felisatti, & Fischer, 2021), as well as constraints determined by cognitive factors (e.g., Bächtold, Baumüller, & Brugger, 1998; Fischer, Mills, & Shaki, 2010; Pinto et al., 2021; Wasner, Moeller, Fischer, & Nuerk, 2014). Thus, the surrounding environment exposes us to different relationships between quantity and space and it triggers SNAs that can flexibly vary in response to context and task changes. 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.

1.1. 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 et al., 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; for replication and alternative interpretation, see: Galarraga, Pratt, & Cochrane, 2021), 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 et al., 2018; Ranzini, Dehaene, Piazza, & Hubbard, 2009; Salillas, El Yagoubi, & Semenza, 2008).

Crucially, many studies have found that the processing of number magnitude elicits effects on the planning and execution of eye movements (Hartmann, 2015). For instance, the SNARC effect has also been observed with eye movements as effectors (Fischer, Warlop, Hill, & Fias, 2004; Schwarz & Keus, 2004), and a number of studies have also found that during number tasks the direction of spontaneous gaze shifts is predicted by number magnitude (e.g., Hartmann, Mast, & Fischer, 2015; Loetscher, Bockisch, Nicholls, & Brugger, 2010; Loetscher, Schwarz, Schubiger, & Brugger, 2008; Myachykov, Ellis, Cangelosi, & Fischer, 2016; Ruiz Fernández, Rahona, Hervás, Vázquez, & Ulrich, 2011). Considering that eye movements and attentional orienting are deeply related (premotor theory of attention: Casarotti, Lisi, Umiltà, & Zorzi, 2012; Rizzolatti, Riggio, Dascola, & Umiltà, 1987), these findings further support the idea that the mental representation of numbers recruits visuospatial attention.

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 et al., 2012; Masson, Pesenti, & Dormal, 2013; Van Dijck, Gevers, Lafosse, & Fias, 2012; Zorzi, Priftis, & Umiltà, 2002; Zorzi et al., 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; Knops, Thirion, Hubbard, Michel, & Dehaene, 2009; Rusconi, Bueti, Walsh, & Butterworth, 2011; 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 et al., 2004), gaze cues (Grade, Lefèvre, & Pesenti, 2013), eye pursuit (Ranzini, Carbè, & Gevers, 2017; Ranzini, Lisi, & Zorzi, 2016), or optokinetic stimulation (Blini et al., 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.

1.2. 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 et al., 2019; Winter & Matlock, 2013); others have provided inconsistent results: vertical SNARC during parity judgments but not during number 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). Again, few studies with ocular movements as effectors found some evidence of SNARC effect along the vertical axis, albeit the results are somewhen inconsistent (Hesse & Bremmer, 2017; Schwarz & Keus, 2004). Overall, 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), or by some degree of SNARC-effector specificity (Hesse, Fiehler, & Bremmer, 2016). Finally, the involvement of visuospatial attention is also supported by studies describing a vertical spatial mapping for numbers 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).

However, studies that explicitly investigated the link between orienting attention along the vertical axis and number processing are sparse. Some experiments focused on the effect of body position or gaze position on random number generation. For instance, Loetscher et al. (2010) investigated unconstrained eye positions during a random number generation task, and they found that, as for leftward gaze shifts, downwards gaze shifts more frequently preceded the generation of a smaller number as compared to the previous one. Winter and Matlock (2013) asked participants to generate random numbers after turning the head toward one of the four directions along the horizontal and vertical planes. The authors found stronger SNAs along the vertical axis (also see Hartmann, Grabherr, & Mast, 2012). 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 et al., 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.

1.3. 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 et al., 2012; Rizzolatti, Riggio, Dascola, & Umiltà, 1987). It consists of observing a visual stimulus (e.g., black and white stripes) which moves coherently toward 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 cognition on attentional orienting (Laubrock, Engbert, & Kliegl, 2008) and 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, Granà, Juncadella, Rico, & Semenza, 2009), as well as on number magnitude processing or 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., Van Dijck, Gevers, & Fias, 2009; Herrera, Macizo, & Semenza, 2008; Priftis, Zorzi, Meneghello, Marenzi, & Umiltà, 2006; 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 (Blini et al., 2019; Ranzini et al., 2015), 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). 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, 2015). Specifically, we made the following hypotheses: i) based on the association 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 in the number comparison task; ii) based on the idea that parity judgment does not rely on visuospatial attention (e.g., Ranzini et al., 2015; Zorzi et al., 2012), we also predicted that OKS would not affect the parity judgment task; iii) concerning ocular movements, we predicted spontaneous downward gaze shifts during processing of small digits, and upward during processing of large digits. We did not expect differences as a function of task because number magnitude is known to influence spatial response codes with both explicit and implicit number processing tasks.

2. Method

2.1. Participants

Twenty-four healthy, right-handed adults (mean age = 24 years old, 17 females) took part in Experiment 1, and twenty-four healthy, right-handed adults (mean age = 23 years old, 18 females) took part in Experiment 2. The group of participants that took part in Experiment 1 was different from the group that took part in Experiment 2. The sample size was established in consistency with previous studies (Blini et al., 2019; Ranzini et al., 2015). 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.

2.2. 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 judgment). Digits from 1 to 9 (w/o 5) were acoustically presented. Audio files were created by a speech synthesizer, and the duration of each audio file was similar to the natural duration of spoken Italian number words (1: "*uno*", 639 ms; 2: "*due*", 691 ms; 3: "*tre*", 529 ms; 4: "*quattro*", 816 ms; 6: "*sei*", 624 ms; 7: "*sette*", 779 ms; 8: "*otto*", 647 ms; 9: "*nove*", 683 ms). The duration of auditory stimuli was not equated to avoid unnatural perception of the spoken number words. Nonetheless, the analyses procedure took into account possible item-level bias related to the spoken digits (see Analyses section for details). 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 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 Fig. 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 OKN, characterized by overt shifts of attention in the direction of the movement (Fig. 1b and c). In both experiments, any condition consisted of 4 blocks, each starting with 8 practice trials

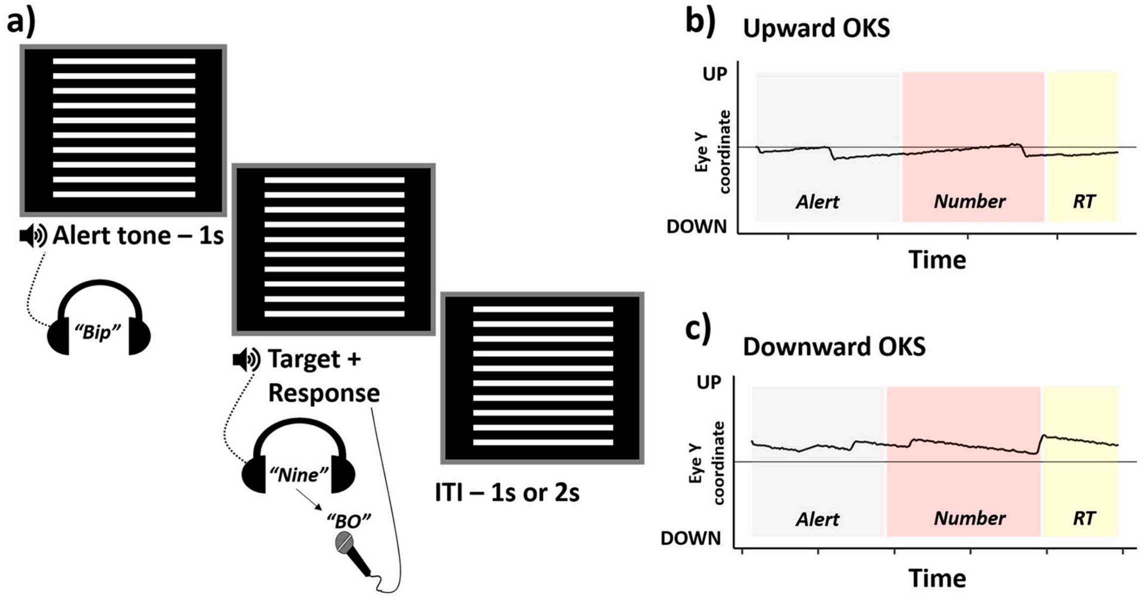

Fig. 1. Panel a shows a schematic representation of the experimental procedure. After a brief alert tone, a one-digit number (range 1–9, excluding 5) was presented acoustically via stereo headphones. Participants responded using two meaningless verbal labels ("BI" or "BO") to indicate the digit's magnitude (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 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.

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-in. TFT monitor using a screen resolution of 1024 × 768 pixels. Eye movements were recorded at 120 hz. Vocal response times (RTs) were collected using a microphone connected to a voice-key.

2.3. Data preprocessing

First of all, we excluded from all the analyses the trials with erroneous responses (0.99% in Experiment 1 and 0.98% in Experiment 2). Then, additional trials with microphone errors (anticipations, i.e. response times <100 ms, or missed detection of the response) were excluded (1.97% in Experiment 1 and 1.72% in Experiment 2). Finally, the response times outside 2.5 SD from the mean for each participant and OKS condition were discarded (2.20% in Experiment 1 and 2.27% in Experiment 2). 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.

To prepare the data for the analyses of GS, we firstly excluded 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 (14% in Experiment 1 and 11% Experiment 2). Second, 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%). Finally, 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.

2.4. Analyses

We used the open source software R (The R Core Team, 2021, R version 4.0.3) for data analysis. Specifically, 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, Mächler, Bolker, & Walker, 2015) and the emmeans package (Lenth & Lenth, 2018) were used to fit the models and to compute the results of follow-up comparisons, respectively. To test whether OKS had an impact on number comparison, we analysed RTs during number comparison (Experiment 1) as a function of OKS (static, downward, upward), Number Magnitude (small, large), and Distance from number 5 (close, far). Our prediction would be satisfied by the presence of an interaction between OKS and Number Magnitude, indicating faster responses for smaller digits during downward OKS, and faster responses for larger digits during upward OKS. To test whether OKS had an impact on parity judgment (hypothesis 2), we analysed RTs during parity judgment (Experiment 2) as a function of OKS (static, downward, upward), Number Magnitude (small, large), and Parity (odd, even). Our prediction would be satisfied by the absence of an interaction between OKS and Number Magnitude. Finally, to test whether number magnitude processing induced systematic shifts of attention in the direction of a vertical mental number line (i.e., smaller digits bottomward, and larger digits upward), we analysed GS as a function of the relevant variables (OKS, Number Magnitude, and Number Distance or Parity) during number comparison (Experiment 1) and during parity judgment (Experiment 2).

The advantage of mixed-effects models is that they allow to take into account subject variability in overall performance (random intercept) and interindividual variability in the observed effect (random slope), on top of their net effect, for each experiment (number comparison, parity judgment) and dependent variable (RTs; GS along the X axis; GS along the Y axis), We first defined the best random effects matrix with a forward procedure: we started from the null model, which only included the variables Subject and Item as random intercepts. Importantly, including Item as random intercept allows control of any source of potential bias related to each spoken digit (including, for instance, audio file duration). Second, we systematically added random slopes to Subject to control for interindividual variability in the observed effects. 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, one at the time, 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 to the next, and the model with the lower deviance following a significant likelihood ratio test (LRT) was retained. This means that in different analyses the random slopes could differ, i.e., in one set of analyses a random slope could improve the model when compared to a model with no random slopes, while in another set of analyses a random slope might not significantly ameliorate the model and therefore it would be not retained in the final model. For a more detailed description of this pipeline, see (Blini, Tilikete, Chelazzi, Farnè, & Hadj-Bouziane, 2020; Blini, Tilikete, Farnè, & Hadj-Bouziane, 2018). In this phase, models presenting fitting problems (e.g., failure in convergence) were systematically excluded, as to avoid overfitting. Then, once selected the most appropriate random effects' structure, we assessed the fixed effects, i.e., OKS, Number Magnitude, Distance or Parity, as well as their interactions. When it was not possible to include both Subject and Item as random intercepts because this led to fitting problems, we firstly analysed data without Item as random intercept, and we then tested a model with the observed effects controlling for Item instead of Subject. *P*-values for the main effects and interactions in the final model 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. Finally, 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.

In the Results section we first reported all the analyses of Experiment 1 (RTs GS along the horizontal axis, GS along the vertical axis), and then all the analyses of Experiment 2 (RTs, GS along the horizontal axis, GS along the vertical axis). When meaningful to further confirm and explain the results, we performed additional data-driven analyses. These analyses are explained in detail in the Results section when they first occur.

3. Results

Tables summarising the main statistical analyses and results described below are also provided for each experiment in the Supplementary Materials.

3.1. *Experiment 1 - Number comparison*

3.1.1. *Response times*

The final model resulting from the selection procedure described in the Analyses section included OKS and Number Magnitude as random slopes, and Item and Subject as random intercepts. The main effect of Distance was significant, ($X^2_{(1)} = 10.64$, $p = .001$), indicating faster responses for far (M = 948 ms, SEM = 28) than for close numbers (M = 996 ms, SEM = 27). As predicted, Magnitude interacted with OKS ($X^2_{(2)} = 7.1$, $p = .029$), as displayed in Fig. 2a. 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 ($|z| = 2.55$, $p = .029$). Also, the difference between large and small digits was visibly smaller in the upward condition as compared to the other OKS conditions (downward vs. upward: $|z| = 1.91$, $p = .056$; static vs. upward: $|z| = 2.56$, $p = .010$). Interestingly, the Distance effect also interacted with OKS ($X^2_{(2)} = 6.6$, $p = .036$; Fig. 2b). Additional planned comparisons revealed that the distance effect was significant in each OKS condition (all $|z| > 2.7$, all $p < .01$), however smaller in the downward condition as compared to the upward one ($|z| = 2.58$, $p = .010$). This pattern of results was unchanged when excluding data based on missing eye-tracking recording (see the Data preprocessing and Analyses subsection for details).

3.1.2. *Additional data-driven analyses on response times*

The interaction between distance and OKS was unpredicted. Therefore, to deeper investigate the effect of OKS on numerical distance, we performed an additional 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 (mean slope = −6.14 (2.2); $t(23) = -2.8$, $p = .006$, one tailed, $d = -0.57$, 95% CI [−1.02, −0.13]). 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, $N = 7$), further confirming the effect of OKS on numerical distance. The same analysis on the individual intercepts did not reveal a significant effect (*t*-test vs. 0: $p > .05$).

3.1.3. *Ocular movements along the X axis*

Due to convergence failures, it was not possible to include in a single final model both Item and Subject as random intercepts. So, we took into account Item and Subject separately. In a first step we excluded Item from the model. In this way, the final model included Numerical Magnitude as random slope, and Subject as random intercept. In line with our hypothesis, 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 (−1.51px (−0.08°), SEM = 1.30) and large digits shifting ocular movements toward the right (3.59px (0.18°), SEM = 2.65). To confirm this result by considering variability due to item-related factors, we tested the Magnitude effect in a model including Item as random intercept and only Magnitude as fixed effect. The result was similar, with the effect of Magnitude approaching significance again ($p = .08$).

3.1.4. *Ocular movements along the Y axis*

Due to convergence failures, it was not possible to include in a single final model both Item and Subject as random intercepts. So, we took into account Item and Subject separately. In the first step we excluded Item from the model. In this way, the final model included OKS as a random slope. The Magnitude effect was significant ($X^2_{(1)} = 6.85$, $p = .009$)

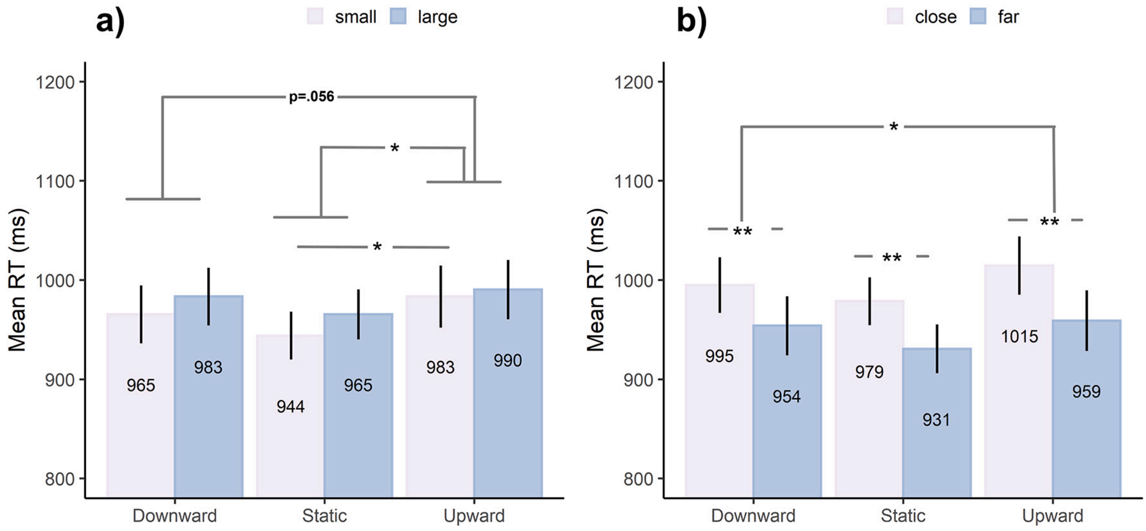

Fig. 2. Panel a: Mean response times as a function of Number Magnitude and OKS. Panel b: Interaction between Number Distance and OKS. In each panel the value within each bar is the mean response time in ms. Error bars represent SEM, and stars refer to significant planned comparisons as described in the Results section (*: $p < .05$; **: $p < .01$; ***: $p < .001$).

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), in line with our hypothesis. 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 confirm the Magnitude effect by considering variability due to item-related factors, we tested the model including only Magnitude as fixed effect and Item as random intercept. This confirmed the effect of Magnitude ($X^2_{(2)} = 5.21$, $p = .02$).

3.1.5. *Additional data-driven analyses on ocular movements*

To further investigate the effect of Number Magnitude on vertical gaze shifts, we performed an additional 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 (mean slope = 11.33; $t(20) = 1.9$, $p = .04$, one tailed, $d = .41$, 95% CI [–.04, .87]): increasing numerical magnitude was associated to decreasing GS (Fig. 3). The number of participants presenting the effect in this direction (positive slope, $N = 15$) was more than twice the number of participants presenting the effect in the opposite direction (negative slope, $N = 6$). The same analysis on the individual intercepts did not reveal a significant effect (*t*-test vs. 0: $p > .05$).

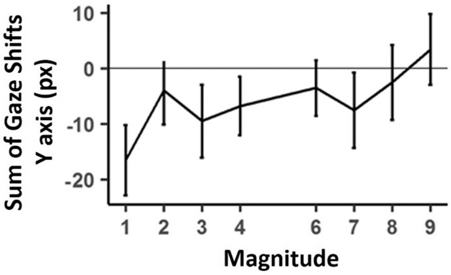

Fig. 3. Mean sum of gaze shifts (GS) as a function of number magnitude. Error bars represent SEM. Positive values indicate gaze shifts upward while negative values indicate gaze shifts downward.

3.2. *Summary of the results of experiment 1*

Result of Experiment 1 confirmed our hypotheses of bidirectional links between number processes and attentional orienting: sensitivity to number magnitude was larger during downward OKS as compared to the other OKS conditions, possibly due to an increase in response times for small numbers during upward OKS (in line with our hypothesis); furthermore, gaze was directed downward when processing small numbers as compared to larger ones (in line with our hypothesis). Interestingly, we also found an unpredicted effect of OKS on numerical distance: sensitivity to numerical distance was larger during upward OKS as compared to downward OKS (see General Discussion for a discussion of this effect).

3.3. *Results: Experiment 2 - Parity judgment*

3.3.1. *Response times*

The final model resulting from the selection procedure described above included OKS and Parity as random slopes, and Subject and Item as random intercepts. The interaction between OKS, Magnitude and Parity was significant ($X^2_{(2)} = 15.25$, $p = .0005$). The mean RTs for each condition resulting from the combination of the three interacting factors are depicted in Fig. 4. Follow-up comparisons revealed a significant magnitude effect (small vs. large numbers: $|z| = 2.62$, $p = .009$) only for odd numbers during downward OKS, and a significant effect of OKS for large odd numbers (upward vs. downward OKS: $|z| = 3.00$, $p = .008$). Another way to look at the triple interaction is to measure the size of the interaction between Magnitude and Parity in each OKS condition: the interaction between Parity and Magnitude was visibly larger in the downward condition with respect to both upward ($|z| = 3.04$, $p = .0024$) and static condition ($|z| = 3.64$, $p = .0003$), with no differences between the latter two ($|z| = 0.63$, $p > .05$).

No other main effects or interactions reached significance ($p > .05$). To confirm these findings, we repeated the analyses after excluding data related to abnormal gaze positions (see the Data preprocessing and Analyses subsections for details). Due to convergence failure, we excluded Parity and OKS as a random slopes from the final model. We confirmed the triple interaction even after exclusion of data related to abnormal gaze positions.

3.3.2. *Ocular movements along the X axis*

The final model included OKS as random slope, and Subject and Item

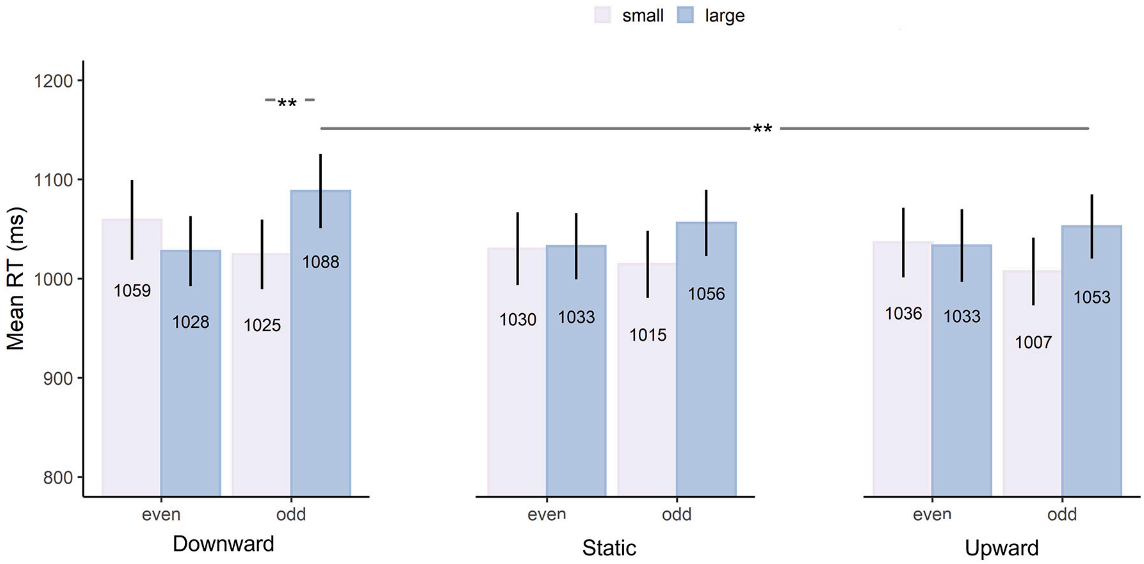

Fig. 4. Mean response times as a function of Parity, Number Magnitude, and OKS. The value within each bar is the mean response time in ms. Error bars represent SEM, and stars refer to significant planned comparisons as described in the Results section (*: $p < .05$; **: $p < .01$; ***: $p < .001$).

as random intercepts. The Parity effect was significant ($X^2_{(1)} = 8.44$, $p = .004$), indicating larger leftward shifts when processing even numbers (M = -4.46px (−0.24°), SEM = 2.47) as compared to odd ones (M = -0.32px (−0.04°), SEM = 1.71). Also, the interaction between Number Magnitude and Parity was significant ($X^2_{(1)} = 5.09$, $p = .024$). Specifically, the Parity effect (odd vs. even digits) was present for large digits (even numbers: M = -5.89px (−0.31°), SEM = 2.61; odd numbers: M = 1.25px (0.04°), SEM = 1.99; $|z| = 3.70$, $p = .0002$), but not for small ones (even numbers: M = -3.00px (−0.17°), SEM = 2.58; odd numbers: M = -1.90px (−0.12°), SEM = 1.92; $p > .05$). Furthermore, the interaction between Number Magnitude and OKS was significant ($X^2_{(1)} = 7.79$, $p = .020$: 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; $|z| = 2.74$, $p = .0062$). However, this two-way interaction was further qualified by the three-way interaction between Number Magnitude, Parity and OKS ($X^2_{(2)} = 7.59$, $p = .023$).

Table 1 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 ($|z| = 4.20$, $p < .0001$). No other main effects or interactions were significant ($p > .05$).

3.3.3. Ocular movements along the Y axis

It was not possible to include the Item as random intercept in the model due to convergence failure. The final model included only the random intercept for participants. Differently from what was expected, no significant main effect or interaction was found (all $p > .05$).

Table 1
Mean GS and SEM for each condition resulting from the combination of the three factors: Parity, Magnitude and OKS.

	OKS					
	Downward		Static		Upward	
Number	*Mean (px)*	*SEM*	*Mean (px)*	*SEM*	*Mean (px)*	*SEM*
Small Odd	−4.72 (0.23°)	4.54	2.25 (0.11°)	4.48	−5.16 (−0.25°)	2.48
Small Even	−10.9 (−0.54°)	5.84	5.28 (0.26°)	5.66	−5.03 (−0.25°)	2.94
Large Odd	−3.42 (−0.17°)	2.82	5.88 (0.29°)	5.16	0.33 (0.01°)	1.90
Large Even	−10.2 (−0.51°)	6.13	−6.34 (−0.31°)	6.30	−2.06 (−0.10°)	3.16

3.4. Summary of the results of experiment 2

Result of Experiment 2 further confirmed the presence of bidirectional links between number processing and attentional orienting, though the pattern of findings was unexpected. Concerning the influence of OKS on number processing, we found a significant magnitude effect only for odd numbers during downward OKS, with numbers 7 and 9 (i.e., odd and large) processed slower as compared to upward OKS. Concerning the effect of numbers on ocular movements, we found unpredicted effects of OKS, magnitude and parity on horizontal gaze shifts: the interaction between all factors revealed that in absence of OKS (i.e., the baseline condition with static stripes) odd large numbers directed the gaze rightward as compared to even large numbers, while this effect was not significant during OKS. More than indicating the presence of bidirectional links between number processing and attentional orienting, these results suggest that during parity judgment mechanisms other than the activation of a spatially oriented mental number line might be at play (see General Discussion for a discussion on these effects).

4. 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 (Blini, Cattaneo, & Vallar, 2013; Gallagher, Arshad, & Ferrè, 2019; Hartmann et al., 2012; Kramer et al., 2011; Loetscher et al., 2008; Ranzini et al., 2015; Ranzini et al., 2016; Winter, Matlock, Shaki, & Fischer, 2015). 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 judgment, Exp. 2; see: Herrera et al., 2008; Van Dijck et al., 2009; Zorzi et al., 2012). Finally, we expected an 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 (Fischer, 2012; Winter & Matlock, 2013; Lindemann & Fischer, 2015;). Importantly, our results confirm and extend previous findings (Blini et al., 2019; Ranzini et al., 2015) showing that mechanisms of attentional orienting along the vertical axis are involved in number processing in both tasks. These findings can be interpreted in light of the embodied cognition framework (Barsalou, 2008; Fischer, 2012; Matheson & Barsalou, 2018). According to this view, physical properties of the world (e.g., gravity law, direction of growing) together with embodied constraints (e.g., human visual system, human hand motor system) and sensorimotor experiences (e.g., reading and writing habits, use of the computer mouse) contribute to the manifold manifestation of SNAs (e.g., Fischer, 2012), possibly via attentional orienting mechanisms. Below we discuss our main findings in light of the embodied cognition framework.

4.1. Vertical displacement of attention and numerical processing in number comparison

In the number 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 (Ranzini et al., 2015; Ranzini et al., 2016; Stoianov et al., 2008), and that this influence is also conveyed by stimulating the vertical dimension. Indeed, upward OKS increased response times for small numbers when compared to the downward OKS condition. This is in line with our starting hypothesis, inspired by the Hierarchical view to numerical cognition (Fischer, 2012) and based on previous studies on number-space mapping along the vertical axis (e.g., Aleotti et al., 2020).

We also discovered, for the first time, that attentional shifts along the vertical axis modulated the processing of numerical distance. This effect was robust across a range of exclusion criteria and indicates that downward OKS decreases the classic distance effect, namely the tendency to respond faster to numbers far vs. close to the reference. Importantly, the impact of attentional orienting 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 et al., 2009; Vuilleumier, Ortigue, & Brugger, 2004; Zorzi et al., 2012).

Moreover, in the present study we observed that the effect of OKS on number distance was independent of number magnitude. Again, this finding is reminiscent of what is observed in neglect patients, where the impairment in number distance 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 in this case performance to the number 4 remains within a normal range. If we consider that the distance effect in number comparison is commonly interpreted as evidence of semantic processing of numbers (Moyer & Landauer, 1967), the effect of OKS together with neglect patients' atypical distance effect further confirms that visuospatial attentional orienting plays an important role in the mental representation and/or manipulation of numerical quantity. Neuroimaging studies corroborate neuropsychological research showing the influence of orienting mechanisms in the mental representation of numerical distance. For instance, Göbel and colleagues (Göbel, Calabria, Farnè, & Rossetti, 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 one to navigate through a variable, task-dependent, mental number line. In this sense, OKS might be an effective tool to restore number line impairments, as shown with coherent motion in neglect patients (Salillas et al., 2009), However, besides showing the involvement of attentional orienting, no study to date has elucidated the mechanism(s) underlying the modulation of the distance effect. One speculative interpretation is that both upward OKS and left-neglect direct attention toward the segment of the mental number line that represents larger quantities and is characterized by more compressive (or noisy) coding (Dehaene, 2003), thereby hindering discriminability of close numbers. Future studies should tackle this issue.

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). Also this result is in line with our starting hypothesis, and it fits with the hierarchical view of spatial-numerical associations (Fischer, 2012). Indeed, showing that the effect of number magnitude on up−/downward gaze shifts is reliable and independent from the direction of OKS (downward, static, upward) they support the strength of vertical dimension as a grounded influence on numerical cognition (see Blini et al., 2019, for discussion).

4.2. Vertical displacement of attention and numerical processing in Parity judgment

In the parity judgment task (Experiment 2), we found an interaction between Number magnitude, Parity, and OKS. Specifically, downward displacement of attention significantly amplified the interplay between Number magnitude and Parity. Influence of Parity on Number magnitude has been previously documented (Krajcsi, Lengyel, & Laczkó, 2018; Nuerk, Iversen, & Willmes, 2004). Nuerk et al. (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, Lengyel, & Laczkó, 2018 found the opposite pattern, highlighting the heterogeneity of this interference.

It has been suggested that the parity judgment task relies more on a linguistic-conceptual representation of numbers rather than on a visuospatial 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 during downward OKS 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 behavioural 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: 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. For instance the body-specificity hypothesis (Casasanto, 2009) finds the origin of spatial association of positive and negative concepts in the quality of long-term human-context interactions. In support of this view, the MARC effect is more body-specific rather than a response-side specific effect (Huber et al., 2015), as shown by the crucial role of handedness in mediating the association between parity and physical space (Fischer, Fischer, Huber, Strauß, & Moeller, 2018).

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.

4.3. *Embodied cognition as unifying framework*

In this study we observed effects of OKS on cognitive processes, both during explicit (number comparison) and implicit (parity judgment) number magnitude processing. First, vertical OKS modulated the processing of both numerical distance and numerical magnitude, while horizontal OKS had an impact on numerical magnitude (Ranzini et al., 2015). Second, vertical OKS affected numerical processing also during parity judgments, while horizontal OKS did not (Ranzini et al., 2015). Our findings, together with results of previous studies inducing exogenous shifts of attention (Ranzini et al., 2015, 2016), suggest the existence of qualitative – rather than quantitative – differences between vertical and horizontal mental number lines. These differences might rely on grounded and embodied factors responsible for the specific spatial representation of numbers.

The term grounding in this context refers to the idea that physical properties of the world, imposing universal and invariant constraints, shape cognitive processes in a predetermined way. For instance, in the field of spatial-numerical associations, the gravity law is a fundamental reference that entails placing increasing magnitude from bottom (natural zero) to top. Consequently, the tendency to map numbers along the vertical axis might be mainly determined by grounded aspects, while number-space associations along the horizontal axis might be mainly determined by embodied aspects (learning-related), such as reading direction and finger counting habits (e.g., Fischer & Brugger, 2011; Göbel, McCrink, Fischer, & Shaki, 2018). 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).

Finally, 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.

5. 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 et al., 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 (Casarotti et al., 2012; Rizzolatti, Riggio, Dascola, & Umiltà, 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/

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. MZ's research is supported a Cariparo Foundation Excellence Grant (NUMSENSE). The authors thank Leandro Cenesi for help in data collection.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2021.104991.

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