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SHORT REPORT

Gaze orientation interferes with mental numerical representation

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Abstract Number comparison tasks are characterized by distance and size effects. The distance effect reveals that the higher the distance is between two numbers, the easier their magnitude comparison is. Accordingly, people are thought to represent numbers on a spatial dimension, the mental number line, on which any given number corresponds to a location on the line. The size effect, instead, states that at any given distance, comparing two small numbers is easier than comparing two large numbers, thus suggesting that larger numbers are more vaguely represented than smaller ones. In the present work we first tested whether the participants were adopting a spatial strategy to solve a very simple numbers comparison task, by assessing the presence of the distance and the magnitude effect. Secondarily, we focused on the influence of gaze position on their performance. The present results provide evidence that gaze direction interferes with number comparisons, worsening the vague representation of larger numbers and further supporting the hypothesis of the overlapping between physical and mental spaces.

Keywords Mental number line · Spatial attention · Gaze orientation · Numerical processing

Introduction

There is strong evidence that numbers are represented in a mental number line (MNL) spatially oriented from left to right (Dehaene et al. 1993). Performance in comparing numbers is characterized by a distance effect, that is, there is a decrease in response time and an increase in accuracy as the distance between the numbers to be compared increases (e.g., comparing 1 vs. 9 is easier than 1 vs. 2) (Dehaene et al. 1993; Moyer and Landauer 1967). Furthermore, for a given distance, the performance drops with increasing numerical size (size effect; e.g., comparing 1 vs. 2 is easier than 8 vs. 9) (Moyer and Landauer 1967), suggesting that the numerical representation in the MNL is more vague for larger numbers than for smaller ones.

Numerical processing and visual-spatial processing interact with each other (Hubbard et al. 2005; Umiltà et al. 2009). Gaze orientation, known to drive spatial attention and to activate the underlying cortical networks (Beauchamp et al. 2001; Craighero et al. 2004), has been shown to bias spontaneous numbers generation (Loetscher et al. 2010), but evidence regarding the interaction between gaze position and numerical processing is still lacking. Recently, in the context of a study on reasoning, we reported that rightward fixation increased the time needed to infer the magnitude relationship between rank-ordered objects in a transitive inference task, where items are thought to be represented in a mental line equivalent to the MNL (Brunamonti et al. 2011).

Given the effect of gaze on transitive inference and the proposed spatial nature of the MNL, we tested whether gaze orientation interfered with the performance in a numbers comparison task. Here, we show that gazing rightward interferes with the task only when comparing large numbers.

Methods

Thirteen subjects (5 males and 8 females) aged between 24 and 39 (mean, 29; SE, 1) years volunteered to participate in

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the experimental testing. Each participant performed the task using their dominant right hand (Edinburgh Handedness Inventory). All subjects were naïve with respect to the purpose of the experiments and the hypotheses being tested.

The behavioral testing was conducted in a dimly lit room. Participants sat 30 cm away from the visual display (a 19″ computer monitor) handling a joystick aligned to their body midline. A chin rest kept their head aligned to the center of the screen. The monitor and the joystick, connected to the USB port, were controlled by a pc running Matlab (http://www.mathworks.com). A custom-made routine, using the Psychtoolbox functions (http://psychtoolbox.org), controlled the stimuli presentation and the response detection.

All experimental procedures were approved by the local ethics board and were performed in accordance with the ethical standards established in the 1964 declaration of Helsinki. Experiments were conducted with the full understanding and written consent of each participant.

Figure 1 displays the time course of the experimental trials. At the beginning of each trial, a fixation point was randomly presented on the computer monitor, according to an intermingled design, either at the center of the screen or 20° to the left or to the right of it. Participants were instructed to move their gaze to the corresponding position on the screen. After 1 s, a pair of Arabic numbers appeared, one above and the other below the fixation point. The participants were required to keep their eyes on the fixation point and pull backward or push forward the joystick if the higher of the two numbers was presented above or below the fixation point, respectively. In this way, the facilitation for leftward or rightward motor response associated with the leftward and rightward orientation of the spatial attention, respectively, was precluded. We reasoned that if any interaction between the numerical processing and the orientation of the gaze was detected, it was not biased by the congruence between the gaze position and the direction of the motor response. The size of the whole visual stimulus was 5° high and 2.5° wide, enough to prevent the visual stimulus to be processed through peripheral view, thus forcing the participants to keep their eyes on it to perform the task. Two different acoustic feedbacks informed the participant whether they had responded correctly or not. Furthermore, if the participant did not respond within 2 s, the trial was aborted and classified as an error trial. On each trial, we calculated the reaction time (RT) as the interval between the stimulus onset and the beginning of the motor response.

Stimuli were pairs of Arabic single-digit numbers between 1 and 9, sorted in two groups according to their magnitude within the selected interval. We considered as "*small*" the numbers lower than five and as "*large*" those higher than five. Comparisons were always performed between numbers belonging to the same group. The number 5 was never presented.

Each participant performed, during the same day, two experimental sessions (blocks) in which both the gaze and the number displacement were counterbalanced. For each pair of numbers to be compared, the position of the greatest number (above or below the fixation point) was randomly selected within each block. A resting period, if required, was allowed between the two blocks. The total number of trials for each block was equal to 144. Each pair (6 for the *"small"* and 6 for the *"large"* group) of numbers was presented 4 times (two times above and two times below the fixation point) for each central, right, and left fixation.

To perform the data analysis, we first sorted the pairs of numbers compared within each group by their symbolic distance (SD). For each group, we obtained 3 symbolic distances: SD1 if the pairs of numbers were consecutive (i.e., 1 vs. 2, 2 vs. 3, 3 vs. 4, 6 vs. 7, 7 vs. 8, 8 vs. 9); SD2 if the pairs of numbers were spaced by one number (i.e., 1 vs. 3, 2 vs. 4, 6 vs. 8, 7 vs. 9), and SD3 if they were spaced by two (i.e., 1 vs. 4, 6 vs. 9). We performed a 3-way ANOVA on the participants' RTs by considering three different factors, the numerical size ("*small*" and "*large*"), the three symbolic distances (SD1, SD2, and SD3), and the three gaze positions (left, central, and right). For each participant, we also quantified the magnitude of the size effect by subtracting, for each SD, the RT of the comparisons within "*small*" numbers from that within "*large*" numbers.

Results

Figure 2 shows both the symbolic distance and the size effect on the participants' RT, as previously described for number comparisons (Dehaene et al. 1993; Moyer and Landauer 1967). The RT for comparing numbers close to each other tended to be longer than for comparing numbers further away from one other. The 3-way ANOVA revealed a significant symbolic distance effect either as a main effect ($F_{(2,24)} = 31.09$; $p < 0.001$) or within each numerical size group (Newman–Keuls post hoc). Comparing "*small*" numbers at symbolic distance 1 (602; SE 21) required significantly more time than comparing them at distance 2 (573; SE 20; $p < 0.05$) and 3 (553; SE 19; $p < 0.05$). A significant difference was also observed when comparing "*small*" numbers at distances 2 and 3 ($p < 0.05$). The effect of the symbolic distance has been also observed within the group of "*large*" numbers. Comparisons at distance 1 (682; SE 23; $p < 0.05$) needed a longer RT than comparisons at distance 2 (635; SE 23; $p < 0.05$) and 3 (641; SE 25; $p < 0.05$). Significant differences were not observed between distances 2 and 3 ($p > 0.05$). We also detected a significant effect of the numerical size on the RT (main effect of size, $F_{(1,12)} = 97.02$; $p < 0.001$). For each symbol, comparisons between "*large*" numbers required a significantly longer time (Newman–Keuls post hoc; ps < 0.001).

Importantly, a significant interaction between numerical size and gaze position was also observed ($F_{(2,24)} = 3.47$; $p < 0.05$). Post hoc tests revealed that the time needed to compare "*large*" numbers was significantly slower when subjects fixated rightward than when they fixated leftward (Newman–Keuls: $p < 0.05$). RTs for central fixation did not differ from either leftward (Newman–Keuls: $p = 0.170$) or from rightward fixations (Newman–Keuls: $p = 0.257$). Significant differences in comparing "*small*" numbers were not observed between the three gaze positions (Newman–Keuls: leftward vs. central, $p = 0.49$; leftward vs. rightward, $p = 0.39$; central vs. rightward, $p = 0.13$). We did not observe any significant interactions between gaze and distance ($F_{(4,48)} = 0.80$; $p = 0.52$), distance and size ($F_{(2,24)} = 1.98$; $p = 0.53$), and distance, gaze, and size ($F_{(4,48)} = 1.05$; $p = 0.39$).

Discussion

In the past studies, several effects observed during numerical processing have helped to understand how people represent numbers. While the size and the distance effects, typically observed during numerical comparisons (Moyer and Landauer 1967), are thought to reveal how numbers are represented and manipulated, the observation of the SNARC effect suggested that the MNL could be oriented from left to right as number size grows (Dehaene 1997). All of these pieces of evidence suggested at least a partial overlap between numerical and spatial competences (Hubbards et al. 2005, for review). With regard to this, it has been shown that numerical processing interacts with the shifting of spatial attention, saccade performance, pointing and grasping movements, line bisection, and handwriting (Fischer et al. 2003; Perrone et al. 2010). On the other hand, it has also been observed that visuospatial variables have an influence on numerical processing. For example, spatial cueing and visual hemifield presentations affect numerical comparisons and MNL bisection (Nicholls and McIlroy 2010; Lavidor et al. 2004). In the present work, we further investigated the relationship between space organization and numerical processing by asking a group of volunteers to compare the same pair of "*small*" or "*large*" one-digit numbers while they were fixating on three different spatial positions. According to the hypothesis of a left to right orientation of the mental number line

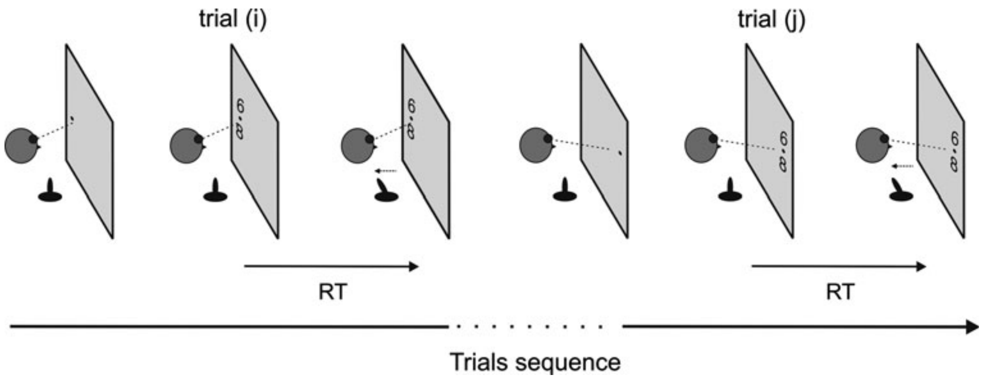

Fig. 1 Schematic of a trials sequence. The two example trials show the choice of the higher between two "*large*" numbers for the leftward or rightward gaze displacement. In each trial, the position of the higher number was randomly assigned to a spatial (low/bottom) position, using an intermingled design (not shown; see Methods for details)

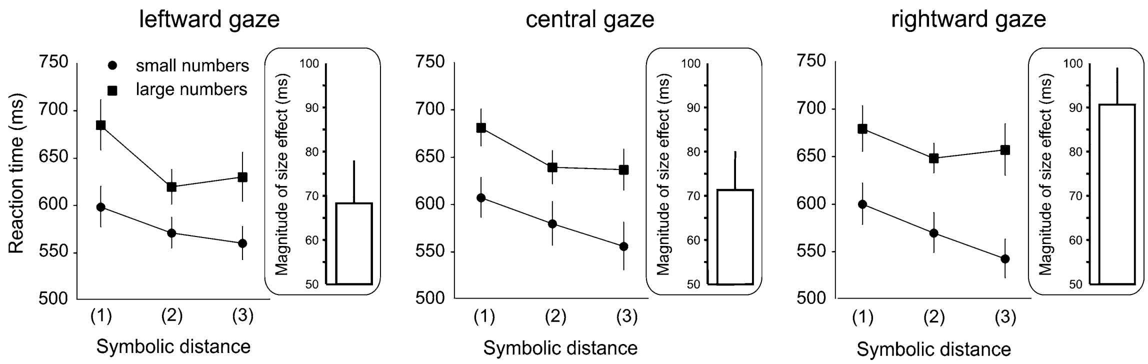

Fig. 2 Response time in the different experimental conditions. Average RT for "*small*" and "*large*" numbers for each of the symbolic distances and for leftward, central, and rightward fixations. For each panel, the magnitude of size effect, that is, the average RT difference between "*small*" and "*large*" numbers, is shown. *Vertical bars* represent ±1 SE

(Hubbard et al. 2005), we expected to observe a facilitation for processing smaller numbers following leftward orientation of spatial attention and a facilitation for processing larger numbers for rightward shifts of spatial attention. Unexpectedly, the present results did not match this prediction. We observed a significant interaction between numerical size and the position of the gaze and that the RT for comparing "*large*" numbers significantly increased for the rightward-oriented gaze.

Although very little research has been performed, there are a few reports showing that directing the gaze toward one visual hemifield activates the contralateral brain hemisphere (De Toffol et al. 1992; Swinnen 1984). Based on this evidence, we interpreted our results assuming that the right hemisphere, generally associated with spatial processing, was less active when subjects gazed to the right, worsening the vague representation of large numbers. A number of studies provide evidence in agreement with this hypothesis. First, the adaptation to left-shifting prisms and the consequent forced visuomotor orientation toward the right space has been observed to affect the perceived midpoint of MNL in normal subjects (Loftus et al. 2008). Second, an advantage of the left visual field has been reported in numerical processing (Ratinckx et al. 2001). Third, patients suffering of neglect as a consequence of a lesion of the right parietal cortex have been shown to be impaired in both spatial and numerical processing (Umiltà et al. 2009). Finally, the posterior parietal cortex, known to play a key role in the construction of an egocentric representation of sensory space used to organize motor interactions with the physical environment (Cohen and Andersen 2002; Ferraina et al. 2009), also shows a right hemispheric specialization for space coding (Husain and Nachev 2007; Sack 2009).

The present results suggest that subjects, by accessing the MNL to solve the task, were adopting a spatial strategy, with an interference of the rightward fixation. However, the effect was limited to "*large*" numbers comparisons. A possible explanation for this "*large*" numbers specificity is that "*small*" numbers might have prevented the effect because of their multimodal representation (Dehaene 1997). Also, we cannot rule out that "*small*" numbers prevented the RT to be sensitive to the interference of the gaze position by inducing a ceiling effect due to the rapidity of their processing.

Our results contrast with the results by Lavidor et al. (2004) who reported an advantage of the right hemisphere in processing large numbers when they were far away from a reference number. It is possible that the different requirement between our and their task might be responsible for the observed incongruence. While in their task each number was compared to the same reference number, in ours the numbers were compared to each other within each group. Therefore, in our task, all the comparisons were performed within only one of the two portions of the hypothesized mental number line, never including its midpoint, an experimental difference that could have led potentially to a different way to explore the MNL. More research is needed to understand these discrepancies and to further disentangle the effect that we are reporting, in particular by testing it using number comparisons relative to a reference number, number naming, or parity judgment tasks.

Conclusion

The present study provides further evidence that numbers are spatially represented and that spatial behaviors are able to affect numerical processing. Here, we showed that the gaze interfered with the representation of larger numbers, during a numbers comparisons task. Also, the study provides further behavioral evidence in favor of the hemispheric asymmetry influence in some forms of numerical processing. The present observation is compatible with a stronger right parietal activation during numerical comparison observed in previous brain activation studies (Chochon et al. 1999; Cohen-Kadosh et al. 2008), even though the left and right parietal lobe dominance in numerical competence is still a matter of debate (Cappelletti et al. 2010).

More generally, the present results contribute to enrich the set of evidence on the interaction between numerical processing and orientation of spatial attention explored previously by hemifield presentation (Lavidor et al. 2004), spatial (Stoianov et al. 2008), and numerical cueing paradigms (Fischer et al. 2003), but not by manipulating the gaze position.

A deeper understanding of the interaction between spatial and numerical processing might offer an opportunity to explore the development of new tools for the diagnosis of and treatment for developmental and acquired deficits in numerical processing such as dyscalculia.

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