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## Abstract

Human subjects' answer to questions like "what number is halfway between 2 and 8" provides insights into spatial attention mechanisms involved in numerical processing. Here we show that mental numerical bisections are accompanied by a systematic pattern of horizontal eye movements: processing of a large number followed by a small number is accompanied with leftward eye movements, a tendency less pronounced or even reversed for the processing of a small number followed by a large number. The eyes thus appear to move along a left-to-right-oriented number line, indicating that shifts of attention in representational space are accompanied by an ocular motor orienting response. These results add to the growing evidence for a convergence of numerical processing, spatial attention, and movement planning in the parietal and frontal lobes. They also demonstrate the homologous relationship between our internal representations of numbers and space, and show that the concept of "number space" is more than a mere metaphor.

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# Looking for the answer: the mind's eye in number space

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**Abstract**:

The answer to questions like "what number is halfway between 2 and 8" provides insights into spatial attention mechanisms involved in numerical processing. Here we show that mental numerical bisections are accompanied by a systematic pattern of horizontal eye movements: processing of a large number followed by a small number is accompanied with leftward eye movements, a tendency less pronounced or even reversed for the processing of a small number followed by a large number. The eyes thus appear to move along a left to right oriented number line, indicating that shifts of attention in representational space are accompanied by an ocular motor orienting response. These results add to the growing evidence for a convergence of numerical processing, spatial attention, and movement planning in the parietal and frontal lobes. They also demonstrate the homologous relationship between our internal representations of numbers and space, and show that the concept of “number space” is more than a mere metaphor.

**Key words:**

Space representation, eye movement, (unilateral) attention, motor cognition, mental number line, numerical processing

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## Introduction:

There is increasing evidence for an automatic and implicit association of numbers with spatial positions (Hubbard et al., 2005). At least in western cultures, small numbers are represented on the left, larger numbers on the right side of a "mental number line". This analogical representation is thought to be pivotal to our intuitive numerical understanding (Dehaene, 1997).

Behavioral, lesion and imaging studies show that numeric and spatial cognition rely on similar functional structures in the parietal lobes (Hubbard et al., 2005). Specifically, it has been proposed that the horizontal segment of the intraparietal sulcus encodes the semantic representation of numerical quantity, while a posterior system enables the attentional orienting along the mental number line (Dehaene et al., 2003). This latter region is not specific to numerical processing, but is rather involved in a wide variety of visuospatial tasks including, amongst others, gaze and attention orienting in space (e.g., Corbetta et al., 2000, Simon et al., 2002).

Numerical and spatial attentional interactions have been convincingly demonstrated by a simple detection paradigm (Fischer et al., 2003). In this task, a non-informative digit was presented at fixation, and after a short interstimulus interval subjects had to detect a visual target presented either to the left or right side of the fixation as fast as possible. Perception of small non-informative numbers (1 and 2) automatically shifted attention to the left, resulting in a faster detection of left sided targets, whereas the perception of larger number (8 and 9) speeded up right sided target detection. Such findings (see also Casarotti et al., 2007, Stoianov et al., in Press), have led to the suggestion that shifting the focus of attention within a mental representation produces a corresponding shift of attention in the external world (Fischer et al., 2003, Hubbard et al., 2005).

Shifts of attention are closely related to ocular motor processes (Rizzolatti et al., 1987, Corbetta, 1998, Nobre et al., 2000), but covert shifts of attention are possible without eye movements (Posner, 1980). Here we addressed the question of whether attentional orienting along the mental number line is reflected in eye movements. We used a number bisection task, originally devised to assess basic numerical skills (Dehaene and Cohen, 1997). In this task, subjects are asked to name the midpoint of a given number interval (e.g. between the numbers 2 and 8). Zorzi et al. (2002) demonstrated the importance of intact spatial attention capabilities to solve this task. Right brain damaged patients with hemispatial neglect not only ignore the left side of physical space, but also of mental space. Specifically, in numerical bisections tasks they displace the subjective midpoint towards the larger number, i.e. to the right side of the mental number line.

## Experimental Procedures

Nine healthy right-handed men (mean age 29, SD 6) participated in the experiment. Sitting in a dark room, subjects verbally indicated the median number of pre-recorded, orally presented numerical intervals and were instructed to respond as fast as possible in order to prevent any calculation strategy. Eleven ascending (e.g. 1-7) and 11 descending (e.g. 7-1) one digit number pairs were read from tape as "halfway between x and y?" in a pseudo-randomised order. The interval varied between 2 (= small interval, e.g. 1-3), 4 (= medium interval, e.g. 2-6) and 6 (= large interval, e.g. 2-8). The inter-stimulus interval was approximately 1.5sec. Eye movements were measured with dual search coils (Skalar, Delft, The Netherlands, see Robinson, 1963, Ferman et al., 1987). Subjects sat inside a 1.4m diameter coil frame, which generated three orthogonal magnetic fields. Voltages induced on the coils are proportional to the orientation of the coil relative to the magnetic field, and so indicate the orientation of the eye-in-space. Our calibration procedure was described by Bergamin et al. (2001). Signals were digitized at 1000Hz and 16-bit resolution. Vocal responses were recorded along with eye and head movements.

Offline, saccades were automatically detected with an interactive computer program on the basis of velocity and noise criteria (Holden et al., 1992). This allowed the removal of fast eye movements and blink artefacts. For each stimulus (i.e. a number pair) the average eye position was calculated 1) for the time period between the end of the first spoken number to the start of the second number (= reference interval), and 2) for the time period between the end of the 2nd stimulus number to the subject's response initiation (=initiation interval). The dependent variable was the change of eye position between these two time periods, calculated as initiation minus reference interval (see figure 1). Testing was undertaken in accordance with the Declaration of Helsinki and all subjects gave written informed consent before participating.

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Insert Figure 1 about here

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## Results

There were 20.5% errors (1, 7, and 12.5 % errors; for small, medium and large intervals respectively). There was neither a difference in the number of errors for ascending and descending intervals (Chi-Square=1.2, n.s.) nor a pseudoneglect, i.e., more deviation errors towards the smaller number (Wilcoxon z=1.0, n.s.). All further analyses are based on correct responses.

To test the modulation of eye movements by the distance between stimulus numbers, taking into consideration their presentation order (ascending vs. descending), we calculated regression analyses using the method of repeated measures data as proposed by Lorch and Myers (1990) and further propagated by Fias et al. (1996). For each individual, a linear regression slope was computed in which the mean change in eye movement was predicted by the number interval (i.e. largest descending to largest ascending, respectively from interval length -6 to 6). In 8 of the 9 subjects the slope for horizontal eye movements was positive, indicating greater rightward change in eye position with increasing interval length (see Figure 2 for data of one subject). Importantly, these individual regression slopes were significantly different from 0 as revealed by a one-sample t-test (Mean = .10, standard error = .03, t(8) = 3.17, p<.05). Analogous slope analyses for the vertical eye movements revealed no significant difference from 0 (Mean = .04, standard error = .04, t(8) = 1.10, n.s.), indicating no systematic eye movements in the vertical direction as a function of interval length. A correlation of individual horizontal and vertical slopes revealed no relationship between eye movements in the two cardinal directions (Spearman's rho = .17, n.s.).

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Insert Figure 2 about here

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Wilcoxon tests were used for comparing the eye movements in the descending to the corresponding ascending interval. For horizontal eye movements (Figure 2, left panel) larger leftward movements during descending compared to ascending bisections were found for large (z=-2.4, p<.01, one-tailed) and medium (z=-2.5, p<.01, one-tailed), but not for the smallest interval (z=-.65, n.s.). By contrast, for vertical eye movements (Figure 3, right panel) no significant change in any interval was found between corresponding ascending and descending number pairs.

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Insert Figure 3 about here

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**Discussion**

In a numerical bisection task, subjects showed larger leftward eye movements to number pairs presented in a descending (e.g. 6-2) compared to an ascending order (e.g. 2-6). This result demonstrates that the search for the number laying halfway between two stimulus numbers is accompanied by a systematic pattern of involuntary horizontal eye movements. The eyes appear to move along a left to right oriented number line, indicating that shifts of attention in representational space are accompanied by an ocular motor orienting response.

Previous research presented evidence that saccades are initiated faster to the left in response to small and faster to the right in response to larger numbers (Fischer et al., 2004, Schwarz and Keus, 2004). Our results extend these findings and suggest that numerical-ocular interactions not only occur when eye movements are required as a motor response, but also when they are task-irrelevant. On the one hand, this indicates that ocular-numerical interactions probably are more tightly coupled than previously thought. On the other hand, our findings do not necessarily imply that lateral eye movements would be an automatic and mandatory consequence of numerical problem solving. They may also depend on higher cognitive, strategic biases. Such biases have been shown previously in the literature on numerical-spatial interactions to vary with the subjects' cultural background (Zebian, 2005) and the specific task demands (Bachtold et al., 1998, Galfano et al., 2006, Ristic et al., 2006).

The fact that, overall, eye movements to the left dominated those to the right may reflect a general left-sided ocular exploration asymmetry found in healthy subjects (Ebersbach et al., 1996). This leftward bias, labeled “pseudoneglect” (Bowers and Heilman, 1980, Jewell and McCourt, 2000), is effector-independent and not confined to the ocular motor system. More importantly, pseudoneglect is not restricted to perceptual space, but was also described for the *representation* of space (McGeorge et al., 2007), and more particularly for healthy subjects’ exploration of number space (Gobel et al., 2006, Loetscher and Brugger, 2007). A recent study has even described significant correlations between individual leftward biases in physical and number space (Longo and Lourenco, 2007). We note, however, that such close associations between number and physical space have not been found by all authors (Doricchi et al., 2005), and we have ourselves shown that pseudoneglect in number space may be correlated to some, but not other hemispatial tasks (Loetscher and Brugger, 2007). In the present experiment, the clear leftward tendency of ocular motor responses was not paralleled by a pseudoneglect in the error pattern (i.e. too small and too large number were named equally frequently). The many errors actually found reassure us that we were able to prevent a general calculation strategy by allowing the subjects only a short time to answer.

Two further observations from the present experiment deserve a comment. First, presentation-order effects (ascending vs. descending stimulus pairs) were particularly prominent for the large  and medium stimulation intervals (e.g. 2-8 and 2-6), but virtually absent for the smallest number pair (e.g. 1-3). One might thus argue that the observed ocular response primarily reflected task difficulty, descending bisections being more difficult than ascending bisections. This seems rather unlikely since for the largest number pair, arguably the most cognitively demanding, there was neither a significant difference in the number of errors nor in the response latency for ascending relative to descending presentations. Therefore, although task-related eye movements were apparent exclusively when task demands were relatively high, the fact that they showed opposite directions for opposite number pairs reflects their genuine role in the exploration of mental space. Second, the analyses of vertical eye-movements did not reveal any stimulus-dependent pattern. Rather, irrespective of stimulus numbers, an overall *down*ward drift was evident during the reflection periods. This contrasts with earlier studies (e.g., Kinsbourne, 1972, Previc et al., 2005), that described *up*ward shifts during problem solving. We do not have an explanation for this discrepancy, but may note that previous findings were mainly based on experimentation in ambient light conditions.

What do our findings imply on an anatomo-functional level? Spatial exploration along the mental number line was considered indispensable for numerical bisections (Priftis et al., 2006) and may be based on the same mechanisms subserving overt shifts of attention in physical space (Zorzi et al., 2002, Hubbard et al., 2005). In addition, there is a close relationship between covert and overt shifts of attention. While it is possible to direct attention without eye movements (Posner, 1980), the reverse may not be true: spatial attention automatically shifts prior to saccades (Deubel and Schneider, 1996). Importantly, parietal regions involved in allocating spatial attention have also been linked to the planning of goal directed eye and arm movements (Colby and Goldberg, 1999, Cohen and Andersen, 2002, Astafiev et al., 2003, Culham et al., 2006). Interestingly, in the lateral interparietal area it has proven difficult to distinguish activity related to the allocation of spatial attention from activity related to motor planning (for example, compare the conflicting interpretation of Colby & Goldberg, 1999 and Cohen & Andersen, 2002, respectively). Thus, even if involuntary, the eye movements we found during numeric processing may have occurred due to the shared processing of numbers, attention, and movement planning in the intraparietal area. This conclusion is in line with the view that this region is "a multifaceted behavioral integrator that binds visuospatial, motor, and cognitive information into a topographically organized signal of behavioral salience" (Gottlieb, 2007, p. 9).

Recent brain imaging experiments have also revealed extensive overlapping neural networks in parietal, frontal and occipital areas for orienting attention to locations in perceptual and mental representations (Nobre et al., 2004, Lepsien and Nobre, 2006).

Compared to the perceptual domain, additional frontal lobe regions were selectively activated once task demands required the mental representation of space (Nobre et al., 2004). The pattern of activation in those frontal areas is, as Nobre et al. (2004) concluded, consistent with previous investigations of working memory and long term memory. Interestingly, impairments of spatial working memory and prefrontal damage have been associated with pathological biases in the number bisection task (Doricchi et al., 2005). Empirical evidence that eye movements interfere with spatial working memory performance derives from another strain of research (e.g., Smyth and Scholey, 1994, Postle et al., 2006), which proposed that shifts of spatial attention could aid in the maintenance of information in spatial working memory (see Awh et al., 2006 for a recent review). Likewise, there is empirical data indicating that eye movements play a functional role in mental imagery (Brandt and Stark, 1997, Laeng and Teodorescu, 2002).

To summarize, cognitive processes as different as attentional orienting, memorizing, the formation of mental images and numerical processing are all reported to be at least accompanied, if not influenced, by eye movements. It has been speculated that these seemingly dissimilar processes may have evolved from common visual perceptual functions (Jonides et al., 2005, Ehrlichman et al., 2007), thus providing a possible basis for the observed ocular-cognitive interactions. Our study illustrates that high resolution eye movement measurements have a great potential to shed light on these interactions. So far, the results suggest that the phrase "looking for an answer" is almost certainly more than a mere metaphor.

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## Legends:

### Figure 1:

Audio wave and English translation of presentation (number pair "4 and 8") and subject’s response ("6"). Average eye position was calculated 1) for the time period between the end of the first spoken number to the start of the second number of the stimulus pair (= reference interval), and 2) for the time period between the end of the 2nd stimulus number to the subject's response initiation (=initiation interval). Dependent variable was the change of the eye positions in these two time periods, calculated as initiation minus reference interval.

### Figure 2:

Example of mean horizontal and mean vertical eye position changes as a function of stimulus number interval (i.e. from largest descending (-6; e.g. 8-2) to largest ascending interval length (6; e.g. 2-8). Data from one subject. Negative values on the y-axis denote leftward changes in horizontal, respectively downward changes in vertical eye positions.

### Figure 3:

The horizontal (left panel) and vertical (right panel) changes of eye position (mean ± standard error) for the ascending and descending number pairs. The interval between stimulus numbers was either 2 (e.g. 1-3), 4 (e.g. 5-9) or 6 (e.g. 2-8) units.