NUMBERS, SPACE AND MOTION, CONVERGENT DATA ABOUT THEIR INTERACTION. BEHAVIORAL, ELECTROPHYSIOLOGICAL AND TMS EVIDENCE.

Doctoral Dissertation

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To Carmen and Jose

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NOTE

The present thesis contains five papers organized in two parts, a general introduction to part-one and part-two and a general discussion. This means that some concepts, definitions and references may be repeated.

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PRESENTATION

We deal with numbers more than it might seem at first thought. We think about numbers within time domains from the time you set your clock, until the time you program the microwave, the time you must arrive at a meeting, the day you have to reach a deadline, etc. We program ourselves with all these numbers. We also calculate shopping, paying our meal and getting the change, thinking how much we will spare in a reduced item. We assign order to things in the environment such as when searching for the number of a new friend´s house. We also classify objects according to a known number such as the number of a bus, or phone numbers. Not to say occupations that require direct management of them and surely the reader has thought of many other situations where numbers are essential. The ability to manipulate numbers and the way they are represented in our minds therefore has an important adaptive value.

Then, how are numbers stored in our brain? A number of empirical works have related a part of numbers representation to *space*. Many mathematical concepts establish a deep connection between numbers and space. The notion of measurement, the concepts of the real number line, Cartesian coordinates, the complex plane, are all metaphors by which numbers are made to correspond to spatial positions that are present in mathematical thinking. The evolution of these culturally-defined representations of numbers has been crucial to the development of mathematics.

Three main effects initially started the discussion about this link: the *distance effect* and the *size effect* (Moyer & Landauer, 1976) and the *Spatial-Numerical Association of Response Codes (SNARC) effect* (Dehaene, Bossini & Giraux, 1993). The distance effect means that bigger distances between numbers are easier to compare than smaller distances. This effect is taken as evidence for the transformation of numbers

into analogue magnitudes that are subsequently compared, and it suggests that numbers and the relationships between them are spatially organized (Dehaene, 1997). Another effect that has been taken as evidence for the analogue quantity continuum is the *size effect*, i.e. the fact that the time necessary to compare two numbers increases with the increase of their magnitude (eg. 8 and 9 vs. 1 and 2) Specifically, the ratio between the two numbers to be compared predicts the time required to compare them. Finally, the *SNARC* (Spatial-Numerical Association of Response Codes) *effect* provides evidence for access to magnitude representation in a left-to-right orientation. Large numbers are responded to faster with the right hand, whereas relatively low numbers achieve a faster response from the left hand. The effect has been proven to depend on the direction of writing (Dehaene, et al. 1993) and it has also been shown for other non-numerical, sequential stimuli, such as the months of the year and the letters of the alphabet (Gevers, Reynvoet, & Fias, 2003).

We will discuss in greater detail on the link between numbers and space in the first part of the thesis and present two studies exploring the electrophysiological correlates of the effect of numbers on attention to space (Fischer et al., 2003). We further explore the origins of this relationship by studying how blind population represents and manipulates the mental number line. This allow us to compare between modalities and in turn, the origins of the space-number relationship.

There exists suggestion of an interplay between number parietal areas and the pathway to which this area belongs, the dorsal pathway (Fias et. al., 2001; 2002). This leads us to explore other functions carried out by this pathway namely the processing of *motion*. In the second part of the thesis we present converging evidence from behavioural and Transcranial Magnetic Stimulation (TMS) methods on the relationship between motion and numbers. In other words can we extend the space-number link also

to motion? And importantly, is the space-numbers link the same that the motion-numbers one?. We will show that indeed that the perception of motion has an interference on number comparison independently from spatial processes . An area in the intraparietal sulcus (Ventral Intrapaprietal Sulcus) is proposed as a possible area of intersection between motion and numerical processes. Finally, we will describe restorative effects of motion into the altered number representational space in hemispatial neglect.

At the end of the thesis I hope to have expanded on what is known about the core representation of numbers and have contributed to clarify its nature.

PART 1. NUMBERS AND SPACE

1. Mental number line and Spatial Attention

Three behavioural effects initially guided the idea that numbers representation were linked to space: the *size effect,* the *distance effect* (Moyer and Landauer, 1976) and the *SNARC effect* (Dehaene, Bossini and Giraux, 1993). We described them in the presentation. In fact, the SNARC effect was interpreted as an index of spatial congruency between the response side (left and right side of the egocentric space) and the relative position of the numerical magnitude in a hypothesis of the mental number line (left and right side of the representational space). This effect has been widely studied. It has been shown that the effect does not depend on hemispheric dominance or on hand preference; rather it is modulated by reading direction (Dehaene et al., 1993). It tends to disappear with numbers bigger than 10 (Dehaene et al., 1993; Fias et al 1996). It seems therefore, that small numbers have an advantage over the semantic representation of magnitude. This automatic activation is further suported by studies that show activation of the magnitude even when a digit is irrelevant to the task (Fias et al 1996; Fias et al., 2001). It has been shown that the SNARC effect can be reverted if numbers are recalled in a clock (Batchtold, Baumuller and Brugger, 1998) which suggest that the representation of numbers depends on spatial characteristics rather than on the magnitude per se. The SNARC effect, in fact, is not only present in the horizontal but also in the vertical dimension (eg. Schwarz and Keus, 2004; Gevers et al. 2006). Just as reading and writing can be performed from left to right and from top to bottom, in the vertical dimension high numbers are associated with the top and low numbers are associated with the bottom. As to the role of the effectors, Müller and Schwarz (2007) have shown for example, that both space-related representation and the side determined by the effectors can influence the SNARC effect. Nevertheless, the SNARC effect arises

when individuals are asked to perform the parity judgement by pointing (Fischer et al 2003) or by making a saccade, instead of a manual response (Schwarz and Keus, 2004) which has lead some authors to interpret this as an effector-independent effect.

Recently Fischer and collaborators adapted the Posner paradigm to the study of the attentional effects generated by the perception of numbers. Part of this thesis is based upon this study. These authors showed that the mere perception of a number generated the orienting of spatial attention.

The Posner Paradigm

A common way to study how spatial attention works is to instruct or cue subjects to attend to specific locations in visual space prior to the presentation of a stimulus. Results from these studies indicate that stimuli appearing at attended locations receive preferential perceptual processing. In one such paradigm, the cued spatial orienting paradigm (also known as the "Posner paradigm" after its developer, Posner and Cohen, 1980), subjects are presented with two boxes to the right and left of a central fixation point. In one form of the paradigm, one of the boxes brightens (the cue). A few hundred milliseconds later a target appears at one of the boxes. Subjects are to respond to the target without moving their eyes from the central fixation point. If the target appears at the box that brightened, the trial is called a "valid" or “cued” trial (see fig. 1). If the target appears at the other box (the one that did not brighten) then the trial is called an invalid trial. Usually most of the trials are valid trials (about 80%) so that the cue is a good predictor of where the target will appear. Subjects are faster to respond to validly cued targets and slower to respond to invalidly cued targets than to targets on neutral or no-cue trials. This situation of predictability of the association between the

target and the cue is taken as reflecting endogenous processes. Facilitation for valid trials occurs in any time interval between cue and target. When the experimental paradigm implies non-predictability of the association between cue and target then the facilitation effect occurs only at short delays (100-300 ms.) between the stimuli. After that (500-1000 ms.), *Inhibition of Return* (IOR) occurs (see fig. 2), that is reaction times (RT) to valid (cued) trials are slower than RT to invalid (uncued) trials. IOR was first described by Posner and Cohen (1984).

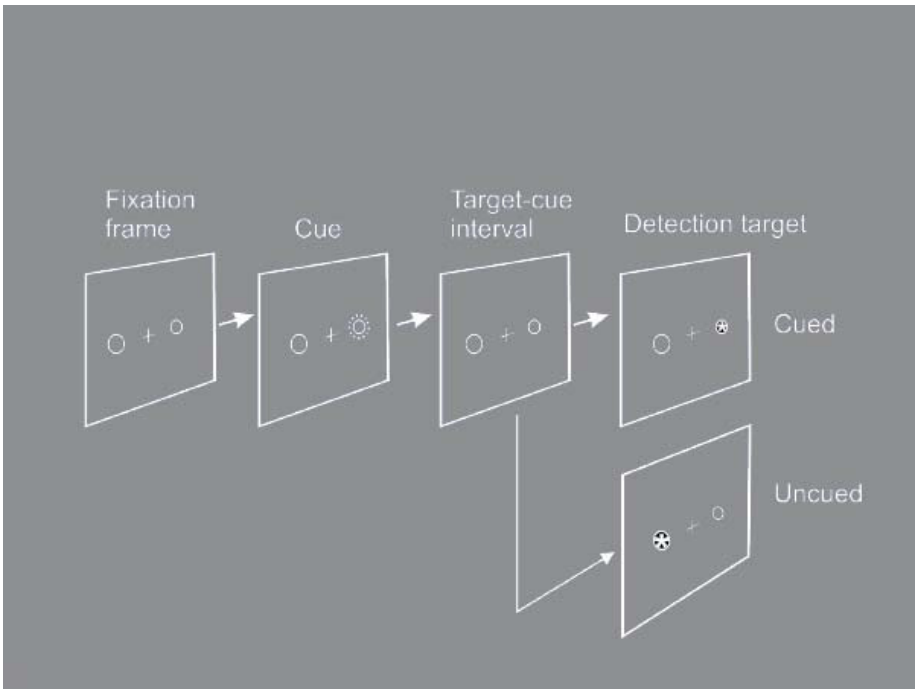


Figure 1. Schematic view of the Posner Paradigm. After a preparatory frame, one circle flashes, then after a variable cue-target interval the target appears.

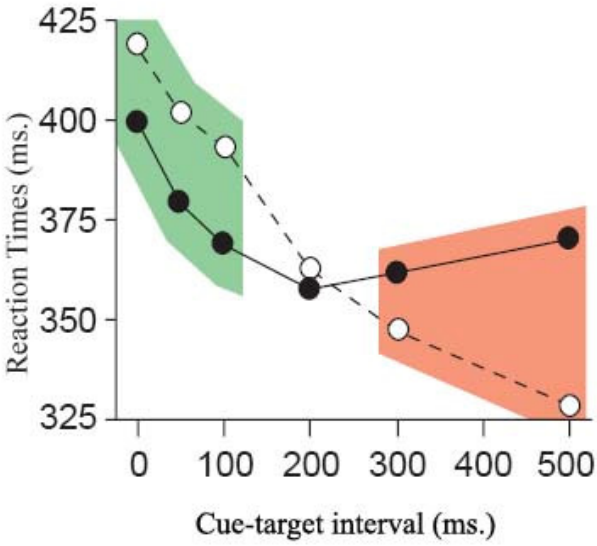


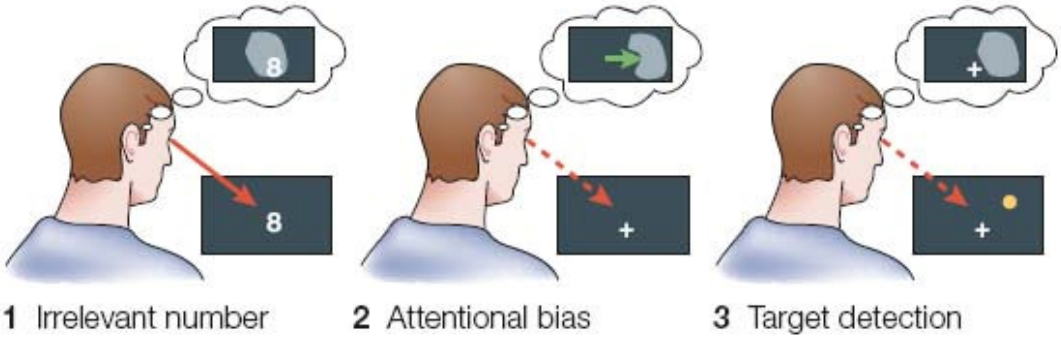
Figure 2. Reaction times in the Posner Paradigm as a function of the cue-target interval. In shorts intervals cued targets (filled circles) are detected faster that uncued ones (open circles). From 300 ms intervals, Inhibition of Return (IOR) appears and uncued targets are detected faster.

It is thought that in order to respond to the target, subjects must attend to it first. This involves moving attention from the central fixation to the location where the target appeared. In the cued orienting paradigm, the cue attracts attention even if the eyes stay fixed on the central fixation point (cover attention). Thus in the valid trials the reaction times are faster because the subject is already attending to the location at which the target appears. In the invalid trials the subject has been cued to the wrong location and the reaction time is longer because the subject must move their attention from the incorrect to the correct location in order to process the target. On the other hand, IOR is explained in terms of preventing to direct attention to the recently attended (cued) space. Therefore IOR is thought to facilitate the sampling of fresh sources of input (for a review, see Klein 2000).

Shifts of attention induced by numbers

Fischer and collaborators (2003) raised the question that if numbers were represented in spatial terms, the allocation of attention over numbers spatial representation may influence attention over external stimuli. In this attention bias effect, presentation of a non-informative digit at fixation lead to an automatic shift of attention to the left or right, which resulted in faster subsequent responses to visual targets.

a)



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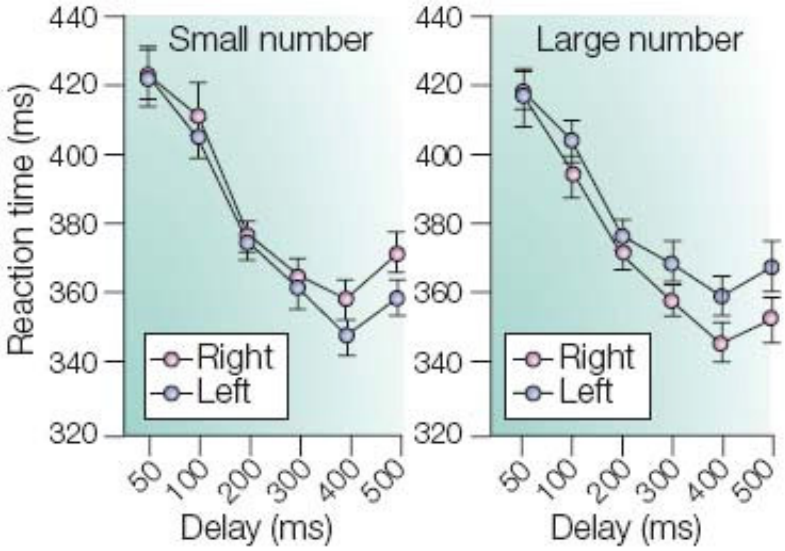

Figure 3. a) schematic view of the paradigm used by Fischer an collaborators (2003). B) Results of the study (From Hubbard et al., 2005)

Specifically, in order to explore whether the representation of numbers could induce shifts of attention to the location of the subsequent target, they presented numbers centrally (1, 2, 8, or 9) followed by the target in the right visual field (RVF) or in the left visual field (LVF). The number, irrelevant to the task, was presented for 300 ms. Then, after a delay that varied from 50 to 1000 ms., the target to be detected appeared on the right or on the left. After perception of large numbers (8 and 9), detection was faster for targets in the RVF, whereas after small numbers (1 and 2) detection was faster for targets in the LVF. This effect appeared at ISIs from 400 ms. until 750 ms. with maximal effect occurring with ISIs of 400 and 500 ms. (see fig. 3).

These results add important evidence with regard to the spatial nature of numbers semantics and importantly they establish the effect of space-number correspondence at the level of the stimulus elaboration. The authors also suggest that the same attentional mechanisms operating over external space act over numbers representation.

2. Further studies on numbers and spatial attention. Neuropsychological evidence from neglect.

Neuropsychological studies have also investigated the link between numbers and spatial attention. For this, neglect patients have been tested. The spatial attentional nature of the deficit opens a window to the study of possible attentional characteristics of numbers representation and to the study of the nature of this representation.

Basis and common symptomatology of neglect

Hemispatial neglect is a common disabling condition following unilateral brain damage, particularly of the right hemisphere. Although it can be caused by different pathological conditions, it is most often observed after cerebral infarction or haemorrhage and affects up to two thirds of right hemisphere stroke patients acutely. Patients with neglect often fail to be aware of or acknowledge items on their contralesional side (the left side for patients with right brain damage) and attend instead to items towards the same side as their brain damage--their ipsilesional side. Damage to many different brain regions causes neglect. Lesions of the right hemisphere are far more likely to lead to severe and enduring neglect than left hemisphere damage (Stone et al., 1993). Cortical damage involving the right inferior parietal lobe or nearby temporo-parietal junction has classically been implicated in causing neglect (Vallar and Perani, 1986). It has become apparent, however, that the syndrome may also follow focal lesions of the inferior frontal lobe (Vallar, 2001). More commonly, however, large middle cerebral artery strokes span both the critical parietal and frontal regions, resulting in a severe and persistent neglect syndrome.

When patients with hemispatial neglect are asked to perform a variety of tasks in space, they neglect the hemispace contralateral to their lesion: they may fail to draw the petals on the contralesional side of a presented flower; when asked to bisect a line, they commonly make their mark toward the ipsilesional side of the line; or when asked to cancel stimuli distributed across a page they usually mark only those items in the ipsilesional side. Neglect may also occur in the internal space. These patients fail to recall from memory the left sided items from the Duomo Square in Milan (Bisiach and Luzzati, 1978) or fail to describe from memory the details of a room (Denny-Brown and Banker, 1954). These last two symptoms are called representational neglect and are of interest for the studies on number representation that we will describe bellow.

Theories of neglect vary from those that describe the deficit in attentional terms and those that assign a representational origin. Some of the first explanations of the deficit referred to defects in attention. Between the attentional hypotheses that have been proposed to explain spatial neglect we find that these hypothesis are not necessarily mutually exclusive:

(1) *Spatial unawareness or inattention to the contralateral hemispace*. Top-down control or bottom-up novelty can alleviate the unawareness (Riddoch and Humphreys, 1983; Butter et al., 1990)

(2) *Ipsilesional spatial attentional bias*. Kinsbourne (1970) posited that each hemisphere attends to the opposite space and inhibits each other. Thus, when one hemisphere is injured it fails to inhibit the opposite hemisphere and therefore there is an hyper-attention to the ipsilesional space. Heilman and Watson (1977) agree with Kinsbourne´s notion of the ipsilesional bias but not with the absolute hyperactivity. If, normally, each hemisphere orients attention in a contralateral direction and one

hemisphere (e.g. the right) is hypoactive, there will be also a ipsilesional attentional bias.

(3) *Ipsilesional attentional disengagement disorder*. Posner et al. (1984) proposed a three-stage model of attention. These three stages consisted of disengage from the stimuli currently attended, movement of attention to the new stimulus and engagement onto the new stimulus. Patients may have spatial neglect because they cannot disengage from right-sided (ipsilesional) stimuli. Evidence for this hypothesis comes from an improvement of performance in cancellation tasks when the cancelled items are erased, thus facilitating disengagement (Mark et al., 1988).

Other explanations of neglect rely on representational origin. That is, they explain the deficit in internalist terms, where a destruction of representation may account not only for a deficit in imagery and memory but also for spatial neglect. The studies of Denny-Brown & Banker (1954) and Bisiach & Luzzati (1978) are well known evidence of this account of neglect. Briefly, knowledge or representations may lead to the selection of attentional process. Attention may not be directed to the left side of space because representations of them in the right hemisphere are damaged, the person has no knowledge of this side of space. Also, intentions to act in the left hemispace are altered due to failure to even represent that hemispace. Not all patients with neglect have representational neglect, therefore altered representations cannot explain all the faces of the deficit.

Hemispatial neglect and number representation

In a study by Zorzi and collaborators (2002) neglect patients were asked to bisect a number interval. The task consisted of auditorily presenting a number interval

defined by two numbers. The patient was asked for the number that would be in the middle of that interval. These authors showed that unlike healthy controls and right hemisphere damaged patients (RHD) without neglect, neglect patients systematically shifted the center of the numerical interval to the right. For example, when presented the interval between 11 and 19, the neglect patient allocate the center on number 17. These results are interpreted as an evidence that the mental number line is more than simply a metaphor, and that its spatial nature renders it functionally isomorphic to physical lines.

Other studies have shown that when making a number comparison task with a reference number 5, neglect patients take more time deciding that the number 4 is lower than five than deciding that the number 6 in higher than five. Specifically, Vuilleumier et al. (2004) showed significant differences between number-comparison times to the number 4 than to the number 6. Interestingly, when the reference number changed, patients showed the same difficulty with numbers smaller than the new reference number (i.e. when the reference number was 7, there were no more difficulties with 4 but with number 6). Vuilleumier et al. (2004) concluded that different spatial representations are constructed, in which different numbers are neglected depending on the number taken as reference in a comparison task.

The transcranial magnetic stimulation (TMS) technique allows to modify brain functions by inducing focal electrical fields in the cortical neurons (Walsh and Cowey, 2000), while inhibiting or facilitating behavioral performance. It is non-invasive and leads to an experimental manipulation of cortical information processing while treating the stimulated areas as an independent variable. In a way, this technique can be taken as a method of generating (controlled) “virtual lesions” with big accuracy. Using this technique, representational neglect-like symptoms in number bisection were recently

shown in healthy participants when repetitive transcranial magnetic stimulation (rTMS) was applied over the right posterior parietal cortex (Göbel et al., 2006).

In summary, these studies show how neglect can be studied to explore the links between numbers and spatial attention or the spatial representation of numbers. On the other hand, the study of number processing within this deficit allows to explore a different kind of pure representation, without the necessity of appealing to memory explanations.

3. Neuroimaging data

Similar parietal networks are activated in tasks involving either numerical or spatial processing (Dehaene, Piazza, Pinel, & Cohen, 2003; Walsh, 2003). Indeed, the neural circuitry in the parietal cortex involved in the processing of numerical quantity appears to overlap with the neural circuitry involved in spatial processing.

Dehaene and collaborators (2003) recently presented a meta-analysis of different fMRI studies and proposed the bilateral horizontal segment of the intra parietal sulcus (HIPS) may be particularly important for the representation of magnitudes. This meta-analysis was allocated in the theoretical context of the Triple-Code model (Dehaene, 1997) where the core representation of numbers, the analog magnitude representation entailed core number processing. This analog magnitude representation is activated mainly by approximation and number comparison, where a less precise representation is required. This representation entails the semantics of size and distance relations between numbers, and is thought to be located in the parietal cortex. This quantity system might be crucial for mediating observed interactions between numerical and spatial representations.

The results from fMRI studies indicate that numerical tasks typically involve a distributed network of areas, including the frontal cortex and the left and right parietal lobes (Dehaene et al., 1999; Pinel et al., 2001; Pinel et al., 2004; Piazza et al., 2003; Chochon et al., 1999; Eger et al., 2003). The activation of left and right intraparietal sulci (IPS) shows to be correlated with the behavioral-distance effect. On the basis of these results and other studies implying different numerical task the meta-analysis performed by Dehaene et al. (2003) identifies the HIPS as having a particular role in quantity representation. The authors signal that the activation may extend to dorsal parietal sites that are thought to be involved in spatial attention orientation. In fact, the

bilateral posterior superior parietal lobe (PSPL) could be implied in the orientation of attention over the number representation as it does over other spatial representations or entities.

In a recent review of the interactions between number and space, Hubbard and collaborators (2005) signaled a possible origin of the space-number relation in some linguistically-learned sequences. They suggested possible connections between the left angular gyrus (lANG), locus of language related numerical processes in Dehaene et al (2003), and the IPS. This raises the possibility that numerical-spatial interactions depend on cardinal and ordinal information.

In general, it is suggested that numerical and spatial tasks entail the activation of a similar posterior-anterior parietal organization. Moreover, further studies confirm that the IPS is involved in spatial processing in macaque monkeys (e.g., Colby, Duhamel and Goldberg, 1995; Lewis and Van Essen, 2000), as well as in humans (Orban, Van Essen, and Vanduffel, 2004).

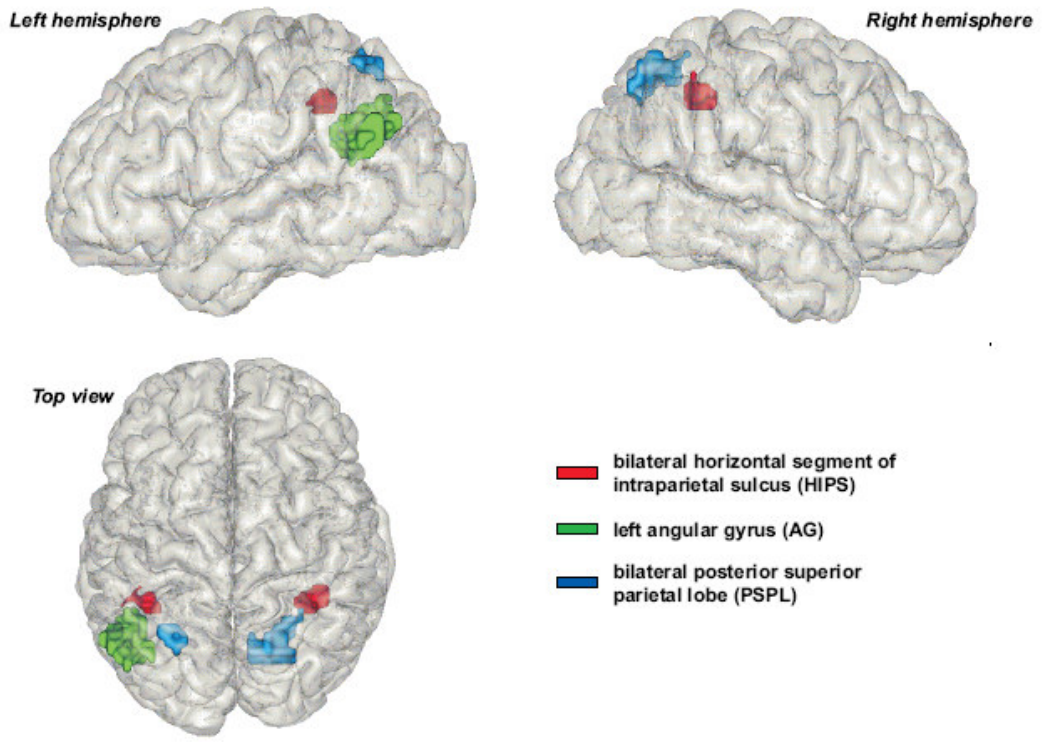

Figure 4. The three parietal circuits for number processing proposed by Dehaene and collaborators (2003). According to the authors, the horizontal segment of the intraparietal sulcus (HIPS) appears as a plausible candidate for domain specificity: It is systematically activated whenever numbers are manipulated, independently of number notation, and with increasing activation as the task puts greater emphasis on quantity processing. Depending on task demands, this core quantity system, analogous to an internal "number line," can be supplemented by two other circuits. A left angular gyrus area, in connection with other left-hemispheric perisylvian areas, supports the manipulation of numbers in verbal form. Finally, a bilateral posterior superior parietal system supports attentional orientation on the mental number line, just like on any other spatial dimension. The model is reminiscent of the Triple Code Model: Dehaene (1992) proposed a triple code model that distinguishes between an auditory verbal code, a visual code for Arabic digits, and an analog magnitude code that represents numerical quantities as variable distributions of brain activation. It is proposed that there are specific relationships between individual numerical operations and different numerical codes. The analog magnitude code is used for magnitude comparison and approximate calculation, the visual Arabic number form for parity judgments and multidigit operations, and the auditory verbal code for arithmetical facts learned by rote (e.g., addition and multiplication tables).

4. Numbers across modalities; is vision required for the development of space-number relationship?

One of the studies presented in this thesis will explore this question. A straightforward way of addressing the relevance of vision in the relationship between space and numbers is to observe whether in the early-onset blind population this link also exist. As mentioned by Castronovo (2007), two exploratory hypothesis guide the study of numbers representations in blind population : the *sensory limitation hypothesis* and the *cognitive compensatory mechanism hypothesis*.

Two exploratory hypothesis

According to the sensory limitation hypothesis, experience and exposure to numbers and numerosities may have an impact in the way we represent (Siegler & Opfer, 2003; Verguts et al., 2005) or access numerical magnitudes (Lipton & Spelke, 2005). Given the absence of vision, people suffering from early onset blindness have necessarily experienced numbers and numerosities in a different way compared to sighted people. Therefore, a repercussion should be found in the way blind people represent numerical magnitudes. This hypothesis is based upon the proposals that vision has an advantage in spatial processing; according to this view, vision presents a much higher information capacity compared to the other senses. In other words, the visual modality shows a quantitative advantage: encompassing greater amount of information and more precision (Thinus-Blanc & Gaunet, 1997). Thus, as signalled by Castronovo (2007): "According to this hypothesis, vision constitutes the principal cue from which the semantic numerical representation is elaborated. People suffering from early visual deprivation should not be able to handle with numerosities and to discriminate them as do sighted people. In consequence, early visual deprivation should have repercussions

on the apprehension and processing of numerosities and should preclude the elaboration of a semantic numerical representation with the same properties to those of sighted people." (p 96).

On the other hand, according to the cognitive compensatory mechanisms hypothesis, blind people approach spatial tasks compensating the lack of vision through other mechanisms (Collignon et al., 2006; Gaunet & Rossetti, 2006). These mechanisms could extend to the representation and manipulation of numbers. The prevalent use of the other senses and their increased working memory resources_more important in time-dependent senses like audition_ could lead blind people to use numbers in a different way. Castronovo and Seron. (2007b) even show that blind people have better estimation capacities.

Studies to date on the relationship between number and space in early onset blindness.

Few studies to date have shown blind´s behaviour and electrophysiological responses in the numerical domain specifically focusing on distance (Szücs & Csèpe, 2005) and SNARC effects (Castronovo et al, 2007a). In the first study, Szücs & Csèpe showed behavioural and electrophysiological distances effects in this population. In an acoustic number comparison task, the authors showed similar distance effects in two event related potential (ERP) components at 200 ms after the presentation of the number: a lateral parietal N2p and a frontal P2. The N2p component was more negative for distance equal to 4 than for numerical distances equal to 1. The P2 component was more positive for distance 4 than for distance 1. Both distance effect and topography of the components did not differ between groups. However, the analysis of the event-related spectral perturbation (ERSP) transformed from the EEG showed some

discrepancies between the blind and the sighted groups in the overall ERSP landscape, electrodes and in the frequency ranges demonstrating distance effects. In any case, the authors clearly concluded that no differences were generated from blindness in the distance effect and therefore the number distance effect is *had-wired.*

Castronovo and Seron (2007a) showed SNARC effects in an early onset blind population. The authors presented auditory numbers to which a parity task had to be performed. In two experiments, using one and two digit numbers, the authors showed comparable effects for blind and sighted. They concluded that the absence of vision does not preclude the left to right representation of numbers. Therefore, the modality-independence of numerical (spatial) semantics is reinforced (see Hubbard for a review, 2005).

The last study of this section addresses the effects that the auditory perception of numbers has on orienting attention in the auditory space. This allow us to compare blind and sighted in central processes that may be affected by the relationship between numbers and space. Moreover, we will be able to compare vision and audition in sighted population.

5. EXPERIMENTAL STUDIES (I)

5.1. Sensory and cognitive processes of shifts of spatial attention induced by numbers: an ERPs study*

* This paper will be published in Cortex 44(2008) 406-413.

ABSTRACT

The relationship between space and number has become a focus of intensive investigation (Hubbard et al., 2005; Walsh, 2003). The present paper aims to explore the nature of attentional shifts induced by the perception of irrelevant numbers as it was shown by Fischer and collaborators (2003). We measured the event related potentials induced by the perception of visual lateralized targets cued by numbers that differed in their magnitude. Congruent trials were defined as those where a target presented in the right visual field followed a large number and those where a target presented in the left visual field followed a small number. Numbers generate a modulation of evoked potentials on targets as soon as 80 ms. after the presentation of the target: congruency of the target determined the amplitude on perceptual P100 and cognitive P300 in both sides of presentation of the target. Although a typical distribution of the components was found, effects of congruency were distributed around anterior and centro-parietal sites. Due to the functional properties of the mentioned components, the present data suggests that, in fact, perception of numbers does affect the location of attention to external space. Moreover, the distribution of the congruency effect signals that the representational nature of numbers makes a difference with respect to the stimuli classically used in cueing studies of visual attention to location. The role of top-down control generated by numbers is discussed.

Introduction

There is mounting evidence that the number representation involves a spatial component (see Hubbard et al., 2005 for a review; Priftis et al., in press). For example, the SNARC effect (Spatial Numerical Association of Response Codes; Dehaene et al., 1993) has been demonstrated using a parity judgment task (odd or even?) about a centrally presented digit. Typically, results show that large numbers (e.g., numbers 8 or 9) are responded to faster with the right hand, whereas small numbers (e.g., numbers 1 or 2) are responded to faster with the left hand. The SNARC effect is generally interpreted as reflecting the automatic activation of an internal representation of magnitude where numbers are represented along a left-to-right oriented mental number line.

More recently, Fischer et al. (2003) adapted the paradigm of Posner and Cohen (1980) to investigate the use of numbers as cues to the detection of lateralized spatial targets. In order to explore whether the representation of numbers could induce shifts of attention to the location of the subsequent target, they presented numbers centrally (1, 2, 8 or 9) followed by the target in the right visual field (RVF) or in the left visual field (LVF). The number, irrelevant to the task, was presented for 300 ms. Then, after a variable delay (Inter-Stimuli-Interval) that varied from 50 to 1000 ms., the target to be detected appeared on the right or on the left. Interestingly, after perception of large numbers (8 and 9), detection was faster for targets in the RVF, whereas after small numbers (1 and 2) detection was faster for targets in the LVF. This effect appeared at ISIs from 400 ms. until 750 ms. with maximal effect occurring with ISIs of 400 and 500 ms.

These findings add important evidence to what is known about the space-numbers relationship, suggesting that the redirection of attention over an internal

representation after perceiving a number influences the allocation of attention in the visual field. According to the authors, similar structures underlie attention shifts across internal representations and external space. Analogous results have been shown in other studies (eg., Tlauka, 2002), although some variations in the paradigm (eg. timing in Keus and Schwarz, 2005) lead to a failure in reproducing the effect.

Other studies such as Gevers et al. (2006) indicate that an association between numbers and space can be detected at the response stage, but additional research is required to determine whether such an association is also present at the attentional stage when participants are initially attracted to the target stimuli. We sought to address this issue by studying the electrophysiological correlates using the paradigm of Fischer and collaborators. The ERP method offers a high temporal resolution in the range of milliseconds and precisely reflects the temporal sequence of perceptual and cognitive computations. We varied slightly Fischer´s paradigm by means of a delayed detection response, where the detection response was not requested immediately after the target but following a fixed time after the target. This variation simply allowed us to capture the stimulus processing phase and to separate it from the preparation of the response. In this way, we examined possible variations in the sensorial and cognitive electrophysiological components time locked to the target, which may be dependent on the previous perception of numbers.

Several experimental studies have explored biases induced by attention on the perception of visual targets using ERPs. Different components (P100, N100 and P300) have been reported to be modulated as a function of previous cueing. One of the most important components related to spatial attention is the P100, a positive component with maximum amplitude peaking around 100 msec post-stimulus onset and typically showing an occipital scalp distribution. Stimuli presented at attended locations elicit

larger P100 components than unattended locations with no change in P100 latencies or scalp distribution (Hillyard et al., 1995; Mangun, 1995; Mangun et al., 1998). Reflexive and top-down orienting produce a similar P100: Both exogenous orienting, generated by non-predictive cues (e.g., salient sensory cue like a flash presented in the periphery) and endogenous orienting, generated by predictive cues (classically presenting an arrow in the centre) produce an amplification of the P100. This component has been also shown to be modulated by the cueing originated in representations held in working memory (e.g. Awh, et al., 2000; see Awh and Jonides, 2001 for a review). According to some authors (eg. Hillyard and Anllo-Vento, 1998; Brefczynski and DeYoe, 1999), the cueing produces a sensory amplification or gain control on subsequent stimulation at the attended location already from the engagement of extrastriate cortex. But this sensory activity can be modulated by other areas. Some neuroimaging studies suggest that parietal areas can modulate this striate activity, indicating the possibility of top-down modulation of the processing of the input to early visual areas (Fink et al., 1996; Wood et al., 2006).

A later stage of processing indexed by the P300 component has been shown to be modulated by attention (Hopfinger and Mangun, 1998, 2001; Hopfinger and West, 2006). The P300 is a high-level positive component that typically shows a Centro-Parietal scalp distribution with maximum amplitude around 300 ms. post-stimulus onset. Different temporal windows have been reported for this component though depending on task demands and experimental paradigms. A number of factors are known to influence P300 amplitude, such as the relevance or frequency of the stimulus, the amount of attention resources necessary to perform a task, working memory updating and decision making (Kok, 2001; Bashore and Van der Molen, 1991; Donchin and Coles, 1988). The modulation of the amplitude in this component is also dependent

on the process measured. P300 is typically larger to attended than to unattended targets. When a probability over targets is manipulated (e.g. oddball paradigm, see Priftis in press), the P300 is larger to infrequent than frequent stimuli (Donchin, 1981). Previous studies have shown that exogenous attention can enhance the P300 showing that the amplitude of the P300 is significantly larger for cued-location than for uncued-location targets at short ISIs (Hopfinger and Mangun, 1998; 2001). Interestingly, the modulation of the P300 produced by endogenous attention seems to be bigger (e.g., Hopfinger and West, 2006).

With respect to the mental number line representation and the cueing paradigm used in our study, four different conditions can be constructed depending on the size of the number and the location of the target (Fischer et al., 2003). A design congruency (2) x side of presentation of the target (2) was chosen due to the moment of measurement of the ERPs: the presentation of the lateralized target. Congruent trials were thus defined as RVF and LVF targets presented after a large or a small number respectively, and incongruent trials were defined as the opposite combination of number size and target location.

Based on the review of the literature using ERP methods and on Fischer et al.´s previous results presented above, we made the following predictions. If shifts of attention across an internal representation (induced by perceiving numbers) influence the allocation of attention in the visual field, then modulations of the P100 and P300 components would be expected, showing larger amplitudes for congruent than for incongruent trials irrespective of the side of presentation of the target. A modulation of these components dependent on the congruency between the number-cue and the target location would agree with the behavioural data of Fischer et al. (2003). Importantly, due to the recording of ERPs time locked to the presentation of the target, an effect on the

P100 would entail an initial sensory process induced by numbers in the processing of the target. This effect would better characterize the interaction found by Fischer et al., between the number and the spatial target, at the level of shifts of spatial attention induced by numbers. The modulation of P300 amplitude by congruency would signal an impact of number representation on higher (spatial) cognitive processes undertaken when detecting a lateralized target. Since P300 is related to the elaboration of the stimulus, and reveals the behavioural relevance computation of the cued location (Hopfinger and Mangun, 1998, 2001), a modulation of the P300 would imply an influence of the number-spatial representation on conditioning higher processes related with the computation of the relevance of a spatial location. In other words, the location activated by the relative size of the number would have been tagged as being more relevant than other locations.

Methods

Participants

After giving informed consent, 12 Italian students (mean age = 23; range = 20-29; 5 males) were tested individually in a single session that lasted for about 30 minutes. All of them were right-handed, neurologically normal and had normal or corrected-to-normal vision.

Stimulus presentation and procedure

Participants were comfortably seated at 90 cm. from a computer monitor and were asked to fixate the centre during the whole the experiment. They completed 240 trials in a simple detection task. Each trial started with a central dot flanked by two peripheral (left and right) empty black square-outline boxes (size 2.54º) presented for

500 ms., and then the fixation point was replaced by the cue. The cue consisted of one out of white digits (1, 2, 8 or 9; visual angle 1.9°) which was centrally presented for 300 ms. After a fix delay (ISI) of 450 ms., the target was presented for 700 ms. The target consisted of a white circle (1.9º), which was presented with equal probability within one of the two peripheral boxes on 67% of all trials (visual angle of presentation 1.88º). In the remaining trials (33%), a target was not presented (catch trials), they were constituted to prevent anticipatory responses. ERPs time-locked to the appearance of the target were registered. Differing from Fischer et al. (2003) experiment, a delayed response was required to avoid that the electrophysiological response to the target being obscured by the preparation of the response. After the target, a question mark was presented in the centre of the screen for 1000 ms. In delayed detection task, participants were instructed to respond as quickly as possible when the question mark appeared by pressing a button with the right hand only if a target, irrespective of its location, had appeared before. The participants were instructed that the digits did not predict target location. The set of 240 trials was divided in two blocks of 120 trials each, with an equal number of trials (40) by condition (large-number/RVF (congruent); small-number/LVF (congruent); large-number/LVF (incongruent); small-number/RVF (incongruent); large-number/catch; small-number/catch). Trials were randomized for each participant within each block. Each block lasted approximately 8 min and a short rest period was provided between blocks. To familiarize participants with the task, the experiment started with a practice session consisting of 10 trials.

Data acquisition and analysis

Continuous EEG was recorded from 28 scalp electrodes mounted on a elastic cap (Electrocap) and located at standard left and right hemisphere positions over frontal, central, parietal, occipital and temporal areas (International 10 / 20 System, at Fz, FCz,

Cz, CPz, Pz, Oz, Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, Ft7, Ft8, Fc3, Fc4, Cp3, Cp4, Tp7, Tp8). These recording sites plus an electrode placed over the right mastoid were referenced to the left mastoid electrode. The data were recorded continuously throughout the task by SynAmps amplifier and software NeuroScan 4.3. Each electrode was re-referenced off-line to the algebraic average of the left and right mastoids. Impedances of these electrodes never exceeded 5 kΩ. The horizontal electro-oculogram (HEOG) was recorded from a bipolar montage with electrodes placed 1 cm. to the left and right of the external canthi; the vertical (VEOG) was recorded from a bipolar montage with electrodes placed beneath and above the eye, to detect blinks and vertical eye movements. EOG activity was subtracted from EEG epochs using a regression method in the time domain (Semlitsch et al., 1986). Epochs from 100 ms. before and 600 ms. after the presentation of the target were extracted from the EEG. The EEG and EOG were amplified by a Synamp´s amplifier and filtered with a band pass of 0.01-30 Hz, and digitized at 500 Hz. Epochs were excluded from averaging if they contained amplitudes outside the range +/-150 µV at any EEG site. ERPs were extracted by averaging trials separately for subjects, electrodes and experimental conditions.

The averages were then baseline corrected, with the 100 ms. pre-stimulus period serving as baseline. ERP averages were analysed by computing the mean amplitude in selected latency windows relative to a 100 ms. baseline. ANOVAs were used for all statistical tests and were carried out with the Greenhouse-Geisser correction for sphericity departures (Geisser and Greenhouse, 1959). ANOVAs were conducted separately for midline and lateral electrodes. ANOVAs for midline electrodes used a repeated-measures design taking as factors congruent/incongruent, side of presentation of the target (Left Visual Field (LVF) / Right Visual Field (RVF)), Localization (2

Regions Of Interest [ROIs] or Area; Anterior and Posterior) and electrodes (3 for each ROI with Anterior including: Fz, FCz, Cz, and Posterior including: CPz, Pz and Oz). ANOVAs for lateral electrodes also used a repeated-measures design with congruency (congruent/incongruent), side of presentation of the target (Left Visual Field (LVF) / Right Visual Field (RVF)), hemispheres (Left vs. Right), Localization (3 Regions Of Interest [ROIs] or Area; Anterior, Centro-Parietal, and Occipito-Temporal), and electrodes (3 for each ROI with Left Anterior including: F7, F3, FC3; Left Centro-Parietal: CP3, C3, P3; Left Occipito-Temporal: T3, TP7, O1; Right Anterior: F8, F4; FC4; Right Centro-Parietal: CP4, C4, P4 and Right Occipito-Temporal: T4, TP8, O2). The electrodes Fp1, Fp2, Ft7, Ft8 were excluded from the analysis in order to obtain ROI including the same number of electrodes.

Results

Behavioural data

Average reaction times for the go-response of the twelve participants were determined with a 2 x 2 ANOVA including two levels of congruency (congruent vs. incongruent) and two levels of side of presentation of the target (LVF/RVF) as factors. Due to the delayed characteristic of the response, no significant main effects or interactions were found. [congruency: $F(1,11)=1.3$; ns; side: $F(1,11)=0.03$; ns; side x congruency: $F(1,11)=2.6$; ns]. The difference between congruent and incongruent was 2 ms. in the RVF and -17 ms. in the LVF.

ERP data.

The traces presented in Figure 1 show the grand average potentials with congruent and incongruent trials superimposed recorded at Cz (central midline

electrode). Visual inspection seems to reveal two positive differences, larger for congruent than for incongruent trials. The first difference was an early positivity with bigger amplitudes distributed around the occipital sites and peaking at 114 ms. (according to peak detection). Based on its latency and global distribution, this first positivity can be identified as the P100 component. The second positivity was distributed around the Centro-Parietal sites and peaking at 314 ms. Based on its latency and global distribution, this second positivity can be identified as the P300 component. With respect to the catch trials, visual inspection shows clearly that these two components (P100 and P300) were not elicited when a target was not presented (see Figures 2 and 3)[1]. In order to examine these congruency effects in further detail, two latency ranges of main interest were selected, both from visual inspection of the ERP traces and from comparison with previous results available in the literature: the 80-130 ms. interval, to test the P100 component and 200-400 ms. to test the P300 component (see Hillyard and Anllo Vento, 1998 for a review; Duncan-Johnson and Donchin, 1982 or Donchin, 1981 for the P300).

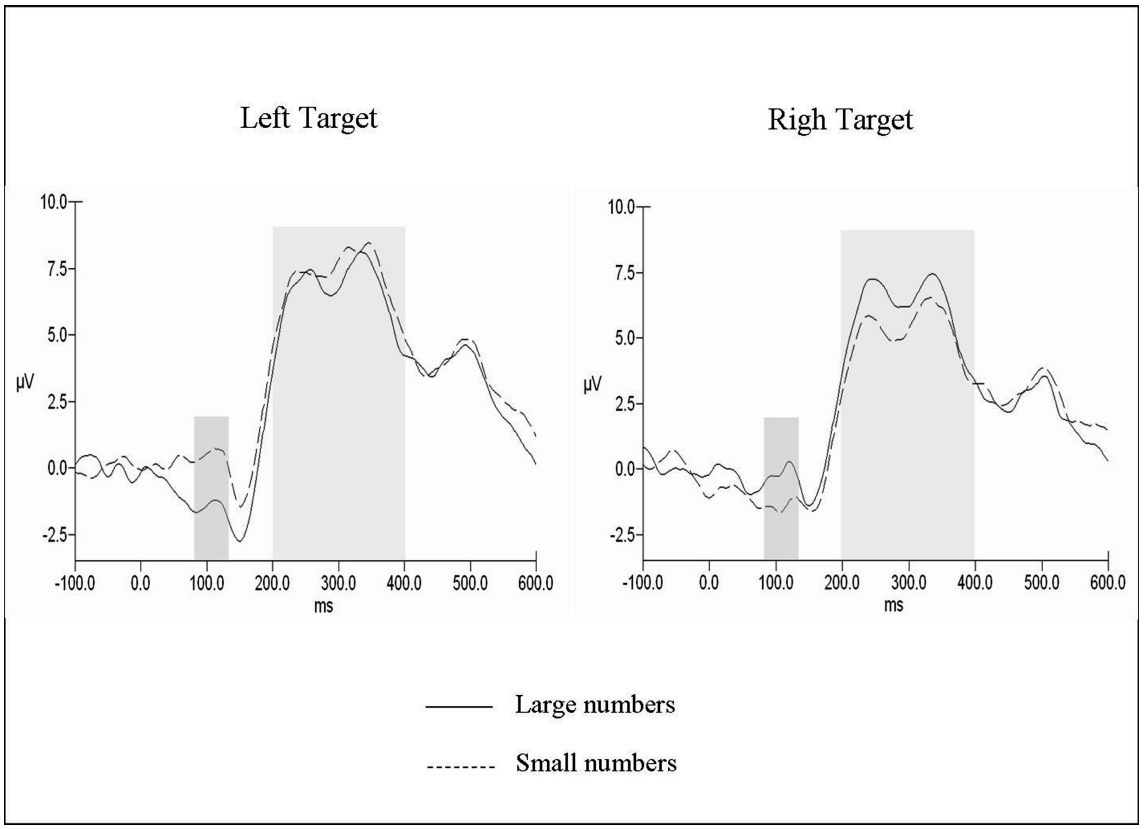

Figure 1. Illustration of the variations in brain electrical activity time-locked to the left target (left panel) and right target (right panel) when large number (solid line) or small number (dashed line) were presented in cue. Each trace represents an average of electrophysiological data from Cz electrode and recorded from 12 participants.

P100 (80-130 ms.).

The first latency range between 80 and 130 ms. showed a significant main effect of congruency both in midline [F(1,11)=11.34; MSe=11.34; p<.001] and lateral [F(1,11)=7.99; MSe=16.37; p<.05] electrodes: congruent trials elicited a larger positivity compared to incongruent trials, with no interaction by side. In the midline electrodes a significant triple interaction congruency X ROI X electrode was found [F(2,22)=12.92; MSe=0.43; p<.001]. Post Hoc analyses showed that the difference between congruent and incongruent trials was significant in all midline electrodes except in Oz. Moreover, congruency interacted by ROI in the lateral electrodes [F(2,22)=5.94; MSe=3.76; p<.05], reflecting that the congruency effect was localized only at the Centro-Parietal [F(1,11)= 13.68; MSe=6.75; p<0.005] and Anterior areas [F(1,11)=5.16; MSe=12.51; p<0.05].

P300 (200-400 ms.)

This second latency range showed again a main effect of congruency both in midline [F(1,11)=16.38; MSe=3.9; p<.005] and lateral [F(1,11)=7.26; MSe=9.1; p<.05] electrodes: congruent trials elicited larger positivities than incongruent trials. Once again, congruency did not interact by side. Midlines electrodes showed also a triple interaction between congruency, ROI and electrodes [F(2,22)=7.57; MSe=2.3; p<.005]: as in previous latency range, Post Hoc analysis revealed that the effect of congruency was present in all midline electrodes except in Oz. Moreover, significant interaction between congruency and ROI [F(2,22)=4.73; MSe=4.73; p<.05] was found in lateral electrodes, reflecting that the congruency effect was mainly distributed around the Anterior [F(1,11)=11.42; MSe=2.88; p=0.006] and Centro-Parietal sites [F(1,11)=9.57; MSe=5.38; p<.01] but not in Occipito-Temporal areas (*F*<1).

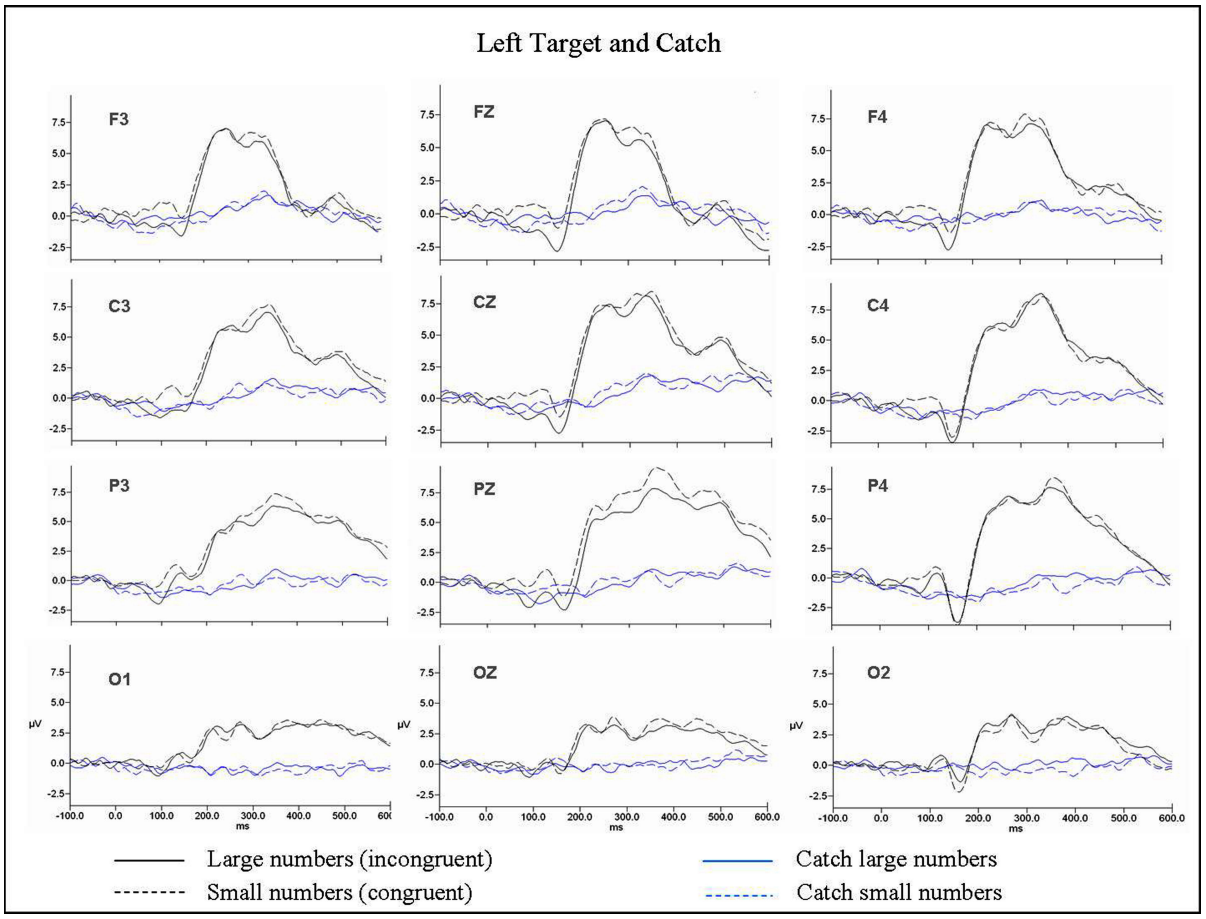

Figure 2. Illustration of the variations in brain electrical activity time-locked to the left target (black trace) and catch (blue trace) when large number (solid line) or small number (dashed line) were presented in cue. Each trace represents an average of electrophysiological data recorded from 12 participants. While EEG was recorded from 28 electrodes, only the most representative clusters of electrodes (24 electrodes) were analysed using ANOVAs, and selected traces from 12 electrodes are presented.

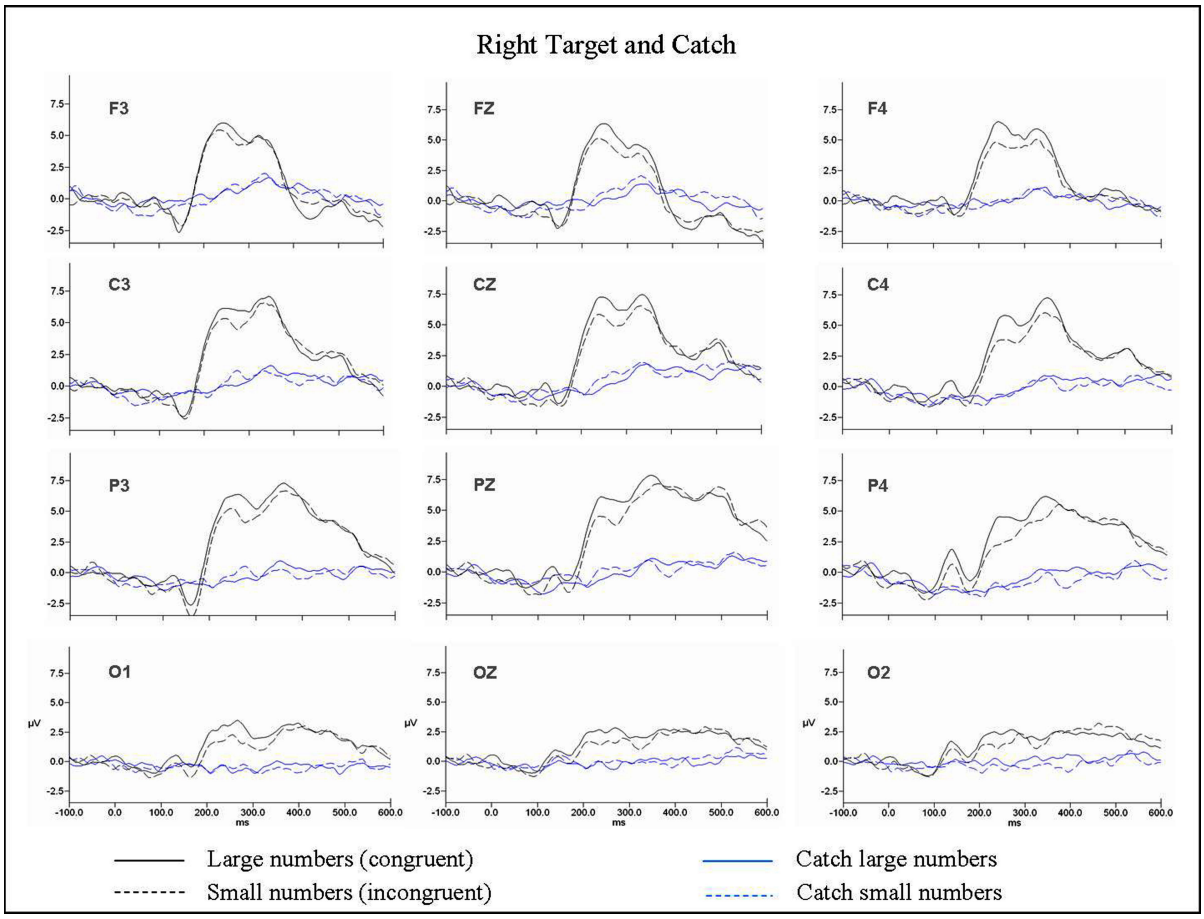

Figure 3. Illustration of the variations in brain electrical activity time-locked to the right target (black trace) and catch (blue trace) when large number (solid line) or small number (dashed line) were presented in cue.

Table 1. Mean amplitudes and standard deviations of the ROI x congruency interaction for the P100 and P300 components.

ROI	P100		P300	
	Incongruent	Congruent	Incongruent	Congruent
Anterior	-1.54 (0.45)	-0.82 (0.36)	3.74 (0.37)	4.31 (0.39)
Centro-Parietal	-1.57 (0.38)	-0.83 (0.42)	6.16 (0.77)	6.82 (0.76)
Occipito-Temporal	-0.61 (0.25)	-0.51 (0.23)	3.63 (0.67)	3.61 (0.59)

Discussion

The ERP results from this experiment are consistent with the behavioural data of Fischer and collaborators (2003) and add new important information: First, as revealed by the modulation of the P100 sensory processes seem to be modulated by the congruency between number-cue and the target location. These early congruency effects begin as early as 80 ms. after the presentation of the target. Second, not only sensory processes but also later cognitive processes are modulated by the congruency between number size and location of the target, as revealed by the modulation of the P300. Third, maximal amplitude differences of the congruency effects are located in Anterior and Centro-Parietal areas (for P100 and P300)

The sensory P100 component has been shown to be enhanced when a target is presented at an attended location, which has been previously cued by an external cue. The effects of congruency in this component are typically distributed in occipital sites and the generators of the P100 have been identified in the extrastriate cortex (Hillyard and Anllo-Vento, 1998; Mangun et al., 1997). The cueing generates an amplification of the signal (i.e. P100 bigger amplitude) when a target appears at the cued location. Some

studies have explored the bias of selective attention to location generated by representational stimuli (e.g. Awh et al., 2000; Nobre et al., 2004), but these studies always entail that a previously presented visual stimulus is held in memory. By contrast, in our study, the shifts of spatial attention generated by numbers were purely representational and there is no explicit spatial stimulation, as the number was presented centrally. Modulation of the P100 (larger positivities for congruent than incongruent trials) provides neural evidence that a centrally presented number-cue can also influence the mechanism of attention to external locations. However, and although the P100 component had a tendency to have larger amplitudes in occipital sites, the effects of congruency were not located in occipital areas (see Table 1). Therefore, the stage of processing indexed by the modulation of the early-P1 could receive input from different generators with external and internal representational spatial cues acting through different mechanisms. This process points to the presence of more widely distributed networks in congruency effects when representations with spatial characteristics like numbers are taken as cues (which may be due to the close relation between parietal cortex and number representation). On the basis of our results, we may speculate that perceiving number cues implies an intermediate spatial representation (generated in the intraparietal cortex) that has a direct effect on the amplitude of the P100. Different fMRI studies have suggested the possibility that parietal areas can exert attentional control over the neural transformations occurring in striate cortex (Fink et al., 1996; Wood et al., 2006), demonstrating top-down modulation of early processes of selective attention. We believe that this top-down mechanism could also explain the distribution of the congruency effect in our experiment.

Not only sensory processes are influenced by congruency: the two congruency conditions differed in their cognitive requirements, as evidenced by the fact that P300

component is modulated by the cue-target congruency. P300 increases in amplitude in congruent trials. This result differs from Mangun and Hillyard (1991) which showed smaller amplitude for valid trials. The difference between their study and ours has to do with the manipulation of the probability of the target. In their study, Mangun and Hillyard presented invalid targets with a lower probability of appearance, which triggered a larger P300. In our study congruent and incongruent trials are equally probable. Thus P300 is an index of validity and not of detection of infrequent stimuli. Our results are rather consistent with those of studies where the degree of endogenous attention to the location of the target increases gradually the amplitude of the P300 (Mangun and Hillyard, 1990). Exogenous (at short ISIs) and endogenous attention can modulate the amplitude of the P300 depending on the cueing condition (Hopfinger and Magnun, 1998, 2001; Hopfinger and West, 2006). This P300 effect is explained in terms of the increase of relevance of the cued location. Endogenous factors have also been described in terms of attention allocation, retrieval and maintenance of a representation in working memory (Kok, 2001; Bashore and Van der Molen, 1991; Johnson, et al., 2007); factors that increase P300 amplitude. We believe that the larger P300 amplitude found for congruent trial signals that a trace of the relevance of a location may have been hold in working memory (Donchin, 1981). In our view, the perception of the digit could activate the spatial representation of the number. Then its position in the mental number line is held in working memory determining the relevance of a certain location in external space. In support to this interpretation, a previous study of neglect patients has shown that right brain damage to prefrontal spatial working memory structures is the main source of pathological rightward deviation observed (Doricchi et al., 2005).

One last comment concerns the degree of control in the orienting effect that comes into play within the present paradigm. Also from this perspective, the present study suggests an endogenous, top-down nature of attention orienting generated by central numbers. According to the timing conditions and the predictive characteristics of the target that have been used in the previous literature no modulation of the P100 and P300 should be found (Hopfinger and Mangum, 2001; Hopfinger and Ries, 2005). Only endogenous orienting would increase the amplitude of the P100 and P300 at the ISI used in the present study (equal to a SOA of 750 ms.). This observation perfectly fits with the point raised by Ristic, Wright and Kingstone (2006). The orienting effect for central digits in this paradigm emerges slowly, suggesting that top-down endogenous processes may be mediating this effect. The authors give behavioural evidence of a flexible representation of the mental number line, which can be controlled endogenously.

Overall, the course of the components described in this paper better specifies the processes taking place in the paradigm proposed by Fischer et al., (2003). Although the digits are irrelevant for the task[2], participants activate a spatial representation (left to right "mental number line"). The relative magnitude of the number, small or large, generates an orienting of attention on this representation towards the left or the right visual field, respectively. More precisely, P100 modulation indicates that this shift of spatial attention cues external spatial representation and is able to amplify the sensory input of the target when it coincides with the cued location. A second process implies that this spatial representation is held in spatial working memory and modifies the relative relevance of the two hemifields, as signalled by the modulation of the P300.

The present data must be taken as another index of the close link between number representation and space representation (Walsh, 2003, Dehaene et al., 2003).

They extend and clearly establish that the perception of irrelevant digits activates the semantic representation of numbers and has an effect on spatial attention to subsequent spatial stimuli. Moreover, these data increase our understanding of the mechanisms behind spatial cueing generated by pure representations and provides a baseline in neurophysiologic terms for this paradigm. Whether changes in the instructions related to the kind of representation required for retention in memory would change the present pattern of ERPs is an open question.

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FOOTNOTES

[1] A separate analysis was made for catch trials comparing large and small numbers. This was made in order to identify possible differences between numbers not due to the experimental manipulation. Results showed no significant differences in both latency bands.

[2] Note that the task is indirect, which according to Cohen Kadosh et al., (in press) allows a clear access to mental representation.

5.2. Numbers in the blind's "EYE"

ABSTRACT

How do the blind represent and process numerical magnitude? Although lacking visual experience with numerosities, recent evidence (Castronovo and Seron, 2007a) shows that the blind perform similarly to sighted persons on numerical comparison or parity judgement tasks. In particular, on tasks presented in the auditory modality, the blind surprisingly show the same effect that appears, in sighted persons, to demonstrate that numbers are represented through a spatial code, i.e. the Spatial-Numerical Association of Response Codes (SNARC) effect (Dehaene, Bossini and Giraux, 1993). But, if this is the case, how is this numerical spatial representation processed in the brain of the blind? Here we report that, although blind and sighted people have similarly organized numerical representations, the attentional shifts generated by numbers have different electrophysiological correlates (sensorial N100 in the sighted and cognitive P300 in the blind). This result highlights possible differences in the use of spatial representations acquired through other modalities than vision in blind population.

Introduction

Blind as well as sighted people show the SNARC effect (Castronovo and Seron, 2007a). This effect (Dehaene, Bossini and Giraux, 1993) consists of the fact that, within a given interval, people in cultures where numbers are written from left to right are faster at making judgements (e.g. odd/even judgements) about smaller numbers with the left hand but are faster with their right hand for larger numbers. This effect has been interpreted to reflect the automatic activation of an internal representation of magnitude where numbers are represented along a left-to-right oriented mental number line. Fischer, Castel, Dodd and Pratt (2003) investigated whether this internal representation could induce a shift of attention in the corresponding visual field. To address this question, they used a detection task in which irrelevant central cues (i.e., numbers 1, 2, 8 or 9) were presented followed by a lateralized target. Following large number cues (e.g., 8 or 9), detection times were lower for targets presented in the Right Visual Field (RVF), whereas after small numbers (e.g., 1 or 2) detection times were lower for targets presented in the Left Visual Field (LVF). In other words, Fischer et al. found a congruency effect where congruent trials are RVF and LVF targets presented after a large or a small number respectively, and incongruent trials entail the opposite combination of number size and target location. This finding suggests that the location of attention that follows number perception influences the location of attention in the visual field and that similar structures underlie attention shifts across internal spatial representations and external space. The electrophysiological correlates of this effect were recently described in sighted people (Salillas, El-Yagoubi and Semenza, 2008). In the present ERP study, we adapted this paradigm to the auditory modality in order to test blind people.

People suffering congenital or early onset blindness have necessarily experienced numbers and numerosities in a different way compared to sighted people. We hypothesized that if shifts of attention induced by the perception of numbers differ between the blind and the sighted, then differences on the sensory (N100) and cognitive (P300) ERP components should be observed. Modulation of the sensorial N100 has been indeed obtained with external cues in blind (sound presented in the left or right auditory space, Röder et al., 1999). Binaurally presented numbers were provided as cues in order to determine if the modulation of this component in the blind is also generated by this internal representation. Moreover, the serial characteristics of the auditory modality, and the higher span of the auditory working memory in blinds (Hull and Mason, 1995) could have an impact in the way that the blind manipulate numerical representations. Consequently, a component like the P300, which is an index of working memory load (Kok, 2001; Johnson, Michell, Raye and D´Esposito, 2007) may be sensitive in this auditory paradigm, especially in the blind who are required to compensate for lack of access to the visual modality. The development of representations with spatial characteristics through other modalities than vision may thus have an impact in the general manipulation of these representations.

Our paradigm (fig 1a) consisted in the binaural auditory presentation of high (8 or 9) or low (1 or 2) numbers. The number was followed by a fixed delay of 450 ms. and then a lateralized target was presented through dichotic listening. Seven sighted (mean age 34.4 years ranging from 22 to 50) and seven early-onset blind participants (mean age 35.4 years ranging from 25 to 50) completed the two experiments. The experimental session was divided in 4 blocks of 60 trials during which a total of 240 trials were presented. ERPs were computed by averaging the EEG records associated with the presentation of the target (see Methods for EEG recording and analysis).

Methods

Stimulus and apparatus

Numbers were recorded by a female speaker and compressed to a fixed duration of 350 ms. using Wavelab 4.0. Intensity of high (8 and 9) and low (1 and 2) numbers was equivalent (70 dB.). Lateralized auditory targets were presented using dichotic listening: in one ear a sine sound (166.67 Hz.) was presented and pink noise was presented in the other ear. Therefore a target on the right occurred when the sine sound was presented in the right ear and pink noise was presented in the left ear. The opposite presentation of the sine sound and noise occurred in the target on the left. Both right and left targets were identical and were generated by cross-splicing the same sound to the corresponding channel, therefore the two targets had exact acoustic characteristics. For catch stimuli, pink noise was presented in both channels. All experimental and catch sounds had a duration of 100 ms.

Procedure

Auditory stimulus were presented through headphones with a fixed volume for all participants (audio format PCM, 44100 Hz, 16 bits, stereo). A number (1, 2, 8 or 9) was binaurally presented with a duration of 350 ms. After a fixed delay of 450 ms. a target was presented through dichotic listening or a catch-noise sound was presented binaurally. Both target sounds and catch sounds had a duration of 100 ms. In the behavioural experiment a detection of the target was requested immediately. If a catch sound had been presented the participant had to do nothing. In the ERP experiment, after a delay of 2000 ms. from the presentation of the target a different sound signalled the moment in which the subject had to press a button if a target had appeared before (delayed detection task). ERPs were measured from the initiation of the target or catch

sounds. In both experiments, the hand used for the response was intermixed across blocks and balanced across participants. All participants were requested to close their eyes while performing the tasks.

EEG Recording and data analysis.

Continuous EEG was recorded from 28 scalp electrodes mounted on a elastic cap (Electro-Cap international) and located at standard left and right hemisphere positions over frontal, central, parietal, occipital and temporal areas (International 10 / 20 System, at Fz, Cz, Pz, Oz, Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, Ft7, Ft8, Fc3, Fc4, Cp3, Cp4, Tp7, Tp8,). These recording sites plus an electrode placed over the right mastoid were referenced to the left mastoid electrode. The data were recorded continuously throughout the task by a SynAmps amplifier and NeuroScan 4.3. software. Each electrode was re-referenced off-line to the algebraic average of the left and right mastoids. Impedances of these electrodes never exceeded 5 kΩ. The horizontal electro-oculogram (HEOG) was recorded from a bipolar montage with electrodes placed 1 cm. to the left and right of the external canthi; the vertical (VEOG) was recorded from a bipolar montage with electrodes placed above and below the right eye, to detect eye movements. EOG activity were detected by wavelet analysis and corrected using a regression method in the time domain (Semlitsch, Anderer, Schuster and Presslich, 1986). Epochs from 100 ms. before and 600 msec after the presentation of the target were extracted from the EEG. The EEG and EOG were amplified by a Synamp´s amplifier digitized at a rate of 500 Hz and filtered with a band pass of 0.01-30 Hz. Another filtering (low-pass filtering cutoff of 5 Hz. (Edgar, Stewart and Miller, 2005) was performed in order to remove alpha rhythm that could be different between blind and sighted participants, with eyes closed. Epochs were

excluded from averaging if they contained amplitudes outside the range +/-150 µV at any EEG site. ERPs were extracted by averaging trials separately for subjects, electrodes, and experimental conditions.

The preceding 100 msec period was used as a prestimulus baseline. ERP averages were analysed by computing the mean amplitude in selected latency windows. ANOVAs were used for all statistical tests and were carried out with the Greenhouse-Geisser correction for sphericity departures (Geisser and Greenhouse, 1959). To explore the potential topographic differences, ANOVAs were conducted separately for midline and lateral electrodes. ANOVAs for midline electrodes used a repeated-measures design taking group (blind /sighted) as a between subjects factor and as within factors congruent/incongruent, side of presentation of the target (Left Visual Field (LVF) / Right Visual Field (RVF)), Localization (2 Regions Of Interest [ROIs] or Area; Anterior and Posterior) and electrodes (2 for each ROI with Anterior including: Fz, Cz, and Posterior including: Pz and Oz). ANOVAs for lateral electrodes also used a repeated-measures design with congruency (congruent/incongruent), side of presentation of the target (Left Visual Field (LVF) / Right Visual Field (RVF)), hemispheres (Left vs. Right), Localization (2 Regions Of Interest [ROIs] or Area; Anterior, and Posterior), and electrodes (6 for each ROI with Left Anterior including: FP1, F7, F3, FT7, FC3, C3; Left Posterior: CP3, T3, TP7, P3, T5, O1; Right Anterior: FP2, F8, F4, FT8, FC4, C4; and Right Posterior: CP4, T4, TP8, P4, T6, O2). A similar ANOVA was performed for the catch trials with Number (high and low) as within factor and group as a between subject factor all ERPs factors being the same.

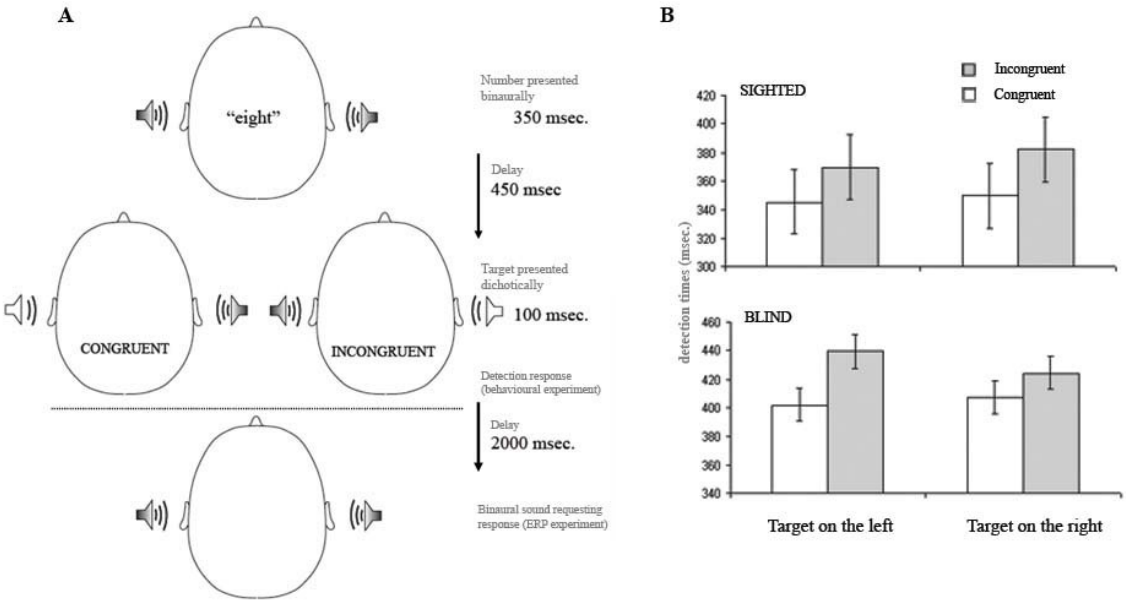

Figure 1. A) Experimental paradigm. B) Behavioural results

Results

Behavioural results.

A behavioural experiment was also conducted with a simple detection task right after the presentation of the target. This experiment was made in order to have reaction times from the experiment, as the delayed detection task in the ERP experiment may prevent to find any behavioural effect due to the time passed between the target and the response. The 2 (congruency) x 2 (side) ANOVA, taking group as a between subjects factor gave an effect of congruency (p=0.001) with not interaction by side or group (sighted: p=0.043; blind: p=0.01). Targets in congruent trials were detected faster than targets in incongruent trials. (Fig 1B)

Figure 2 and 3 provide a comparison of the ERPs for congruent vs. incongruent trials in each side of the presentation of the target for sighted (fig 2) and blind (fig 3) participants. A visual inspection of the ERPs of congruent vs. incongruent trials showed two main components that were differentially modulated by congruency depending on the group: while a negativity at the latency and distribution of N100 component showed a modulation by congruency in sighted individuals, a positivity at the latencies and centro-parietal distribution of P300 component showed modulation by congruency in blind individuals. A peak-latency analysis in a window between 80 and 180 ms. for the N100 and between 200 and 500 ms. for the P300 did not reveal any difference in latency between the groups or conditions in any of the components for the experimental trials (average peak latency of 140.5 ms. for the N100 and 314.2 for the P300).

Statistical analysis by a 2 (congruency) x 2 (side) x 2 (hemisphere) x 2(ROI: anterior/ posterior) x 6 (electrode) ANOVA for the lateral analysis and by a 2 (congruency) x 2 (side) x 2 (ROI) x 2 (electrode) ANOVA for the midline electrodes, confirmed these observations. An interaction between group and congruency showed

that the N100 (latency band between 100 and 180 ms.) was modulated by congruency only in sighted participants (lateral: p=0.013; midline: p=0.014). In this group, congruent trials elicited larger amplitudes than incongruent trials independently of the side of presentation of the target (p=0.019; p=0.03). The N100 for both groups as well as the congruency effect in sighted participants were localized in anterior sites as shown by a main effect of ROI (p<0.001; p<0.001) and the interaction between congruency and ROI in the sighted participants (p=0.03; p=0.018; anterior sites: p=0.008; p=0.01; posterior sites: n.s.). The P300 (latency band between 260 and 380 ms.) showed also a modulation by congruency, but in this case, only in the blind group as shown by the group x congruency interaction (p=0.004; p=0.007). Larger amplitudes for congruent trials appeared in the blind group, with no interaction by the side of presentation of the target (p=0.04; p=0.015).

Catch trials.

In the latency band of the N100 an effect of ROI was also shown in the catch trials (p=0.02 for lateral electrodes and p=0.001 for midline electrodes), therefore, the distribution of this component was the same for experimental and catch trials, with bigger amplitudes in anterior sites. An interaction number x hemisphere (F(1,12)=6.31; MSE=1.46; p=0.02) appeared. This interaction showed bigger amplitudes for low numbers in the right hemisphere, while there were no differences in the left hemisphere. The simple effects for this interaction were not statistically significant. No interactions by group or other effects were found in this component.

In the latency band of the P300 (300-420 msec) the same number x hemisphere were found in the lateral electrodes (F(1,12)=17.9; MSE=0.39; p=0.001). High numbers elicited a bigger positivity than low numbers in the right hemisphere. The simple effects of this interaction did not reach significance.

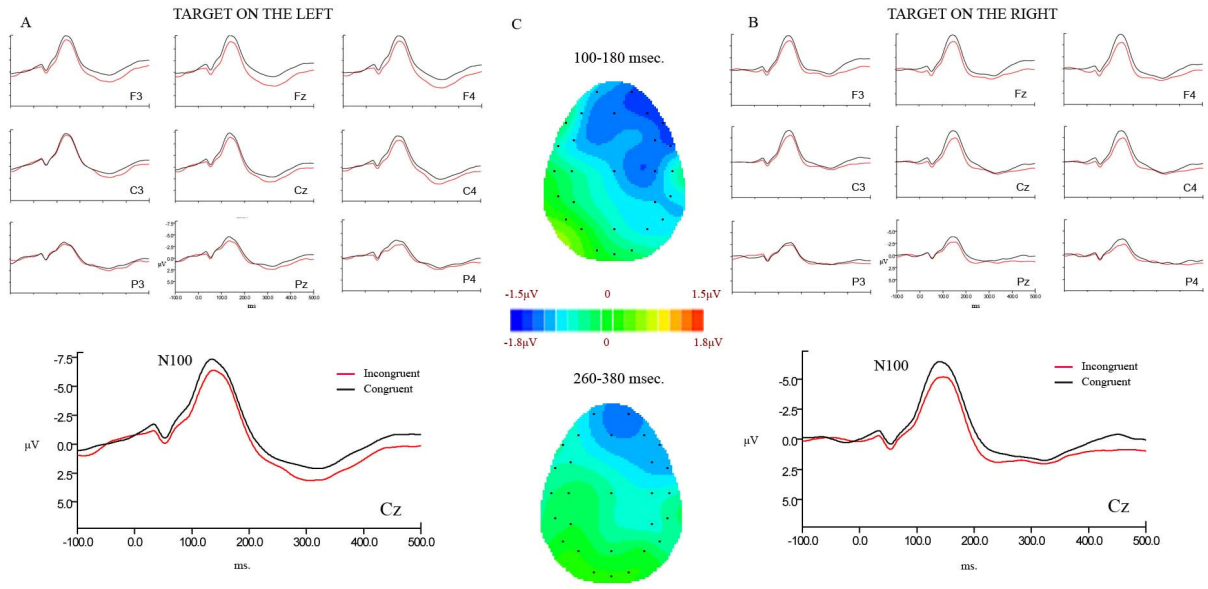

Figure 2. ERPs elicited by the target in sighted participants. 2a) target on the left; 2b) target on the right. Black line represents congruent trials and red line incongruent trials. 2c) Difference between congruent and incongruent conditions in the two latency windows.

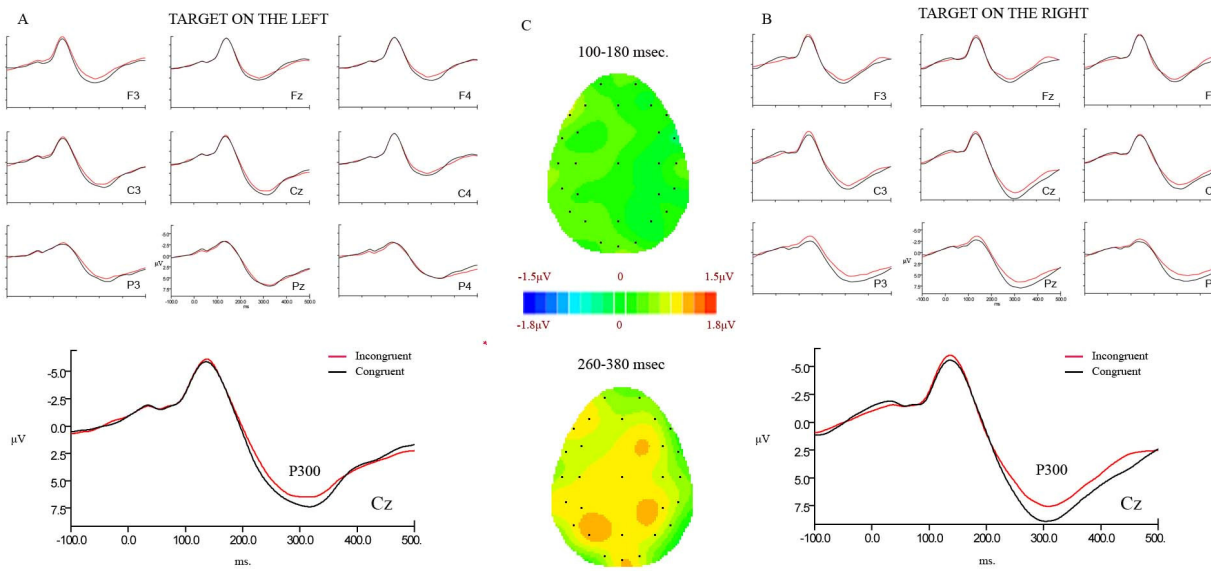

Figure 3. ERPs elicited by the target in blind participants. 3a) target on the left; 3b) target on the right. Black line represents congruent trials and red line incongruent trials. 3c) Difference between congruent and incongruent conditions in the two latency windows. A continuation of the N100 is shown in the latency window of the P300 (see Methods).

Discussion

The results of these experiments are consistent with the behavioural data of Fischer et al. (2003) and the ERP data from Salillas et al (2008), obtained in the visual modality and extend them to the auditory modality. Our behavioural data show the same spatial organization of the mental number line in blind and sighted populations. This was previously demonstrated by Castronovo and Seron (2007a). Importantly, however, the present work shows how the size of a heard number generates shifts of spatial attention also in the auditory space: this happens not only in sighted but also in early blind participants. However, different ERP congruency patterns occurred for blind and sighted. In the sighted, the early sensory component N100 was modulated by congruency. Previous work has shown enhanced N100 for the same stimulus when attended as compared to unattended sound location (Luck, 1998; Woods, 1990; Hillyard and Picton, 1987 for reviews). It has been suggested that these effects are generated by an enhancement of information received from the selected source, according to the amount of attention allocated to that input (Hilyard and Picton, 1987). Evidence further suggests that effects of selective attention to location exert an early influence already in the primary auditory cortex (Petkov, et al., 2004; Hugdahl, et al., 2000). In our experiment, access to a spatially organized internal numerical (Dehaene, Piazza, Pinel and Cohen, 2003) exerts spatial shifts of attention over the auditory space. Moreover, as signalled by the modulation of the N100, the effect of congruency between number and target location can be explained as an amplification of the auditory sensory processes. Importantly, this amplification may be the consequence of a top down mechanism: the sensorial activity of primary areas seems to be modulated by a higher order representation.

By contrast, in the blind group, ERP congruency effect was only observed in the cognitive P300 and not in the early N100 component. The P300 effect is explained in terms of the increase of relevance of the cued location (Hopfinger and Mangun, 2001; Hopfinger andd West, 2006). It is also described in terms of attention allocation, retrieval and maintenance of a representation in working memory (Kok, 2001; Johnson et al., 2007). Attending to these functional explanations of P300, the larger P300 amplitude found for congruent trials signals a trace of the relevance of a location may have been held in working memory. The absence of the same modulation in the N100 suggests that the activation of the number representation does not influence the sensory processing of the target. Accordingly, blind people restricted the processing of congruency to a cognitive level (P300) applying working memory resources to the computation of congruency. The absence of a modulation of P300 amplitude by congruency in the sighted group could be due to the modality of presentation of the stimuli. Provided that there is use of the visual modality, auditory working memory in the sighted is less necessary than in the blind (Thinus-Blanc and Gaunet, 1997). A different use of spatial representations may derive from the lack of vision. The manipulation of representations like those of numbers may become more dependent on working memory resources and thus more controlled.

In summary, although our RTs data as well as previous behavioural studies[1] show the same pattern for blind and sighted participants, our study has uncovered radically different neurophysiological correlates. The absence of visual input and the use of the auditory channel with less discriminative power and greater working memory requirements, may lead blind people to manipulate the mental number line in a more controlled way with respect to sighted, relying on working memory. This could explain why superior number estimation performance is found with respect to sighted people

(Castronovo and Seron, 2007b). To rely on a more controlled process when doing number estimation would result in a more accurate outcome.

In conclusion, this study demonstrated how numbers represented in the blind mind's "eye" are processed in a more controlled way with respect to sighted people. This may explain the superior performance of non-sighted people in some estimation tasks and, more in general, why in many cases of blindness math abilities reach a very high level of skill.

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5.3. Comparison across modalities: vision vs. audition in the relationship between number and space.

According to Hubbart et al. (2005) the accumulated data around the SNARC effect indicate that numbers automatically elicit task-, modality- and effector independent spatial representations, even when these spatial representations are not strictly relevant to the task. Numerical information can be conveyed in many ways, e.g., with Arabic or Roman symbols, in the form of finger postures, dot patterns or number words, and using either the visual, auditory or tactile modality. If the SNARC effect indicates access to the abstract representation of number magnitude then it should be insensitive to these variations. Several studies have obtained SNARC effects both when numbers were presented as Arabic digits or as written words (e.g., Fias et al., 2001; Dehaene et al., 1993; Nuerk et al., 2003). The SNARC effect has been used to index automatic access to a central semantic and amodal magnitude representation. This assumption of modality independence has been recently tested in other modalities. Nuerk et al. (2005) examined this question by systematically varying modality/notation (auditory number word, visual Arabic numeral, visual number word, visual dice pattern). The SNARC effect was found consistently for all modality/notation conditions, including auditory presentation. The size of the SNARC effect in the auditory condition did not differ from the SNARC effect in any visual condition. The authors conclude that the SNARC effect is indeed a general index of a central semantic and amodal number magnitude representation. Another evidence of SNARC effect in the auditory modality comes from the study of Castronovo and Seron (2007a) already described in the introduction. On the other hand, Rusconi et al (2006) described what they called the

SMARC effect (Spatial–Musical Association of Response Codes) where a SNARC-like association between pitch and space was described.

The ERP study we have just presented address this issue in a more strait-forward way. Certainly numbers generate shifts of attention in the auditory space thus, the semantic representation of numbers is accessed regardless the input modality for the number and the modality of the target. Both the behavioural and the electrophysiological data showed effects of spatial congruency between numbers and lateralized targets in blind and sighted participants. Nevertheless our study showed also some differences between the visual and auditory presentation of number-target pairs in the ERP components modulated by congruency.

When the attended space is auditory, sighted participants do not elaborate further the stimuli as blind people do (i.e. they do not show a modulation of the P300 component). The modality of the stimulus and the generated representation does not reach the kind of representation necessary to be able to cognitively manipulate it. Sighted participants show a modulation in the P300 when the target is visual probably reflecting a preferred visual modality for the representation of the mental number line. The relevance of the visual space is probably done through a visual image held in working memory. In fact, the P300 is shown to be more sensitive to unimodal cueing.

Teder-Sälejärvi et al. (1999) show precisely that early components such as the N1 are modulated when the attended modality is other that the actual modality in which the target is presented. The authors suggest that cross-modal interactions occur early in attention to spatial cues. Importantly, later components such as the P300 are only modulated in unimodal situations and show how a modulation of the P300 is absent in cross-modal conditions. That is, both early and late components show to be modulated in unimodal situations but only early components show modulation under cross-

modality. Similar modulations of the P300 only to the attended modality have shown by other studies (Nager et al 2006; Eimer and Schroger, 1998; Eimer, 2001).

This leads to the possibility that the visual modality is the preferred representation for numbers in sighted participants. That is why they show modulations in the P300 thus being able to further process the congruity when both the number and target are visual. When numbers and targets are auditory, it seems that only cross-modals effects appear at the N1 and no effects on the unimodal P300 are shown. The findings in reaction times studies lack the sensitivity to this differentiation and therefore show similar outputs of different underlying processes.

But what is happening in blind participants?. There are two possibilities: (1) that the representation of numbers has an auditory nature, some kind of "auditory image" as a consequence of a preferred modality and higher reliance on this modality in congenital blindness; (2) that this representation is less dependent on modality. Both possibilities entail modulations in the unimodal P300. And in any case, the absence of modulation in early processes (N1) points to different ways of manipulating numbers in blind population as stated in the second paper. Thus, the same left to right numbers´ basic representation held in early blindness. The lack of sight may influence the modality status of the mental number line, and the degree of control over this representation.

Blind subjects can held their amodal representation of the mental number line in working memory, while sighted participants can only further manipulate this representation when the context is visual. Thus reaction times studies that propose amodality of this left to right representation (Castronovo et al. 2007; Nuerk et al. 2005) may be final reflections indeed of different underlying processes for the auditory vs. visual for sighted and between sighted and blind participants. Our study, similar to that of Fischer et al. (2003) goes further in the phase of elaboration of the stimulus, therefore

it is more accurate in the study of space – numbers representational association. The ERP methods used in our studies allow to uncover processes that remain hidden when we pay attention to reaction times.

This lead us to think about the two theories on blindness and numbers representation described in the introduction: the sensory limitation hypothesis and the cognitive compensatory mechanism hypothesis. In light of our findings it is reasonable to propose that the lack of vision entails a difference not in the basic representation of numbers but in its manipulation and in the kind of imagery developed on it. While sighted develop a more visual-dependent representation, blind population represent numbers in a auditory or modality-independent format. Thus the present data favours the cognitive compensatory mechanism hypothesis: lack of vision leads to another kind of representation with same left-to-right characteristics which is manipulated in a different, more controlled way.

PART 2. NUMBERS AND MOTION

1. Why numbers representation may be related to motion.

Our initial exploratory hypothesis about the link between motion and numbers came from known interactions between tasks that imply dorsal pathway functions and the processing of numbers (e.g., Fias et al 2001). Dorsal pathway implies the processing of spatial localization (Ungerleider and Miskin, 1982) in the control of action (Goodale, 1995). The processing of motion as well as the processing of location are thought to be processed within the dorsal pathway (Ungerleider et al., 1998). The premise of highly interconnected networks related to the processing of numbers in the parietal cortex and those processing space (Dehaene et al., 2003; Walsh, 2003) could be extended to the interaction between numbers and motion.

The work of Fias et al. (2001) showed how when attending to the orientation of lines the presence of irrelevant digits generated SNARC effects on the response to orientation. When the task required the judgement about colors (object feature supported by the ventral pathway) the SNARC effect was not observed. The authors conclude that the efficiency of feature-based attention is determined by the degree of neural overlap of structures dedicated to processing relevant and irrelevant information (i.e. line-orientation and number semantics). More recently, Izard et al (2008) showed that in adults and 4-years-old children, number sense relies on a dorsal system of bilateral intraparietal areas, different from the ventral occipitotemporal system sensitive to object identity. Scalp voltage topographies and cortical source modeling revealed a similar distinction in 3-months-olds, with changes in object identity activating ventral temporal areas, whereas changes in number involved an additional right parietoprefrontal network.

Then, parietal cortex process also motion (see Culham et al 2001). As Culham suggests, an area in the ventral intraparietal area of monkeys is implied in the processing of polymodal motion (Bremmer et al 2001) (for a later report of this area as an area related to the horizontal intraparietal sulcus (HIPS) see Hubbard, 2005). Other authors have shown the implication of the intraparietal sulcus in motion processing (Shulman et al., 1999; Sunnaert et al., 1999; Braddick et al., 2000; Cabeza and Nyberg, 2000). Specifically and between other works, the paper of Sunnaert reports 17 areas of the human brain, including five in the parietal cortex, that respond to stimulus motion without eye movements. The authors emphasize that many potential motion areas exist other than human MT+ (the middle temporal area and surrounding regions) and provide a starting point for further investigations. One of these areas is the ventral intraparietal sulcus (VIPS), area that will be focus in the fourth paper of the present thesis. Cabeza and Nyberg (2000) reviewed 275 PET and fMRI studies and plotted activation foci for a wide variety of cognitive tasks. The authors reported parietal activation for perceptual and mental imagery tasks (particularly those that involve spatial or motion perception). The figure 5 shows the areas implied in space-motion perception and imagery. It can be clearly seen that these areas extend over parietal areas belonging to the dorsal pathway.

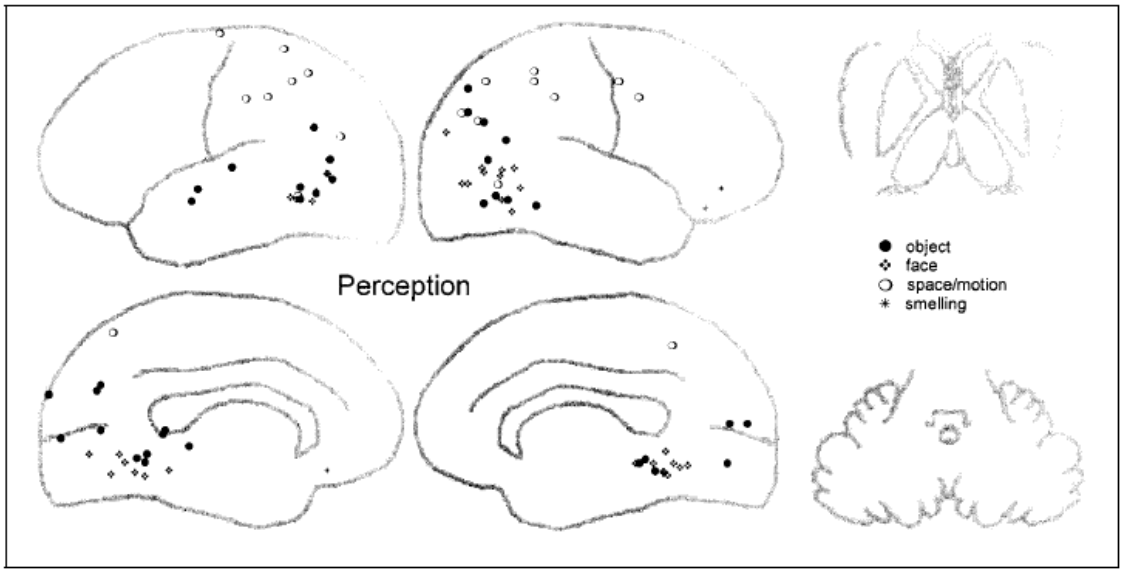

Figure 5 From Cabeza and Nyberg (2000). Space and motion areas are signaled by open circles.

This author reports also areas related to motion imagery in parietal areas. Motion imagery may be important to the possible motion processes along the mental number line, since we are talking about an internal representation over which a displacement of attention could be occurring. This distinction may be empirically developed as it remains partly speculative in light of the data provided by the present thesis.

In light of these anatomical correspondences, we attempted first to explore possible influences of motion in a task that implies the access to number semantics: number comparison. Once these influences were established, the second step was to provide empirical evidence of the anatomical overlap of motion and number processing.

Another related functional proposal made by McCrink et al. (2007) states that approximate arithmetic operates according to precise quantitative rules, perhaps analogous to those characterizing movement on an internal continuum. This proposal comes from the idea of an operational momentum effect, whereby addition problems are

overestimated and subtraction problems are underestimated. Nevertheless, these authors do not provide clear evidence of interference between motion and number processing.

The following two papers directly address (1) the possible influences of motion in the number comparison process, (2) a possible neural overlap between the two processes in the ventral intraparietal sulcus (VIPS) an area known as a motion processor and (3) the effects that the perception of motion has on the manipulation of numbers in hemispatial neglect.

2. Why VIPS as an area of intersection between numerical and motion processes.

A way of showing that motion processes (i.e. motion representation) is implied in numeric processes is to show how an area that responds to the perception (Sunnaert et al, 1999; Orban et al 2003) and imagery of motion (Goebel et al., 1998), when altered, affects numerical processes as well. This can be done by using Trancranial Magnetic Stimulation (TMS) and transitorily disrupting the functioning of this area while the participant performs a numerical and a motion perception task. The association would give us evidence of overlapping networks implied in these two processes.

As has been described, areas in the intraparietal sulcus have been shown to respond to numerical processes (HIPS) (Dehaene et al. 2003). We selected the motion area VIPS, which is localized in the intraparietal sulcus, due to its location with respect to the motion pathway and also to HIPS. Projecting from V3a into the intraparietal sulcus, the motion pathway continues in VIPS and extends more dorsally (Orban, et al. 2003; Vanduffel, 2002). Thus, if this motion network is connected to number network, VIPS is the optimal area to stimulate. Besides, as our hypothesis regards to the disruption of a motion area not previously related with numbers, we needed an area that allowed independent stimulation, and VIPS is far enough from HIPS for this.

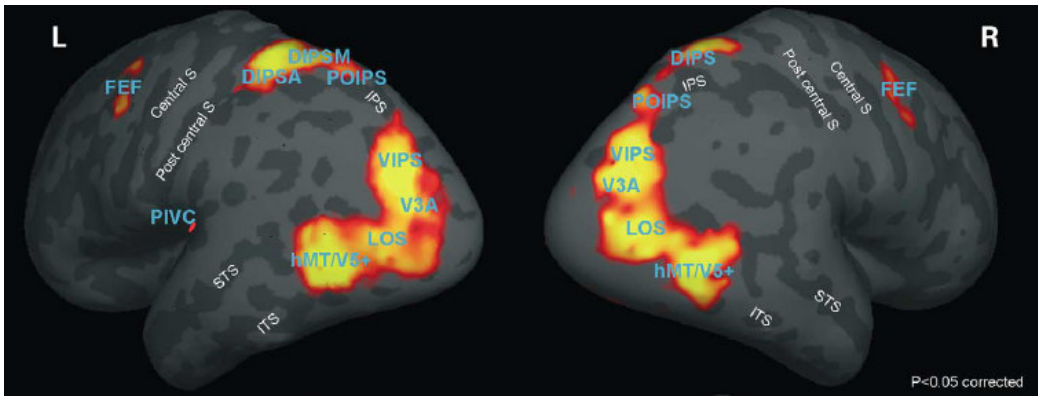

Figure 6. From Orban et al. (2003). Areas implied in the perpection of motion.

Indeed, it has been suggested that areas responding to motion in monkeys (VIP) could correspond to HIPS in human (Hubbard et al 2005). From this follows that these networks would be connected. We should emphasize we do not stimulate directly HIPS as our main thesis is that an area not previously related to numbers and known as processing motion can be shown to be linked to numbers.

3. EXPERIMENTAL STUDIES (II)

3.1. Effects of attention to motion on number processing.

ABSTRACT

In this study we aimed at exploring the impact of exogenous covert attention to moving stimuli on the process of numerical comparison. Number comparison is thought to imply the direct activation of the core quantity system, analogous to a mental "number line" oriented from left to right (e.g. Dehaene et al. 2003). Experiments 1 and 2 test the influence of motion perception in the process of number comparison. This process showed to be sensitive both to the direction of the signal on concurrent random dots kinematograms (RDKs) and to their level of coherence. Horizontal and vertical motion had an impact on number comparison times, which were facilitated when the target numbers concurred with rightward or upward motion. Overall, the results show that attention to motion can affect the process of number comparison, and that this effect may be independent from the effects of attending to location.

Introduction

Is there motion along the mental number line? Restle (1970) suggested that subjects calculate by mentally moving along an oriented number line, for instance shifting attention one step to the left of 3 to compute 3-1. If this is correct, then capturing the attention to a determinate direction of motion should affect this "mental moving" along the mental number line. One of the motives for studying the involvement of motion in number processing is the partial overlap between neuronal circuits processing spatial cognition and numerical representations in the dorsal pathway (Fias et al, 2001). For example, the inferior parietal areas (Chochon et al. 1999; Dehaene et al. 2003; Pesenti et al. 2000; Pinel et al. 2001) have been shown to sustain comparison tasks. Due to the sharing of circuits between motion and location processing along the dorsal pathway (e.g. Ungerleider et al. 1998), it seems plausible to also detect behavioural relations between numbers and motion as those found between location and numbers (Fischer et al 2003). For example, Fias et al. (2001) showed effects of irrelevant numbers on the judgement of orientation of lines, indicating an overlap between numbers and a task related with dorsal structures. On the other hand, some studies focussed on the brain areas implied in motion processing have shown the proximity of these areas to those that have been related to number processing (e.g. Braddick et al. 2001; Orban et al. 2003; Hubbard et al. 2005). Although both processed in the dorsal pathway, location and motion are two features whose processing seems to be hierarchically organized (eg. Anllo-Vento and Hillyard 1996): selection to location precedes selection to motion. Therefore, these features seem to be processed independently and consequently, also their possible relationship with numbers representation may have different characteristics.

Here we test the question of whether attention to motion can somehow bias the process of numerical comparison. The capture of attention to motion was done by means of the presentation of random dot kinematograms (RDKs), a stimulus that entails the processing of motion and its direction independent of attention to location. This is an optimal stimulus for extracting the direction of motion and not the relative position of a moving element. An RDK consists of a large number of moving dots randomly positioned within a restricted area. Each dot is assigned a particular motion vector. With these stimuli, a variable percentage of dots can be moved towards a single coherent direction (signal), while the rest of the dots carry on moving in random directions (noise). The perception of motion here is based on the joint displacement of the single elements, and the probability of a single dot being displaced toward a determined direction is called *coherence of element displacement*. The threshold of perception of motion is typically on 5-10 per cent of coherence. The dots appear and disappear in the window at different positions: due to the large number of dots (thousands) it is impossible for the observer to compute the relative position of any dot (Bosbach et al. 2004; Shadlen and Newsome 1996). This is a problem for other static moving elements such as gratings and may imply the computing of location rather than of motion. These stimuli allow to explore the effects of perception of motion, independently from a possible interaction between the direction of motion and the size of the number which could be explained by a process of attention to location (i.e. ending or initial point of motion) (Fischer et al. 2003).

We captured attention to motion by means of these stimuli and presented numbers to be compared. Due to the aforementioned overlap between dorsal pathway and number parietal areas we predicted an effect of motion perception on number comparison. We further hypothesized that the capture of attention by rightward motion

is expected to facilitate the comparison of one-digit numbers, as a default preferred direction, following the left to right direction of the mental number line (Dehaene et al, 1993).

One further question that may raise is whether this effect of motion in the direction of the mental number line also applies to the vertical dimension. Indeed, the mental number line has been found to adapt also to verticality: the SNARC effect, in fact, is not only present in the horizontal but also in the vertical dimension (eg. Schwarz and Keus, 2004; Gevers et al. 2006). While reading and writing are done from left to right but also from top to bottom, in the vertical dimension high numbers are associated to the top and low numbers are associated to the bottom. Therefore, we tested the possible interference of vertical motion on numbers in the upward direction. The impact of attention by motion on number processing would then follow the mental number line bi-dimensionality. Capturing attention to motion in rightward direction or upward direction would facilitate the process of comparison due to the facilitation of motion processes already present when we explore the mental number line.

Finally, we explored alternative explanations in terms of general preferences for perceiving rightward or upward motion. To do so, we presented RDKs with horizontal and vertical motion concurring this time with the presentation of colours that must be discriminated. A general preference for upward and rightward motion would lead to a preference for these directions in this task too. Otherwise, if this preference is related to the process of numerical comparison, no interferences of motion direction on colour discrimination should be found.

EXPERIMENT 1

The goal of Experiment 1 is to explore the effects of leftward or rightward horizontal motion on the comparison process by using RDKs that precede and coincide with the presentation of the target number. Three variations in coherence were introduced: 20 per cent, 40 per cent, and noise (0 per cent), with no coherent motion. Under these circumstances, we predicted: 1) A distance effect that would also prove the access to the analogue representation of numbers by the comparison process; 2) A motion effect should be found in the comparison process, showing the presence of attention to motion as a mechanism on the representation of numbers 3) This effect may be independent of the magnitude of the number, being equal for numbers higher or lower than 5; it is likely to find lower comparison times for motion to the right rather than motion to the left, and to the absence of coherent motion; 4) An effect of the coherence, as an indicator of the degree of capture of attention to motion.

Method

Participants

A total of 18 undergraduate students from the University of Trieste participated in the experiment, receiving credit for their participation.

Stimuli

The RDKs were created using VisionEgg, written in Python 2.3. A pool of 50 frames was generated as bitmap files. The velocity of the dots was 20º per sec. The total number of dots was 2000, and their size was 2 pixels. As one dot disappeared from the screen, another appeared in another random location beginning from the opposite edge. The bitmaps were then transformed into movies that lasted 2 sec each, using JPGVideo Version 1.05.0.0 (Independent JPEG group), and then into mpeg files. Five different movies were created this way, two with 20 per cent of coherence; in one of them the

coherent motion had a horizontal rightward direction, and, in the other, the coherent motion had a horizontal leftward direction. The other two RDKs had 40 per cent of coherence, again, one to the right and one to the left. The background in all of these movies was noisy, that is, the remaining 80 or 60 per cent of the dots were moving randomly across the window with an orientation of 45º. The last RDK was one of 0 per cent coherence: in this case, all the dots were moving randomly as described before. The background of the RDKs was black and the dots were white.

The digits (2, 3, 4, 6, 7, and 8) were white and had a size of 0.3º. As we will see below, they appeared while the movie was playing. During the whole trial a white cross (sized 0.3º) was present in the centre of the kinematogram, except when the number replaced the cross. The screen was set to black and its resolution was 1024 x 768 pixels.

Several aspects of the stimuli are relevant to the purpose of this experiment. Firstly, as in the other experiments, a cross was presented in the centre of the screen with the function of controlling eye movements. Secondly, in order to make sure the participants did not fix on or attend to the onset location of individual dots, as this could imply confounds of attention to location, the number of dots was high and the overall pattern did not move. So motion to the right and motion to the left were computed and not an initial or ending point of the motion stimulus. The dots moved across a limited central window with dimensions 600 x 500. Thirdly, the likelihood of presence or absence of a dot at a particular location was equal, and this information was never useful for the comparison task.

Procedure

The experiment was controlled from a portable PC-compatible Samsung X05 and was programmed using Presentation software. Each participant sat in front of the

screen at a distance of 60 cm, and was asked to perform a go-no go task: press a button only if the number was bigger or smaller than 5, depending on the requested response in the block. Left and right hand were also balanced in each block. The sequence of each trial was as follows: a cross appeared in the centre of the screen and was the only stimulus until the movie (RDK) began after 1000 ms. The number appeared 1000 ms. after the beginning of the movie and it remained in the centre of the screen until a response was given or after 1500 ms. As the movie lasted 2000 ms., the number coincided with motion during 1000 ms. or until response. If the response was not made before 1000 ms., the RDK stopped and the number remained for 500 ms. more or until response (see figure 6). Participants were not told about any relationship between the visual stimulus and the target number and they were asked to fixate at the central cross.

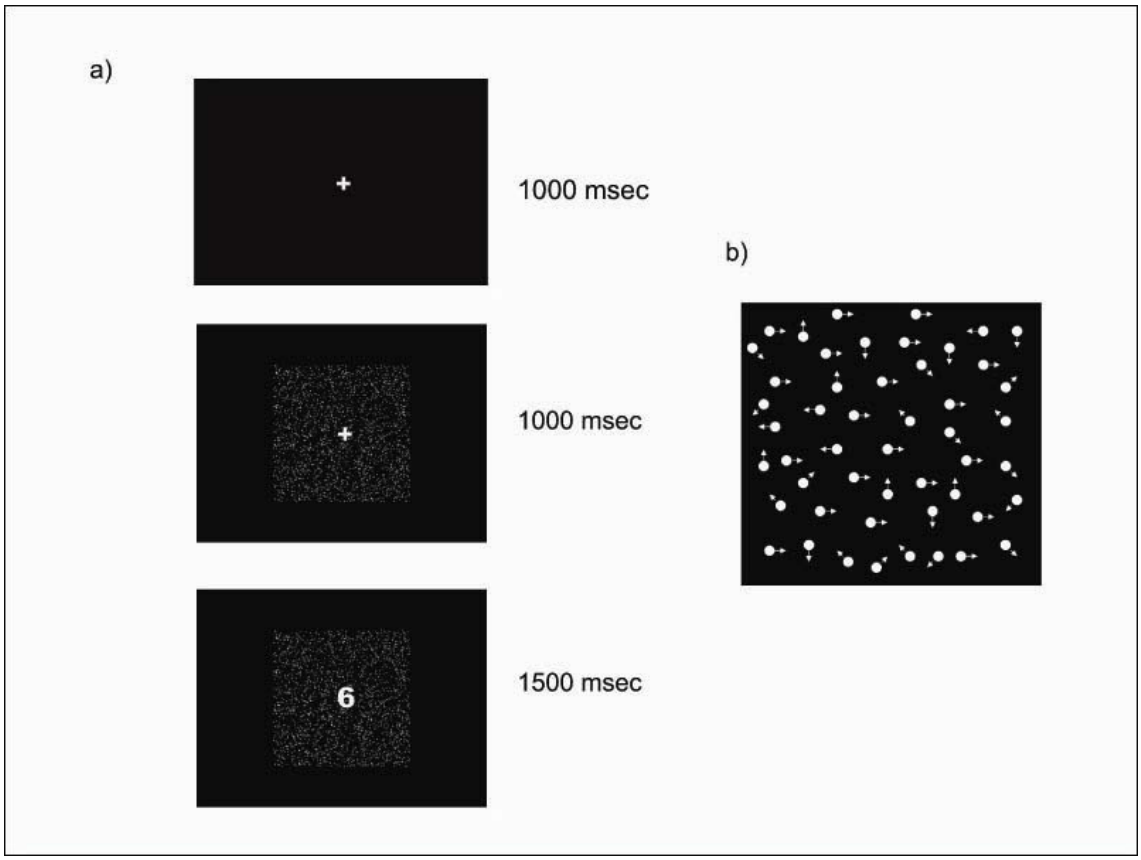

Figure 1. a) Experimental paradigm b) schematic view of a RDK with 40 % of the dots moving coherently. Vectors indicate the direction of the dots.

The total number of trials (including go and no-go) was 480, divided into eight blocks. The hand used and the number to which the response was made were fully randomized across blocks, obtaining 8 scores for each condition.

Results

Averages of comparison times were entered in a 2 (number: high/low) x 3 (distance: d3, d2, d1) x 2 (motion: to the right/to the left) x 2 (coherence: 20/40) analysis of variance (ANOVA). None of the block orders coincided between subjects, thus an analysis of block order was not necessary. Two participants were removed from the analysis due to mistakes in the hand-response combination.

A distance effect appeared, with higher comparison times for lower distances ($F(2,30)=38.2$ *MSE*= 1,472, $p<0.001$) than for shorter ones. A motion effect also appeared: comparison times were lower when the number was paired with motion to the right than when it was paired with motion to the left ($F(1,15)=13.68$, *MSE*= 470.1, $p<0.002$; $\eta 2=0.47$. Finally, a coherence effect was found: it was easier to compare numbers after an RDK of 40 per cent coherence than after an RDK of 20 per cent coherence ($F(1,15)=7.13$, *MSE*= 778.5, $p<0.017$; $\eta 2=0.32$), (see Figure 2).

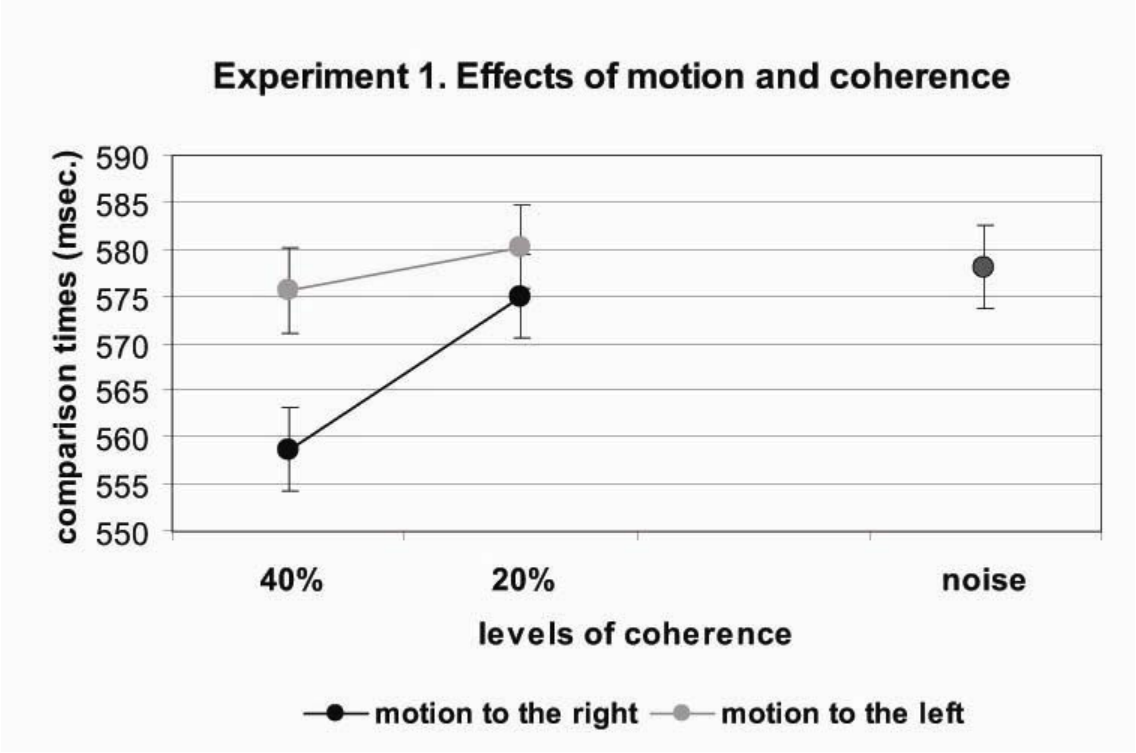

Figure 2. Experiment 1. Mean comparison times as a function of motion coherence and direction.

We performed an analysis between noise and each condition of motion and coherence in a 2 (number) x 3 (distance) x 2 (motion) ANOVA in order to compare each condition of motion and coherence with the condition where there was no coherent motion, that is the 0 per cent coherent RDK. For the 20 per cent of coherence the comparisons between noise and motion to the left, noise with motion to the right and between motion to the left and motion to the right did not show any effect of motion. Thus, the reported main effect of motion was mostly due to the 40 per cent of coherence conditions: the comparison in this level of coherence between motion to the right and noise was significant ($F(1,15)=6.832$, $MSE= 1303.4$, $p=0.02$) and also motion to the right versus motion to the left ($F(1,15)=6.495$, $MSE= 913.5$, $p=0.02$); the comparison between noise and motion to the left was not significant.

We performed a 2 (number) x 3 (distance) x 2 (coherence) ANOVA that allowed us to see the effects of coherence for each direction of motion. The effects of coherence were significant in the condition of motion to the right ($F(1,15)=12.86$, $MSE= 414.6$, $p<0.003$) and not significant in the condition of motion to the left ($F<1$).

An analysis of possible interactions with SNARC and Simon effects was performed. With regard to the SNARC effect, we grouped data in congruent and incongruent trials according to the presented associations of hand and number. Congruent trials were those where the right hand was used to respond to high numbers and those where the left hand was used to respond to low numbers; incongruent trials were those where the right hand was used to respond to low numbers and left hand to respond to high numbers. A 2 (congruent/incongruent) x 2 (motion to the right/motion to the left) x coherence (20 per cent / 40 per cent) ANOVA was performed. No effect of congruency ($F<1$) nor any interaction between congruency and motion was found, the

comparison times were always faster in front of rightward motion. The comparison between congruent and incongruent essays for the noise condition was not significant.

Similarly, we explored the possible influences of congruent and incongruent Simon trials (Bosbach et al. 2004). Congruent trials were defined as those that implied congruency between the direction of motion and the hand used: leftward motion and left hand, and rightward motion and right hand; incongruent trials were those that presented rightward motion and were responded to with the left hand and those that presented leftward motion and were responded to with the right hand. A 2 (congruent/incongruent) x 2 (motion to the right / motion to the left) x 2 (20 per cent of coherence/ 40 per cent of coherence) ANOVA was performed. The analysis did not show any effect of congruency ($F<1$) or significant interaction of congruency by motion ($F<1$).

The RT distribution in 6 bins was computed collapsing the variable distance. A 2(number) x 2 (motion: to the right/ to the left) x 2 (coherence) x 6 (bin) showed an interaction motion x coherence x bin ($F(5,75)=3.84$; $MSE= 2,367$; $p<0.04$) showing an effect of motion with coherence of 40 per cent and not on 20 per cent as shown in the first analysis and with an effect of motion that gets stronger in the last bin in this level of coherence (see figure 3). An analysis of each bin separately showed a significant effect of motion only in the sixth bin ($F(1,15)=6.35$; $MSE=4,516$; $p<0.023$).

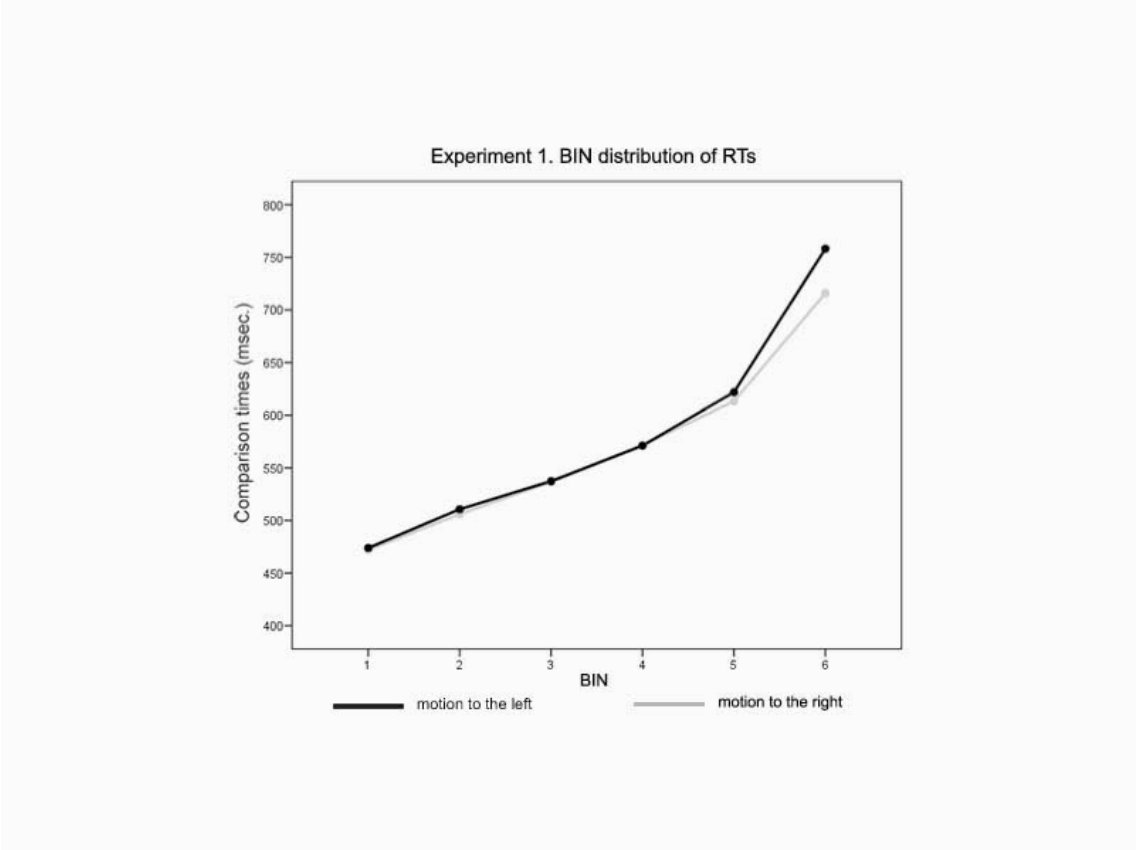

Figure 3. Experiment 1. Mean comparison times as a function of bin and direction of motion

Discussion

Besides the distance effect, that can be considered as a signal of access to the magnitude analogue representation of quantity, Experiment 1 gives an initial answer to the question of the possible existence of processes of attention to motion on the mental number line. The RDK is a stationary moving signal and what the participant perceives is the direction of motion and not a location with respect to the fixed cross (Bosbach et al. 2004). It should also be pointed out that the experiment involves the precedence but also the simultaneity of the visual motion and the number that is being compared in our task. This simultaneity was chosen in order to avoid an effect from the ending or starting point of the motion which would have been equivalent to study location, and

therefore, in order to detect the effect of motion. Under these conditions, facilitation is found for motion towards the right compared to motion towards the left and noise. As predicted, no interaction with number was found, with comparison times both for high and low numbers reduced when the comparison process is paired with rightward motion, indicating an independent process from that of attention to location (Fischer et al. 2003; Tlauka 2002). In addition, the comparison process was sensitive to the level of coherence of motion in the RDK: motion toward the right with 40 per cent of coherence having the strongest effect on the number comparison task. Moreover, it is interesting to notice that the coherence effect was stronger when the motion was towards the right, and this would discard the possibility that the effect of motion is due to a facilitation of motion to the right *per se* and not to the effects of the motion in the comparison task. For what concerns the comparison between coherent motion and noise, if we take the noisy situation as a baseline of no coherent motion, the data show facilitation from motion towards the right compared to noise and motion towards the left, especially when the motion had 40 per cent coherence. Motion to the left did not apparently inhibit the comparison process with respect to noise either at 20 per cent, or 40 per cent coherence, having the same effect as noise.

Having accessed the analogue quantity representation, as shown by the distance effect, the main effect of motion and the effect of coherence in rightward motion show that concurrent rightward motion helps the process of number comparison in relation to leftward motion and non-coherent motion. In other words, selective attention to rightward motion has an effect on number comparison times: this points to the overlap of these two processes. This effect is independent of the effect of location and is independent of the distance effect. Thus, a role of motion on the manipulation of numbers representation can be proposed. Due to the lack of interaction with distance,

this presence of motion processes in the mental number line seems to be independent of the spatial aspects in this representation. Regarding the preference for rightward direction, we certainly cannot propose this direction of displacement for all numerical tasks. Tasks as subtraction are proposed to generate a shift of attention to the left (Hubbard et al. 2005) therefore it may be predicted that when subtraction was used, a preference for leftward motion would be found. This question should be tested in the future.

EXPERIMENT 2

The proposed presence of motion in the comparison process, that is independent of the effect related to location (Fischer et al. 2003), would be reinforced if similar results were found using vertical motion. Therefore, a second experiment was conducted using coherent vertical motion instead of horizontal motion. We have pointed out the report of a vertical SNARC effect, where the mental number line is arranged from bottom to top. Thus, paralleling the results of horizontal motion, an upward motion preference and no interactions between the size of the number is expected. As rightward motion, upward motion reflects the direction of the mental number line, the direction to which magnitude increases. Similarly, an effect of motion coherence is predicted, leading to lower comparison times on its higher value. As it happened with horizontal motion, the effects of coherence should appear when the preferred direction of motion is present, thus reflecting not an increased general facility of integrating coherent motion, but a filtering of coherence through the preferred direction in the comparison process.

Method

Participants

16 undergraduate students from the University of Trieste did the experiment, receiving credits for their participation.

Stimuli

Vertical motion RDKs were generated in the same way as those of Experiment 1, with all parameters equal except that the signal was directed 90 or 270 degrees obtaining vertical upward or downward motion. In these vertical RDKs, the amount of coherent signal was again of 40 or 20 per cent.

Procedure

The procedure was identical to that of Experiment 1.

Results

Averages of comparison times were entered in a 2 (number: high/low) x 3 (distance: d3, d2, d1) x 2 (motion: upward/downward) x 2 (coherence: 20/40) analysis of variance (ANOVA). None of the block orders coincided between the subjects, thus an analysis of block order was not necessary.

An effect of distance appeared again with smaller distances from the reference number having slower comparison times than bigger distances ($F(2,30)=49.3$; $MSE=918$; $p<0.001$). The direction of motion and coherence also affected the comparison times, resembling the pattern of results found with horizontal motion (see figure 4). All comparison were faster when the number concurred with upward motion, as it was shown by a main effect of motion ($F(1,15)=4.65$; $MSE=617$; $p<0.04$; $\eta 2=0.23$)

and when they concurred with RDKs of 40 per cent of coherence, as it was shown by a main effect of coherence ($F(1,15)= 6.612$; $MSE=671$; $p<0.02$; $\eta 2=0.3$). No interactions by the size of the number were found, nor there were other main significant effects or interactions.

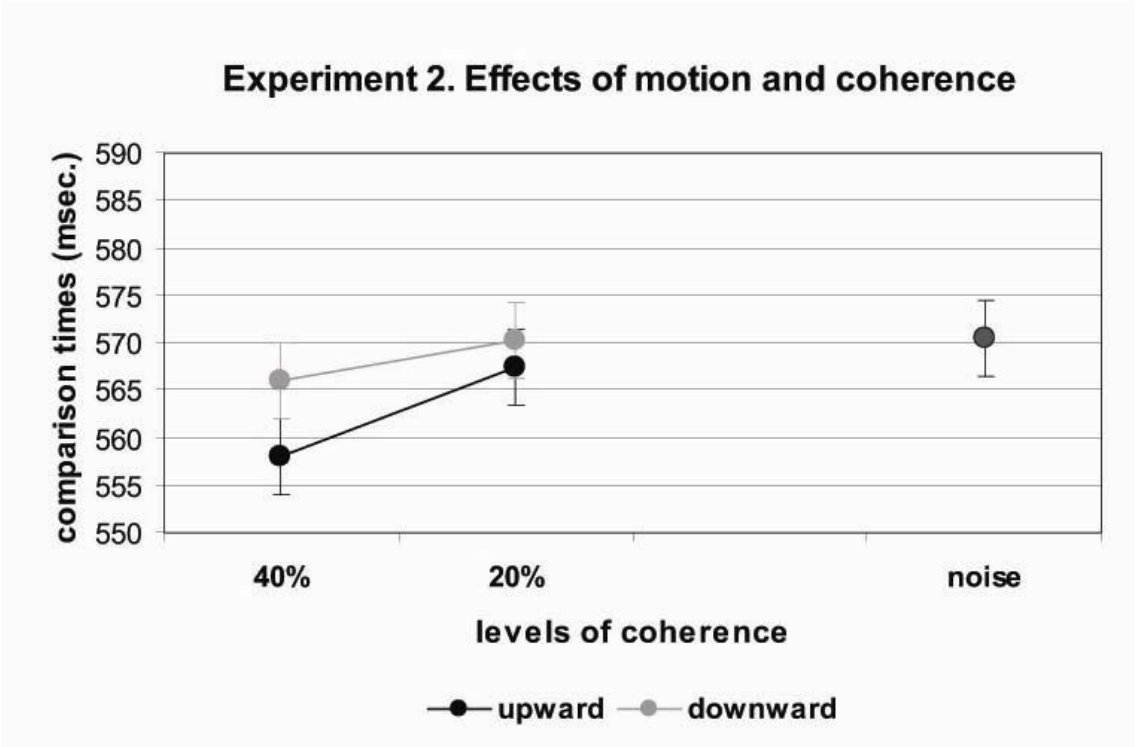

Figure 4. Experiment 2. Mean comparison times as a function of motion coherence and direction.

With respect to the condition of no coherent motion, 0 per cent o coherence, as in Experiment 1, a 2 (motion) x 2 (number) x 3 (distance) ANOVA was performed for each direction of motion and coherence in comparison to the noise condition. None of the directions of motion on 20 per cent of coherence showed to be statistically significant from the noisy condition. In 40 per cent of coherence, upward motion differed from random motion, showing lower comparison times when upward motion was presented with the number ($F(1,15)=4.71$; $MSE=1,573$;$p=0.046$).

The 2 (motion) x 2 (number) x 3 (distance) ANOVA for each level of coherence showed that the effect of motion on number comparison times was present only when the coherence level was 40 per cent ($F(1,15)=4.42$; $MSE=703$; $p=0.05$). And also similarly to what happened in Experiment 3, the effects of coherence were restricted to upward motion: the 2(coherence) x 2 (number) x 3(distance) ANOVA for downward motion did not show any effect of coherence, but it was shown for upward motion ($F(1,15)=5.76$; $MSE=734$; $p=0.03$).

The temporal distribution of the effect of motion was assessed in a 6 (bin) x 2 (motion) x 2 (coherence) x 2 (size). An interaction bin x motion was shown ($F(5,75)=8.94$; $MSE=2219$; $p=0.004$). The analysis of each bin showed that the effect of motion was allocated in the sixth bin ($F(1,15)=10.40$; $MSE=2923$; $p=0.006$). As in Experiment 1, no interaction between the direction of motion and the size of the number was found in any of the bins. Similarly to what happened in Experiment 1, and as expected from the main analysis, the effect of motion was only significant in the 40 per cent of coherence condition as the interaction motion x bin ($F(5,75)=5.45$; $MSE=3096$; $p=0.019$), with the only significant effect of motion in the sixth bin ($F(1,15)=7.37$; $MSE=4128$; $p=0.016$; $\eta 2=0.3$) (see figure 5).

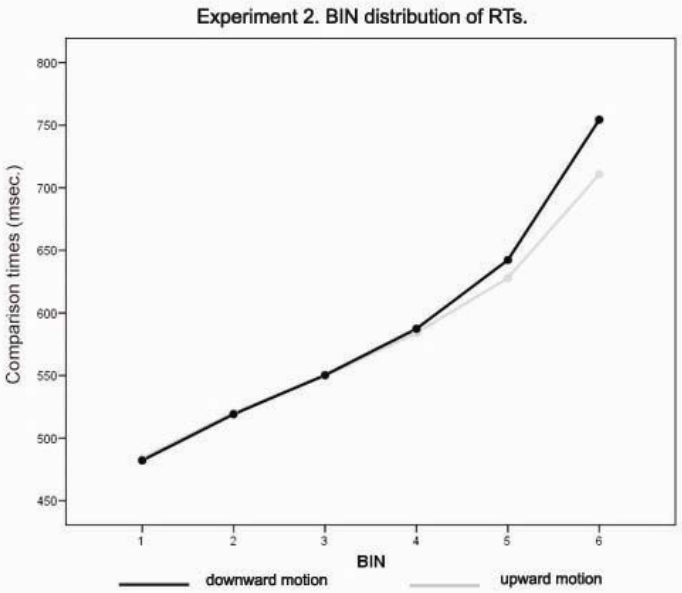

Figure 5. Experiment 2. Mean comparison times as a function of bin and direction of motion.

Discussion.

As in the previous experiment, an effect of distance appeared, pointing again to the actual access to the magnitude representation. Importantly, when vertical motion is manipulated, a similar pattern of comparison times arises as a function of direction and coherence of motion. No interaction between the size of the number and the direction of motion appeared. It is always easier to compare numbers when they are seen at the same time of upward motion, regardless of the size of the number and of the distance to the reference[1]. The independence from the size of the number indicates that the effects of attention to motion on the mental number line cannot be taken as the effects of attention to location. Thus, what the participants perceived was direction of motion, and this

direction cannot be reduced to its initial or ending point, which would have led to an interaction with the size of the number. Coherent motion *per se* is perceived and some directions of dots displacement seem to be congruent with the process of number comparison: rightward and upward motion, the directions of an (at least) bidimensional mental number line.

The effects of coherence are a second outcome of Experiment 2. Firstly, effects of motion are significant in front of coherence levels of 40 per cent, which would point to the necessity of perceptual salience of coherent displacement of dots in order to interfere with the process of comparison. Nevertheless, it has to be pointed out that both 20 and 40 per cent of RDKs coherence are well over the reported thresholds in the conscious perception of coherent motion. Moreover, the effects of coherence in vertical motion, as it happened with horizontal motion, are only present in front of what we can call congruent upward motion. It seems that the performance of the comparison task, as it was reflected by the pattern of number comparison times, is sensitive to the coherence of concurrent coherent motion only when this motion has a certain direction, namely, upward or rightward. This last finding would suffice to discard the possibility that the effects of motion showed here were due to default preferred directions. Experiment 3 was carried out in order to further discard this possibility.

EXPERIMENT 3

The purpose of this experiment was to find a classification task similar to the previous comparison by classification, with similar parameters in terms of choice options, but this task should not include numbers and should not imply dorsal overlap. The chosen task was a classification of colours as warm or cool. If under the same instructions of classifying targets other than numbers that concur with motion,

participants show preferences that coincide with those found in Experiment 1 and 2, then rightward and upward preference in these experiments would be a general perceptive preference. Otherwise, number comparison would be a process linked to motion. In this way, we could isolate possible preferences on the direction of coherent motion that were not dependent on number comparison. If preferences for upward and rightward motion were found here, as well as coherence effects for these directions, then the results of the last two experiments would be rather better explained as default preferences in motion perception which had nothing to do with the number comparison process. On the contrary, if this task is found to be independent of the motion parameters, then the motion and coherence effects found before should be linked to the comparison process.

It exists a fundamental psychological distinction between the composite categories warm and cool (Lindsey and Brown 2006). The category warm includes red, yellow, orange, purple, pink and brown, while the category cool is more restricted, including blue, green and "grue", a composite category (green or blue). Warm and cool colours are indistinctly localized on the right or on the left in colour carts, so an interaction with direction was not expected. Besides, colour and motion are processed in separately pathways and show temporary differences (eg. Wang et al. 2006; Livingstone and Hubel, 1988; Felleman and Van Essen, 1991).

Method

Participants

14 undergraduate students from the University of Trieste did the experiment, receiving credits for this participation.

Stimuli

The RDKs were the same as those used in Experiments 1 and 2: rightward, leftward, upward and downward motion with 20 or 40 per cent of coherence, plus a RDK with 0 per cent of coherence.

A coloured square was presented in the centre of the RDK, the dimension of the square were 0.3º x 0.3º. Warm colours were yellow (RGB colour code: 255, 255, 0), red (255, 0, 0) and orange (255, 140, 0), while cool colours were green (0, 255, 0), blue (0, 0, 255) and sea green (78, 238, 148).

Procedure

In order to ensure that participants performed well the classification task, they were presented the two categories of colours with the three colours in two displays. Once they had understood this classification, which was obvious for all of them, the experiment began.

Vertical and horizontal motion was presented randomly. The sequence and timing of the task was the same as in Experiments 1 and 2; the only difference was that instead of a number the coloured square was presented. The task was also a go-no go task: in some blocks they responded when there was a warm colour, while in some blocks when there was a cool colour; in some blocks they responded using the right hand and in others using the left hand. The whole experiment entailed 240 (go plus no go) trials, divided into vertical (96 trials), horizontal (96 trials) and noise (48 trials) in a total of four blocks. In this way, we kept the proportion of coherent motion / noise perceived by the subject in experiments 1 and 2.

Results

A 2 (color) x 2 (motion) x 2 (coherence) ANOVA was performed on the classification times both for horizontal and vertical motion. No main effects or interactions were found. In figure 6, the motion by coherence times are plotted, both for horizontal and vertical motion. As it can be seen, reaction times are in a similar range as those of number comparison; this shows that the two tasks are matched in difficulty.

Although no effects of motion were found, a similar motion (2) x bin (6) analysis of reaction times distribution in bins was performed for these data; which did not show an effect of the direction of motion in any of the bins.

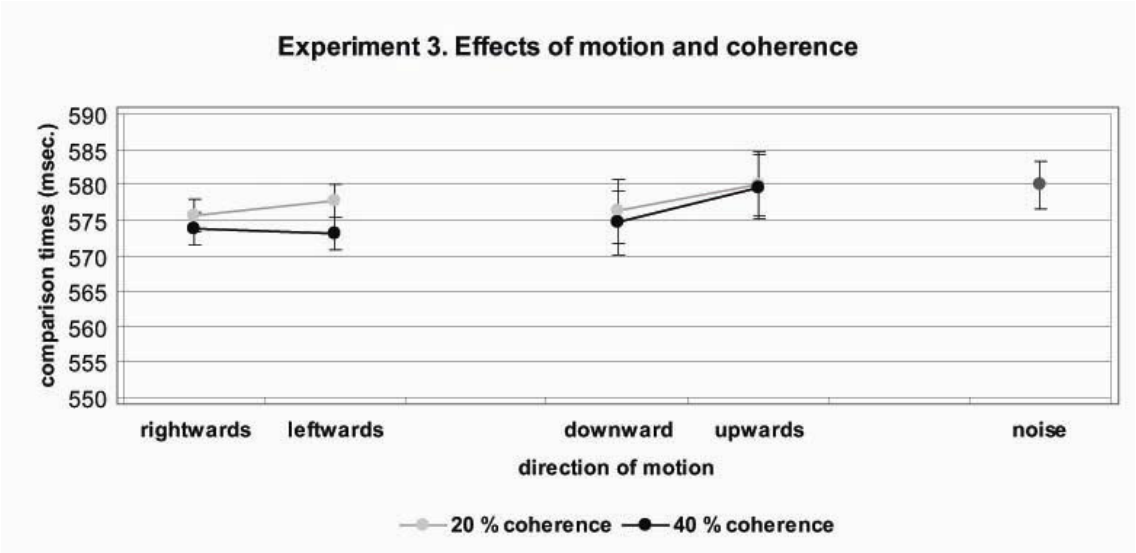

Figure 6. Experiment 3. Mean comparison times as a function of motion coherence and direction.

Discussion

The outcome of this control study supports the independence of the colour classification from the concurrent perception of motion. As we have reported, the

reaction times for this task were in a similar range as those of Experiments 1 and 2, which excludes an explanation of the differences between them in terms of difficulty. Even if the time course of possible interferences between colour classification and motion perception were different from those on number comparison, the present data suggests that the effect found in the latest reaction times for horizontal and vertical motion are due to an interference with the numerical comparison process and not to a general facilitation for upward or rightward motion at those intervals.

GENERAL DISCUSSION

In the first and second experiments, we made a first attempt to study the possible implication of motion in number processing. From the present data the possibility arises that processes of selective attention to motion are also implied in number comparison. Thus the outcome of the experiments, where rightward (Experiment 1) and upward (Experiment 2) motion has a general facilitation effect on number comparison, leads us to consider the possibility that actual motion happens in the analogue representation of numbers when a number has to be compared to another taken as reference. This preference for specific directions of motion during the comparison process agrees with experiments that explore the multidimensional character of the mental number line (Schwarz and Keus 2004; Gevers et al. 2006). Further evidence supporting this relationship is given by the fact that the facilitation of rightward or upward motion on number processing is modulated by the intensity of the motion signal, as shown by the effect of the percentage of coherent motion.

Results did not show any interaction of the direction of motion and the size of the number to be compared (see Fischer et al., 2003, for an interaction between size of the number and shifts of attention to location). Thus, motion and space-related

processes on the mental number line during number comparison would be somehow related, insofar they depend on the disposition of numbers in the mental number line. However, they are distinct processes, as shown by the lack of interaction between motion and the position of the number to be compared or between the motion and the distance effect.

With regard to the neural basis of these interactions, motion processing is thought to involve neural paths that are also activated in location processing, namely the dorsal pathway (e.g. Kaneoke et al. 1997, Ungerleider et al. 1998, Wang et al. 1999). The behavioural data presented here shows a relationship between this processing of location and motion and number processing, which would share neural circuits. There are proposals that have indicated a parietal involvement in number processing (Dehaene et al. 2003), both related to the analogue mental representation (horizontal segment of the intraparietal sulcus) or more related to attention processes in this semantic representation (posterior superior parietal lobe). Hubbard et al. (2005) have recently signalled the likely correspondence between the Horizontal Intraparietal Sulcus and Ventral Intraparietal Sulcus in monkeys, an area related to polymodal motion (Bremmer et al. 2001). That would connect a core representation of numbers with motion processes, although no empirical evidence has been provided so far. Further work using neuro-imaging techniques would shed some light on the actual neural intersection and functional mechanisms between number and motion, which we believe could involve more extended areas related to motion processing.

Footnotes

[1] Due to the similar pattern of results for horizontal and vertical motion, a joint analysis of experiments 1 and 2 taking rightward and upward motion as preferred direction was performed. It did not show any interaction between distance and motion or number and motion. The absence of this interaction in each experiment and the joint analysis suggest that a lack of statistical power cannot explain the absence of these interactions.

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3.2. Motion on numbers: Transcranial Magnetic Stimulation on VIPS alters both numerical and motion processes.

ABSTRACT

In this paper single pulse transcranial magnetic stimulation was applied to the Ventral Intraparietal Sulcus (VIPS), this showed to alter the performance in both motion detection and number comparison tasks. In the motion detection task, random dot kinematograms were presented with different levels of coherence: reaction times and the threshold for the perception of coherent motion increased when VIPS was stimulated with respect to the stimulation of the central sulcus (control site). In the number comparison task, numbers from 1 to 9 had to be compared with the reference number 5: again, reaction times slowed down when the stimulation was applied to VIPS with respect to the control site. These data reveal that TMS stimulation in an area implied in motion perception alters the number comparison process thus showing that motion and the processing of numbers in a comparison task are associated. If a process devoted to motion is what was altered by TMS stimulation, then a mechanism implying motion may – in turn – be operating on the mental number line.

Introduction

Different studies hypothesized a relationship between number representation and space (for a review see: Hubbard et al., 2005) and there is increasing evidence regarding the connection between these two domains. Indeed, previous data had shown interference between tasks known to be processed in the dorsal pathway, such as line orientation and the irrelevant presence of numbers (Fias et al., 2001). However, besides object location, the dorsal pathway is also implied in motion perception (Ungerleider et al., 1998). Although a predominance of attention to location processing over attention to other features such as color or motion has been shown (eg. Hillyard and Anllo-Vento, 1998), motion perception leads to the emergence of independent motion-related electrophysiological processes (Anllo-Vento and Hillyard, 1996). The independence between motion and location perception makes the independent study of motion possible. In this work we will focus on the relationship between motion and calculation processes. Our starting point is that a motion component is present in the process of number comparison and, likely, in other numerical processes that imply core number activation. If this is the case, areas known as processing motion should show to be implied in numerical processes. We thus tested for the existence of interference on both motion and number processing in a specific area of the Intraparietal Sulcus (IPS).

The parietal cortex has been shown (Culham and Kanwisher, 2001) to be involved in many processes, mainly performing spatial analysis (such as attention, working memory, representation) and other high cognitive processes (calculation and – to some extent – language related processes). Besides the human homologue to the macaque´s MT/V5, some parietal areas have been identified as motion sensitive (for a recent review see Orban et al., 2006). Four areas have been identified in the Posterior

Parietal Cortex (PPC; see anatomical distribution in Orban et al., 2003, and Sunaert et al., 1999): the Ventral Intraparietal Sulcus (VIPS) is the most posterior one, in the occipital part of the IPS; the second area, the parieto-occipital IPS, resides at the confluence between the parietal and occipital parts of the IPS; the other two areas are located in the parietal or horizontal segment of IPS and they are referred as dorsal IPS: medial and anterior. VIPS corresponds to human vIPS (Shulman et al. 1999) and to the junction of intraparietal and transverse occipital sulci (IPTO) (Wojciulik and Kanwisher, 1999), but it is different from the multimodal area responsive to motion in the IPS (Bremmer et al., 2001), referred as VIP area (Hubbard et al., 2005). The highly motion-sensitive area V3a - whose BOLD activations in front of motion stimuli normally follow in magnitude the activations of MT - is more posterior following VIPS. In humans, it has been hypothesised that motion information may reach IPS through projections from V3a (Orban et al., 2006; Vanduffel et al., 2002). On the other hand, in general, human IPS is more involved in the perception of motion than its monkey counterpart. This distribution of motion areas in human IPS and its proximity to other areas related to numbers, lead us to select VIPS as the focus area in our study. We hypothesized that an area implicated in motion processing could also overlap with the network processing numbers (Nieder, 2004), and would thus function as a neural locus of convergence of these two processes.

In the Triple Code Model of number processing (Dehaene and Cohen, 1995), recently revised by Dehaene and collaborators (2003), the authors proposed that numbers are coded in three representations, each one located in a different cerebral area, differentially activated depending on task requirements. The horizontal segment of the intraparietal sulcus (hIPS) would implement the core representation of quantity, in the likely form of a mental number line, and it is suggested to be domain-specific. This

representation would be mostly activated in magnitude comparison and approximation tasks. The posterior superior parietal lobule would support the hIPS via attentional orientation on the mental number line, like on any other spatial dimension. Finally, the left angular gyrus would complement the hIPS in language mediated numerical tasks. The hypothesis that VIP area could be associated to the number processing system, which has also been proposed as a multimodal motion responsive region (Hubbard et al., 2005; Bremmer et al., 2001) is relevant for this study. Certainly, the VIP area has an anatomical localization similar to the hIPS of Dehaene et al (2003); nonetheless, neither evidence of a possible relationship between numbers and motion, nor any neural substrate have been previously shown. On the basis of these considerations, we selected VIPS (Orban et al 2006) as our area of interest for the following reasons: a) it is not considered an area related to number processing by Dehaene et. al. (2003) or Hubbard et. al. (2005); b) it is close to these areas, yet far enough to allow its independent stimulation; c) it is indeed an area sensitive to motion.

The transcranial magnetic stimulation (TMS) technique allows to modify brain functions inducing focal electrical fields in the cortical neurons (Walsh and Cowey, 2000), while inhibiting or facilitating behavioural performance. It is non-invasive and leads to an experimental manipulation of cortical information processing while treating the stimulated areas as an independent variable. TMS has been used so far in a few studies aimed at evaluating the neural correlates of number comparison. The angular gyrus has been shown to be involved with two digit number comparison, bilaterally. Stimulation on left angular gyrus altered the comparison times of numbers greater than the reference; in contrast, the right angular gyrus rTMS stimulation altered both higher and lower number comparison times (Göbel et al., 2001). Repetitive TMS stimulation of the left inferior parietal lobule disrupted processing of number comparison in Sandrini

et al. (2004) with an interaction with the distance of the number to the reference. Moreover, Andres et al.(2005) obtained a slow-down in the comparison of close digits when stimulating the left posterior parietal cortex, while a bilateral stimulation of the same area caused an effect on the comparison of far numbers. Nonetheless, bilateral parietal implications in number processing have been repeatedly found in neuropsychological and neuroimaging literature (Cipolotti et al., 1991; Chochon et al., 1999; Dehaene and Cohen, 1997; Eger et al., 2003; Piazza et al.; 2002; Pinel et al., 2001; Simon et al., 2002; Zorzi et al., 2002).

In the present study we propose the existence of a locus of intersection between numerical and motion processes, whereby motion would be a critical process associated to the exploration of the mental number line. In order to demonstrate an overlap of the networks functionally performing the two processes, the application of magnetical stimulation to the VIPS regions should interfere with both motion perception and number comparison. Number comparison was chosen, since this task (Dehaene, 2003) implies the activation of the quantity system, i.e. the semantic representation of numbers and has been shown to rely on intraparietal areas. Random dot kinematograms (RDKs: Newsome and Pare, 1988) has been used to evaluate motion processes. This type of stimulus consists of a pool of dots that move in a restricted area of space. The level of coherence of the RDK refers to the proportion of dots moving in the same direction, while the rest is moving randomly. It is important to notice that RDKs only imply a manipulation of motion, not of space or location. The observer cannot track the motion of single dots, and, as one dot disappears from the area of motion, another dot appears in the opposite side and the general pattern does not move. Single TMS stimulation was delivered to one hemisphere at one time, thus stimuli should be processed only in the

stimulated hemisphere. Thus, RDKs, numbers and shapes were presented as lateralized, while subjects were looking at a central fixation point. Therefore mechanisms common to the two tasks may also relate to the preparation of saccades (Sereno, et. al. 2001) or to general attentional load. In order to partial out the possible effects of the alteration of these common processes, a control task was added in which round corners must be detected from squared corners. This task requires a visuo-spatial detection of the pattern, as well as attentional resources, thus allowing to dissociate stimulation effects on motion and numbers processing from those on other more generic mechanisms. Event related potentials data show that both number comparison and motion processes occur at around 200 msec from stimulus onset (Temple and Posner, 1998; Pinel et al., 2001; Schwarz and Heinze, 1998; Niedeggen and Wist, 1999). Therefore, three different SOAs from the presentation of stimuli (at 100, 150 and 200 msec) were chosen in order to capture the temporal evolution of the stimulus processing in the VIPS region.

According to our hypothesis, the stimulation on VIPS should lead to a decrease of motion detection processes as compared to the stimulation of a central control site: Participants should thus show increased detection times in detecting coherent motion. Moreover, they may need a percentage of signal to noise bigger in the coherence of the RDKs in order to detect a coherent motion in the pattern. These effects would add new evidence to the implication of VIPS in motion processing. Importantly, the stimulation on VIPS is expected to lead also to a increased difficulty in the numerical comparison process when compared to the stimulation of the central control site, and higher reaction times are expected. The absence of effects on the corner detection control task would exclude an alternative explanation in terms of general attentional mechanisms or preparation of saccades derived from the lateralized presentation of all the stimuli.

Methods

Participants

Twelve right handed healthy participants (3 men; mean age: 22.3 years) from the University of Pavia participated in the study. All of them gave an informed consent before doing the experiment. The experiment was allowed by the ethic committee of the Department of Psychology of the University of Pavia.

Design

The experiment was performed in two sessions by the same twelve participants. In one of the sessions comparisons on numbers higher then the reference had to be made. Coherent motion to the right had to be detected. In the other session the response was made to numbers lower than the reference and coherent leftward motion had to be detected. In addition, the detection of corners control task was introduced in one of the sessions. The manipulation of Visual field / side of stimulation (RVF-stimulation of left VIPS /LVF-stimulation of right VIPS), the conditions of central stimulation (RVF-central stimulation / LVF-central stimulation, and the three SOAs (100/150/200), resulted in a 2x2x3 design 2 (visual field: RVF/LVF); 2 (site of stimulation: VIPS/central); 3 (SOA). The same design was applied to the three tasks in a within-subjects design with the exception of the corner detection task, in which the visual field of presentation of the stimuli (paired with the hemisphere stimulated) was balanced between subjects. Half of the participants saw the shapes on their LVF while central or right VIPS stimulation was applied and the other half saw the stimuli in the RVF with central or left VIPS stimulation. Participants were randomly assigned to each of these conditions.

The dependent measures for the number comparison task was reaction time in the go-no go task (accuracy provided no information thus no errors have been reported). In the motion detection task both reaction times and proportion of detection for each level of coherence were measured. In the corner detection task the reaction times were collected (again, no errors occurred in the performance).

Stimuli

In the number comparison task numbers were sized 40 points and were white in black background. For the motion detection task, RDKs were built using VisionEgg, generating a pool of 60 frames. Then, jpg files were merged into mpeg video files of 15 frames/sec. Thus, the duration of each movie was 4 sec. The total number of dots was 3000, sized 1.5 pixels. The dot life span was 0.5 sec. The percentage of coherently moving dots was varied from 0 to 37% generating 9 different RDKs. In the rightward motion stimuli the signal in the RDKs was set to 0 degrees, in the leftward motion stimuli the signal was set to 180 degrees. The dots were white and the background black. The shapes of the control task were white over a white background: they can be seen in figure 1.

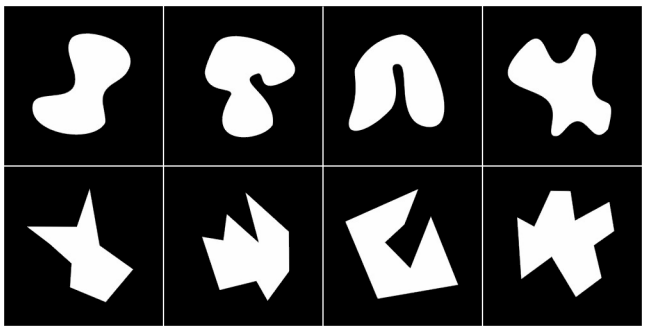

Figure 1. Shapes used in the corner detection task.

Procedure

The experiment consisted of two sessions that were randomly assigned to each participant. In one of the sessions, participants were tested in two tasks administered in different blocks: a) comparison on numbers (1 to 9) to a reference number 5, and b) detection of coherent rightward motion on random dot kinematograms (RDKs: Newsome and Pare, 1988) with 9 levels of coherence from 0 up to 37%.

Participants had to press the spacebar in the two go/no-go tasks: when the number was bigger than five, and when a coherent rightward motion was perceived. In motion detection task, the perceptive threshold was defined as the minimum percentage of coherence perceived in the 75% of the trials, determined in the logistic fit predicted values from the direct proportions. Additionally, RTs from the beginning of the movie were collected for the motion detection task. Only those RTs corresponding to stimuli over the maximal threshold for all conditions and participant were considered. Single pulse TMS was applied using a Magstim 200 stimulator: monophasic posteriorly directed TMS pulses were delivered at the 110% of the phosphene threshold, using a 70 mm figure-of-eight coil with its centre positioned over the cortical site tangentially to the scalp, oriented parallel to the mid-sagittal line, with the handle pointing upward. Experimental stimulation was delivered either to the right and left VIPS (±24, -76, 30), at one out of three Stimulus Onset Asynchrony (SOAs: 100/150/200 ms) from the presentation of the number or the RDK. Stimuli were presented lateralized with respect to a central fixation cross (visual angle: 11º), in order to be projected only to a single hemisphere (the one stimulated), at one time. The stimulation was made at one hemisphere at a time, therefore the stimuli (RDKs, numbers or shapes) were presented lateralized in the right visual field (RVF) or the left visual field (LVF) while the stimulation on VIPS was applied to the contralateral hemisphere, the one where the

stimuli was mainly projected. In a control-site condition, the same blocks were presented while stimulating the interhemispheric sulcus (0,-76, 30) with the same parameters in time and intensity of the experimental stimulation. The correspondence between coil positions and stimulation sites was continuously controlled through the FasTrak Polhemus neuronavigation system (Figure 2).

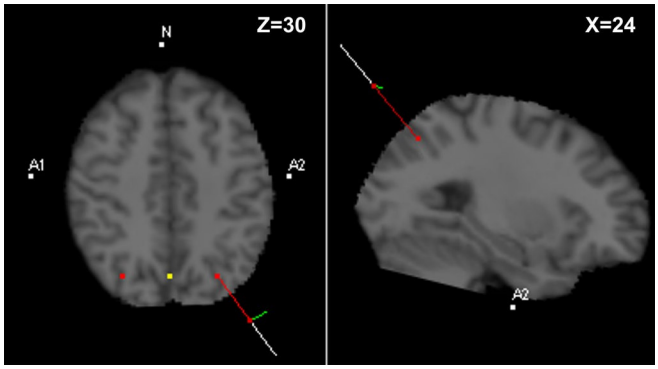

Figure 2. Sites of TMS stimulation. Yellow: central control site (Talairach coordinates: 0, -76, 30). Red: Left and Right VIPS (-/+24, -76, 30).

The other session involved the same participants, re-contacted two months later. In this session, number comparison go trials corresponded to judgements on numbers lower than five while in the motion task leftward coherent motion had to be detected. Besides, a new task of corners detection in shapes was included in order to rule out an explanation of the results in terms of a general attention mechanism of orienting to the hemifields. In this novel task, participants had to detect shapes with rounded corners, with respect to those with squared ones, among eight different irregular shapes (see Figure 1).

Results

Number comparison.

When the go response was related to numbers *higher* than five, VIPS stimulation caused longer RTs with respect to the control central stimulation (Figure 3a). The ANOVA visual field of the target (left visual field: LVF / right visual field: RVF) x stimulation (experimental / control) x SOA (100 / 150 / 200) confirmed a main effect of stimulation ($F_{1,11}$=17.48; m.s.e.=1,873; p<0.002). Although the interaction between stimulation and visual field was not significant**,** we explored RTs through simple effects of the three-way interaction: Post-hoc (DMS: Minimum Significant Difference) analysis showed a significant effect of stimulation at SOA = 100 for the RVF ($t_{1,11}$=2.575; p<0.03), for the LVF ($t_{1,11}$=2.282; p<0.04), and an effect of stimulation at 150 and 200 ms only for targets presented in the RVF ($t_{1,11}$=2.662; p<0.02 and $t_{1,11}$=2.915; p<0.01, respectively).

The 2 x 2 x 3 ANOVA showed a main effect of stimulation in the number comparison task to numbers *lower* than five ($F_{1,11}$=14.95; m.s.e.=5,377; p<0.005, Figure 3b). Conversely to the comparison of numbers higher than five, a stronger LVF/right hemisphere involvement appeared. When the stimuli were presented to the LVF, all 100, 150 and 200 ms SOAS showed an effect of stimulation (respectively: $t_{1,11}$=2.849;p<0.02, $t_{1,11}$=3.486; p<0.005, $t_{1,11}$=3.115; p<0.01). When stimuli were presented in the RVF only a marginal effect of stimulation was found at SOA=150 ($t_{1,11}$=1.894; p=0.08).

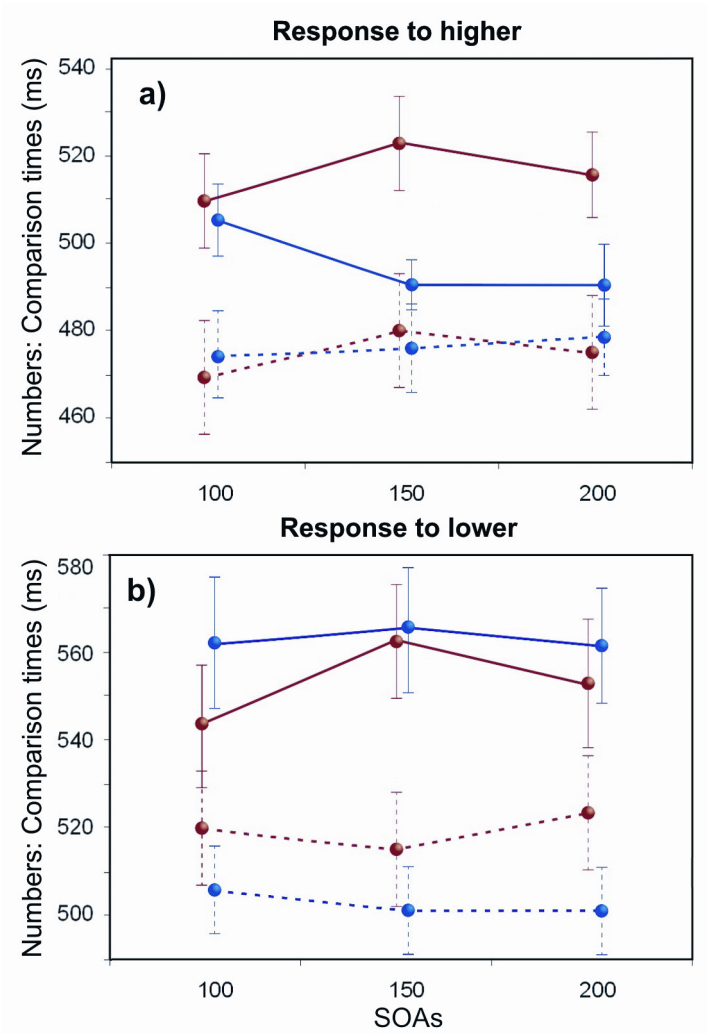

Figure 3. Results of the number comparison task as a function of SOA, visual field and site of stimulation. In red: RVF, in blue: LVF. Continuous line: stimulation on VIPS, dashed line: central stimulation. Figure 3a) responses to numbers higher than the reference; figure 3b) responses to numbers lower than the reference.

Motion detection task

In the rightward motion detection task, the same ANOVA 2 x 2 x 3 on the RTs confirmed a main effect of stimulation ($F_{1,11}$=51.73; m.s.e.=34,901; p<0.001, Figure 4a). Regarding the threshold of motion detection, participants needed more dots moving coherently to perceive coherent motion when VIPS was stimulated (23.7% to 26.3%: $F_{1,11}$=19.09; m.s.e.=12.71; p<0.001, Figure 4b).

When leftward coherent motion had to be detected, the 2 x 2 x 3 ANOVA once more showed an effect of stimulation on the RTs ($F_{1,11}$=8.35; m.s.e.=90,217; p<0.01, figure 4c). Again, a significant displacement of the threshold was found (24.7 to 26.5: $F_{1,11}$=13.25; m.s.e.=8.99; p<0.004, Figure 4d).

Corner detection task

In the control task, no significant effects of stimulation appeared. A 2 x 3 (stimulation x SOA) ANOVA including the field of the target presentation as between subjects factor, shower neither an effect of stimulation nor an interaction between stimulation and visual field/hemisphere. The very low percentage of errors and the similar range of reaction time values suggested that this task was as complex as the number comparison task in the control conditions (see figure 5). The absence of effects of stimulation in the control task allows us to exclude possible interpretations of the previously reported stimulation effects as due to an interference with more general attentional processes.

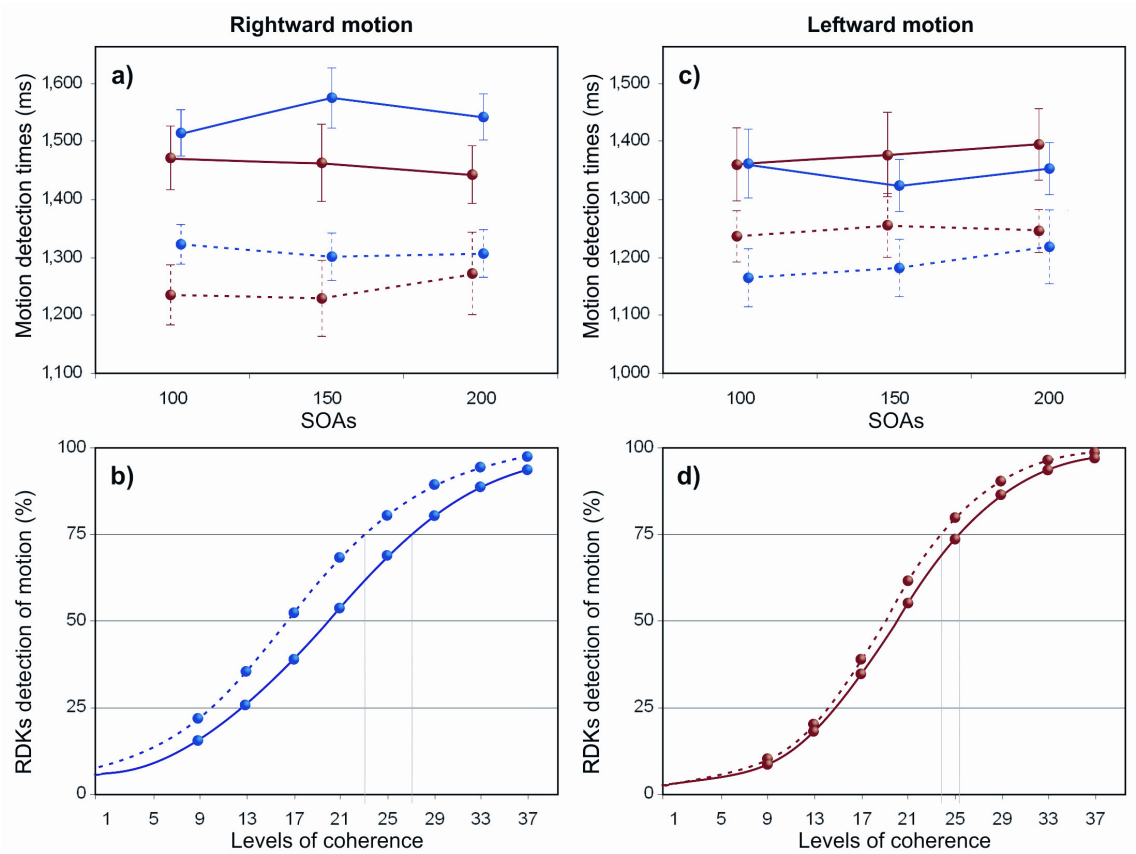

Figure 4. a) and c): results for the rightward (a) and leftward (c) motion detection task as a function of SOA, visual field and site of stimulation. b) threshold for rightward motion as a function of stimulation d) threshold for leftward motion as a function of stimulation. In a) and c): red: RVF; blue: LVF. In a) b) c) and d), continuous line: stimulation on VIPS and dashed line: central stimulation

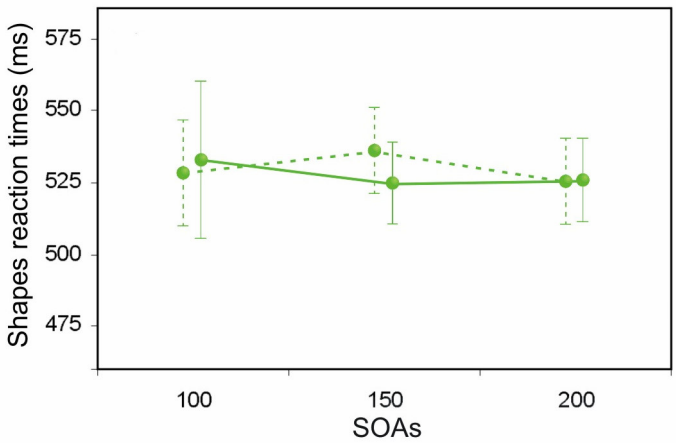

Figure 5. Results for the corner detection task as a function of SOA and site of stimulation. Dashed line: central stimulation; continuous line: stimulation on VIPS.

Discussion

The data reported in this study provide strong support to the hypothesized implication of VIPS in visual motion processing. Besides, this area seems also crucial for performing numerical comparison, a task that is thought to imply access to the core representation of numbers.

Indeed, the main finding of the present study is the association in the VIPS of motion and numbers processing. No study until the present one has focused on this relationship, although it has only been suggested that the VIP, where core quantity processing is thought to be processed, corresponds to a polymodal motion area (Hubbard et al., 2005; Bremmer et al., 2001). The VIP area is referred with the same anatomical distribution of hIPS but it is different from the area that has been stimulated in the present study. If number processing implies a motion component, there should be a motion related area, whose inhibition would disturb number processing. The area that we targeted for stimulation has been recently described as sensitive to motion (Orban et al., 2003) and its stimulation was shown to affect also numerical processes. The mechanism behind the reported association may be one of functionally related networks that share some areas, one of them is VIPS. The present data suggest that number comparison could be behaviourally modulated by the presence of motion. As a part of a circuit, the VIPS may be the main area involved in the process, but other areas (like MT/V5 or V3a or the group in IPS signalled by Orban et al., 2006) may perform part of the task. It could be interesting to evaluate the differences in performance while stimulating the other areas functionally related to VIPS.

A second finding is the tendency to a hemispheric predominance in the processing of numbers when they are presented as lateralized. This pattern of lateralization differs from that reported in previous TMS studies (Sandrini et al., 2004),

but it agrees with several neuroimaging studies finding bilateral support in number-related processes. A similar outcome is presented by Lavidor and colleagues (2004): for large distances, numbers of small magnitudes were detected faster in the LVF than in the RVF, while the opposite result was found for large magnitude numbers. Similarly, in the present study, when the numbers to detect are higher than the reference, the process of comparison is more affected when they are presented in the RVF and then projected to the left VIPS that is being stimulated. The processing of numbers lower than the reference is more altered when they are presented in the LVF and right VIPS is stimulated. By no means, these data should be taken as evidence of a pure and constant lateralization of high and low numbers, this hypothesis has been discussed in other papers (Vuilleumier et al., 2004). Instead, a temporary lateralization dependent on the task may be proposed as an evidence of the spatial nature of the mental number line. Like other spatial stimuli, numbers are thought to be represented from left to right depending on the interval chosen in the task and the number taken as reference. Thus, for example different results would emerge for the number 4 if the reference number were 3, because in that case the number 4 would have been higher than the reference. However, the temporary impact of the number size on the hemispheric preference indicates that VIPS stimulation altered the process of number comparison and hence this interference is not due to other more global processes. Moreover, this pattern of lateralization in number comparison suggests to allocate the interference in the process of comparison and not simply in the access to numbers representation.

The present findings suggest that motion could occur in numerical operations and show that at the neural level there is a connection between motion processing and the mechanisms underlying number comparison. These mechanisms could correspond to selective attention to motion (Hillyard and Anllo-Vento, 1998; Beer and Röder 2004,

2005; Lewis et al., 2000). If this process devoted to motion is what was altered by TMS stimulation, then a mechanism implying motion may – in turn – be operating on the mental number line.

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3.3. Leftward motion restores number space in neglect

ABSTRACT

In the present study, a group of patients with left-sided neglect performed a number comparison task that co-occurred with coherent motion in different directions or with random motion. Their performance was compared to that of a healthy control group and to a group of patients with right hemisphere damage but no signs of neglect. The presence of leftward motion alleviated the difficulties neglect patients typically show with the number previous to the reference number 5. Moreover, the standard distance effect was only present when the task co-ocurred with leftward motion. These effects were not present in the group of participants with right hemisphere damage without neglect or in the control group. The data suggest that an external redirection of attention by the perception of motion may restore the altered access to the representation of the mental number line in neglect

Introduction

The accounts of unilateral spatial neglect have been classically split into "internal", *representationalist*, and "external", *attentionalist*, explanations. Attentionalists explain the deficit as a spatial bias in attention (eg. Kinsbourne, 1987,1993; Heilman, et al., 1993; Posner et al., 1984), whereas the representationalists construe it as a systematic deficit in the very content of the spatial representation itself (Bisiach and Luzzati, 1978). These two approaches are not opposed but rather complementary and respond to an explanation of different symptoms.

Research on number representation has recently focused on spatial neglect with the general goal of finding evidence of the relation between numbers and space. Zorzi et al. (2002) presented numeric intervals (e.g.1-5) to neglect patients aurally and asked them to make a judgement about the central number of the interval. Just as these patients do with line bisection, they systematically displaced the centre of the number interval to the right. For Zorzi et al. (2002), this finding demonstrated the spatial nature of the mental number line and its striking functional isomorphism to physical lines. Other studies have shown that neglect patients have difficulties in processing a number "located" in the left side of a reference number (i.e. a smaller number) against which a number comparison has to be made (Vuilleumier et al., 2004). Interestingly, when the reference number changes, patients show the same difficulty with numbers smaller than the new reference number. Vuilleumier et al. (2004) concluded that different spatial representations are constructed, where different numbers are neglected depending on the number taken as reference in a comparison task. Representational neglect-like symptoms in number bisection were recently shown also in healthy participants when repetitive transcranial magnetic stimulation (rTMS) was applied over the right posterior

parietal cortex (Göbel et al., 2006). In summary, these studies imply that patients with neglect may represent numers as they do with information in other spatial dimensions.

Number representation thus seems to be coded in spatial terms and this spatial representation, or its access (see also Priftis et al., 2006), is altered in neglect. The present study is based on the prediction that changes in external attention can ameliorate the internal representational deficit. Indeed, previous studies have shown that random dot patterns moving coherently on the background of the stimulus display have a positive effect on the line bisection errors in neglect (Bisiach et al., 1996; Mattingley et al., 1994; Pizzamiglio et al., 1990). Moreover, Rossetti et al. (1998) showed how prism adaptation can improve line bisection in unilateral neglect. Rossetti et al. (2004) also showed that this visuo-motor adaptation can in fact improve bisection of number intervals. This finding is taken as an effect of visuo-motor adaptation on an internal representation. The described associations between space and number representation would be grounded on common action principles: "visuo-motor plasticity functionally links parietal areas involved in space and number representation" (Rossetti et al. (2004)).

The present study investigated the effects of covert attention to motion stimuli on the access to number representation as measured by the distance effect in a number comparison task. It is predicted that simple perception of coherent motion can act as a compensation mechanism over partly neglected access to the internal representation of numbers. In fact, if the mechanisms of attention that operate on external stimuli are altered in neglect, as argued by "attentionalism" (eg. Kinsbourne, 1987, 1993; Heilman et al., 1993), can the external compensation for this bias affect the allocation of attention to the neglected internal representation of numbers? This effect would also link attentionalism to representationalism, since an internal, neglected representation would

be affected by externally induced changes. In this work, this compensation consisted of the redirection of covert attention by motion, from the "good side" to the "bad side". Indeed, the same attentional mechanism that operates externally may be acting internally and would have an impact on the number representation or on its access. The manipulation of the direction of motion and a condition of random motion were expected to have different effects on the behaviour of neglect patients in number comparison. First, if perception of leftwards coherent motion has a compensation effect on the allocation of attention over the mental number line, the effect reported by Vuilleumier et al. (2004) should decrease. In other words, leftward coherent motion should lead to a lower difference between the number smaller (thus on the left) of the reference number, while rightward motion and noise would not. Second, the manipulation of the direction of motion may also prevent the appearance of a distance effect when the mechanisms of attention over the representation of numbers are externally disrupted by rightward or noisy motion. The *distance effect* (Moyer and Landauer, 1967), is a classic and robust effect that occurs when making number judgments, in which smaller distances between numbers require more time to be processed than larger distances (e.g. comparing 4 and 5 takes more time than comparing 1 and 5). This effect is taken as evidence of the transformation of numbers into analogue magnitudes that are subsequently compared. Thus the normal pattern is an increase of reaction time when the numbers to be compared are closer to one another.

Methods

Participants

22 right-handed individuals participated in this study: 14 with right hemisphere damage (7 with left spatial neglect and 7 without neglect) and 8 healthy controls consisting of volunteers, matched in terms of age and education to the neglect patients. Except for one case of trauma, the aetiology of the lesion was determined by vascular accidents in the territory of the middle cerebral artery (Table 1).

All patients were tested with the Behavioural Inattention Test (BIT, Wilson et al., 1987), the Bell test (Gauthier et al., 1989) and the Balloon test (Edgeworth et al., 1998). Unilateral representational neglect was detected with a test equivalent to Bisiach and Luzzatti's (1978) "Duomo di Milano" test. Personal neglect was either shown as denial of ownership of contra-lesional limbs or it was tested by asking patients to find and reach for their contra-lesional hand (see Bisiach et al., 1986; Berti et al., 1986). All patients were well preserved in the comprehension of Arabic numerals as shown by their above cut-off performance in a number comparison task and in a parity judgement task taken from the Number Processing and Calculation Battery of Delazer et al., (2003). Demographic, clinical and psychometric data for the brain damaged participants are reported in Table 1. Informed consent was given by each participant.

Table 1. Neuropsychological assessment. Demographic, clinical and psychometric data of the right hemisphere patients

Patients	***Age*** *(years)*	***Education*** *(years)*	***Lesion site***	***Lesion etiology***	***Time since lesion*** *(months)*	***BIT*** *(Cut off 129)*	***The Bell Test*** *(Cut off 32)*	***The Balloon Test*** *(Cut off B<17; Laterality < 55%)*			***Unilateral Representational Neglect***	***Personal Neglect***
								Tot A	*Tot B*	*Laterality B*		
RHD N1	44	8	FTP	IS	6	56	13	9	5	0%	+	-
RHD N2	67	17	FT	HS	9	65	12	19	7	43%	+	-
RHD N3	60	10	FTP	IS	5	22	7	5	1	0%	+	+
RHD N4	50	8	TP	IS	48	127	27	20	12	33.3%	+	+
RHD N5	61	14	D	IS	6	122	28	19	17	41.2%	-	-
RHD N6	73	3	D	HS	4	86	16	15	12	16.6%	+	-
RHD N7	66	8	D	HS	3	126	28	20	12	33.3%	+	+
RHD 1	52	16	TPD	Tr	50	141	35	20	20	50%	-	-
RHD 2	57	8	FTP	IS	4	142	34	20	18	50%	-	-
RHD 3	44	14	TP	IS	14	140	35	20	16	56%	-	-
RHD 5	50	18	FTP	HS	12	146	35	20	20	50%	-	-
RHD 4	78	8	FP	HS	7	140	33	20	17	47%	-	-
RHD 6	48	14	TD	IS	5	145	32	20	20	50%	-	-
RHD 7	50	10	T	IS	12	146	33	20	20	50%	-	-

RHD, Right Hemisphere Damaged patient; N, with Neglect; F, frontal; T, temporal; P, parietal; IS, ischemic stroke; HS, hemorrhagic stroke; Tr, Trauma: D: deep structures, subcortical

Stimuli

The stimulus chosen for extracting direction of motion was a stationary moving element called random-dot kinematogram (RDK). An RDK consists of a large number of moving dots randomly positioned within a restricted area. Each dot is assigned to a particular motion vector. With these stimuli, a variable percentage of dots can be moved towards a single coherent direction (signal), while the rest of the dots carry on moving in random directions (noise). The perception of motion is based on the joint displacement of the single elements, and the probability of a single dot being displaced in a determined direction is called *coherence of element displacement*. The dots appear and disappear in the window at different positions and due to the large number of dots (thousands) it is impossible for the observer to compute the relative position of any one dot (Bosbach and Prinz, 2004, Shadlen and Newsome, 2001). This addresses a critique that has been made on other static moving elements as gratings

The RDKs were created using VisionEgg, which runs under Python 2.3. A pool of 50 frames was generated as bitmap files. The speed of the dots was 20º per sec. The total number of dots was 2000, and their size was 2 pixels. As one dot disappeared from the screen another appeared at another random location beginning from the opposite edge. The bitmaps were then transformed into movies that lasted 4 sec each, using JPGVideo Version 1.05.0.0 (Independent JPEG group), and then into mpeg files.

Three different movies were created. The first two had 40 per cent coherence: in one the coherent motion had a horizontal right direction, while in the other the coherent motion had horizontal left direction. The background in these movies was noisy, that is, the remaining 60 per cent of the dots were moving randomly in the window with an orientation of 45º. The third RDK was one of 0 per cent coherence: in this case, all the

dots were moving randomly as described above. The background of the RDKs was black and the dots were white.

The digits (2, 3, 4, 6, 7 and 8), presented in yellow, had a size of 0.6º and appeared while the movie was playing. A yellow cross (also with a size of 0.6º) was present in the centre of the kinematogram throughout the entire trial, except when the number substituted the cross. The screen was set to black and its resolution was 1024 x 768 pixels.

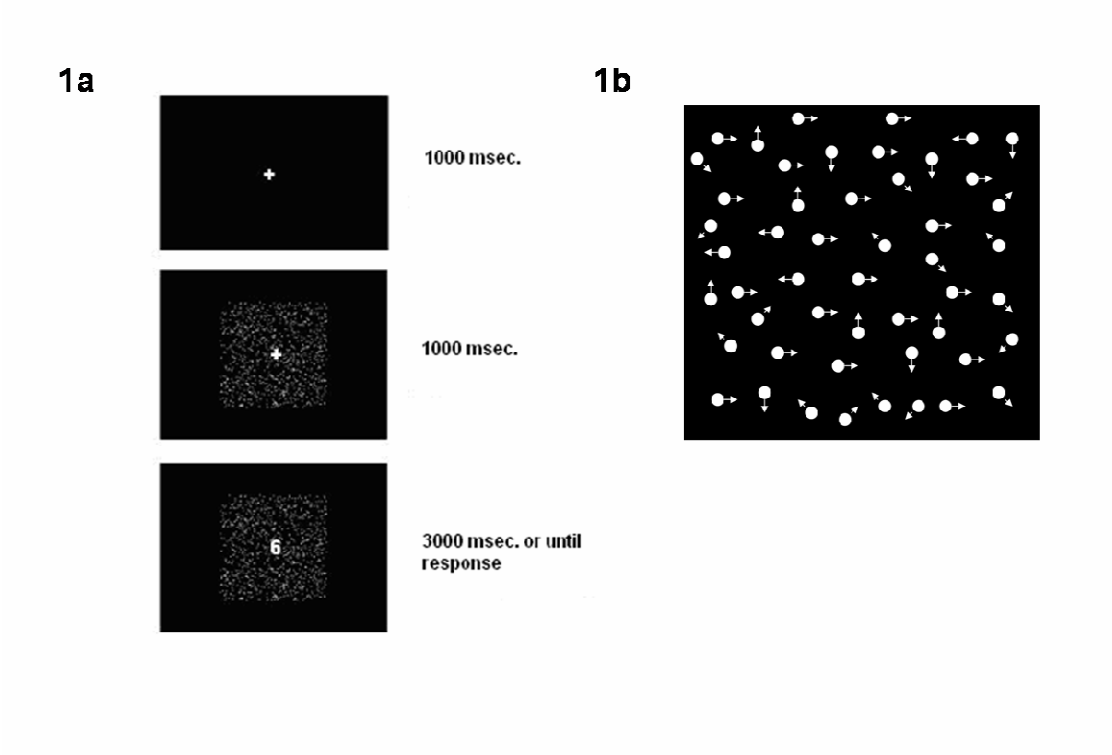

Figure 1: 1a) Experimental paradigm 1b) Example of a RDK.

Procedure

The experiment was controlled from a portable PC-compatible Vaio WGN-S1XP and was programmed using Presentation software. Participants sat in front of the screen at a distance of 60cm and were asked to perform a go-no-go task. In some blocks they had to respond to numbers higher than 5 and in other blocks they had to respond to

numbers lower than 5[1]. The sequence of each trial was as follows: a cross appeared in the centre of the screen and remained the only stimulus until the irrelevant motion (RDK) began after 1000ms. Participants were asked to fixate to this central cross and maintain this central fixation for the duration of the experiment. The number appeared after 1000msec of the beginning of the movie and remained in the centre of the screen until a response was made, or after 3000 ms. As the movie lasted 4000msec, the number coincided with motion during 3000 ms. or until response (see figure 1). Participants used the right hand for responses. The total number of trials was 432, divided into six blocks. Response to higher or lower than five was varied along the blocks, so in three blocks the go-response corresponded to numbers higher than five and in the other three blocks the responses corresponded to numbers lower than five. The order of the blocks was randomized. At the end 12 data points per condition were obtained. In order to ensure the participants' attention, the experiment was divided in three sessions, with two blocks in each session.

Results

Right hemisphere damaged participants made a maximum of 12.87 % of errors (7.75 % for neglect patients and 3.21% for right hemisphere patients without neglect). Errors were equally distributed, in each participant, in false positive and false negatives: no systematic bias was observed. The reaction times for error responses were substituted with the average reaction time of the condition in each subject. Punctuations over and below of 1.5 standard deviations of the average by subject and condition were also substituted by the average of the condition in each subject.

The average comparison times were then entered in a four-way ANOVA, 3 (group: neglect, right damaged without neglect and control, entered as a between subjects factor) x 2 (number: higher/lower) x 3 (distance: d3, d2, d1) x 3 (motion: to the

left/to the right/noise). The analysis revealed a main effect of group ($F(1,2)= 17.36$; mse= 556,183; $p<0.001$) with controls having faster RTs, followed by the right hemisphere damaged patients and then by the neglect group. A group x number interaction was shown ($F(2,19)= 6.94$; mse= 20,636; $p=.005$), with a general tendency in neglect patients to have higher reaction times for low numbers while this was not the case in the other two groups. Moreover, a group x distance x motion x number interaction ($F(8,76)=2.36$; mse=3,700; $p=.025$) was also shown.

In order to analyze this four-way interaction and the differences between the groups, a separate analysis was done for each group. In a 2 (number) x 3 (distance) x 3 (motion) ANOVA, the control group and the RHD group showed a standard distance main effect (control: $F(2,14)=21.52$; mse=636; $p<.001$; RHD: $F(2,12)=6.1$; mse=45,395; $p=.015$); no other interactions or main effects were significant[2]. In the neglect group a main effect of number was found ($F(1,6)=8.46$; mse=21,133; $p=0.027$) in which low numbers generated higher comparison times. Importantly, a three-way number x distance x motion interaction was found in this group ($F(2,24)=3.59$; mse=6,861; $p=0.02$). A number (2) x distance (3) analysis was performed for each level of motion in order to test our predictions about the distance effect. Neither in the rightward motion nor in the noisy motion condition a distance effect appeared. When leftward motion was presented, a distance effect did appeared in the comparison times ($F(2,12)=5.25$; mse:5,598; $p=0.014$). The comparison times between the pair 6-4 in each condition of motion were then compared (Vuilleumier et al., 2004), observing statistically significant differences in the rightward motion ($t=2.87$; $p=0.028$) and noise motion ($t=2.95$; $p=0.026$) conditions, but this pair was not different when leftward motion was presented ($p=0.1$). In the other groups these comparisons were not statistically significant.

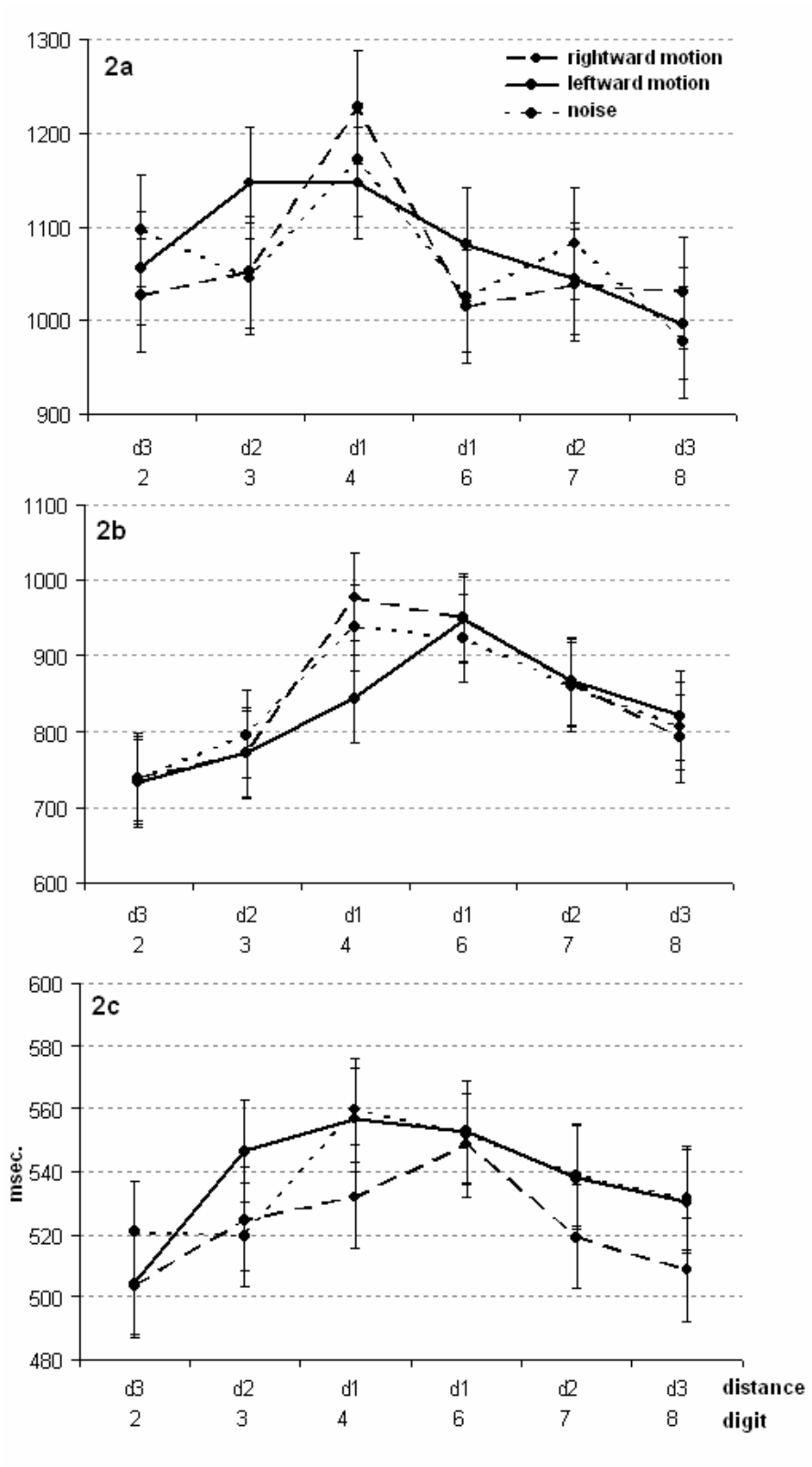

Figure 2: Mean comparison times plotted with +/- 1 SE as a function of the distance to the reference number 5 (d1, d2, d3) and the condition of motion. 1a) neglect group 1b) RHD control group 1c) control group.

Discussion

The main result of the present study is that the direction of motion has an effect on number comparison and on the distance effect in neglect patients. The performance of neglect patients becomes regular when their attention is externally captured from the right "good side" to the left "bad side" by motion. A covert external capture of attention has an impact on the internal activation of number representation.

Leftward motion allowed neglect patients to compensate for the rightward bias: this is reflected by the decrease in difficulty in the processing of numbers on the left of the reference number (Vuilleumier et al., 2004). Moreover, in this condition of motion, the pattern of the distance effect was the expected one, in contrast to when rightward or noisy motion was presented.

No effects of the direction of motion on the processing of the number on left of the reference number (number 4), or on the distance effect for right hemisphere damaged participants and for the control group were shown by the results. Therefore it seems that the interaction cannot be attributed to damage to the right hemisphere. Thus, it is the specific altered network behind the neglect symptoms that must be implied in the alteration of attention to this representation. And this appears, in turn, to have been compensated by the perception of external moving stimuli.

In general, the performance on the number comparison task argues for an altered access to the internal representation of numbers in neglect participants, that has also been proven to be altered in other studies (Zorzi et al., 2002; Vuilleumier et al., 2004). Dehaene et al. (2003), has suggested that the same mechanism operating over other spatial dimensions may act upon the internal representation of numbers. This conclusion appears to be basically correct, and compatible with the present results, even if specific

electrophysiological responses were recently found for internal and external cueing (Salillas et al.). This altered access is compensated by the perception of leftward motion. Importantly, no visuo-motor adaptation is required in the present experiment, suggesting that the correcting mechanism could be perceptual (differing from Rossetti et al., 2004). Rossetti's study employed prism-adaptation to compensate the right bias which in turn was translated into better performance on number bisection. On the contrary, in our study the compensation exerted by the perception of coherent motion cannot be explained by a link based on action between number and space.

As for theories of neglect, the present data allows us to link both attentionalism and representationalism. In fact an altered access to an internal representation of numbers is corrected by an external redirection of an otherwise biased attention mechanism. A neglected internal representation is shown by the altered distance effect in absence of coherent motion or rightward motion and by the difficulty with number 4 in these conditions; this could be explained by the representationalist accounts (Bisiach and Luzzati, 1978). Nonetheless, the mechanism of recovery by external leftward motion has an attentional source. Therefore, the present data can also be explained in terms of the different attentionalist models mentioned above. According to Kinsbourne's (1987, 1993) model, each hemisphere shifts attention towards the contralateral hemispace by inhibiting the other hemisphere. In other words, each hemisphere generates a vector directing attention in the horizontal plane towards the opposed direction. The vector from the left hemisphere is of higher intensity than the vector from the right hemisphere. Each vector inhibits the other. In this framework, shifts of attention by leftward motion could be operating as a compensating horizontal vector to the left. Rightward motion, instead, respects the vectors system but fails in redirecting attention. In fact it redirects attention in the sense of the strongest, in neglect,

overwhelming vector. As our data show, difficulties with the numbers on the left of the reference number 5 were higher in this condition. The absence of coherent motion in the condition of random motion leaded to the most altered distance effect, which may indicate the disruption of the vector system in the attention over the numbers representation. Another attentionalist model was proposed by Heilman et al. (1993). This model also assumes differences between the brain hemispheres in their involvement of attention, but, unlike in Kinsbourne's model, the bias is not due to a hyperactive left hemisphere. It rather assumes asymmetric capacities in the exploration of space. The right hemisphere has a special role in space-related behaviour, with orientation of attention to both hemispaces, while the left hemisphere orients unilaterally to the right. Neglect would derive from an hypoarousal of the right hemisphere. Leftward motion could be reactivating an hypoactive right hemisphere, by the redirection of attention to the left hemi-field. In this case rightward motion should be the worst situation, which is what we found, as signalled by the difficulties with number 4 in this condition of motion. Finally, leftward motion would entail compensation in the failure to disengage from ipsilesional stimuli, as proposed by Posner et al. (1984). Again, rightward motion would be the worst situation. Consequently, our data are compatible with both attentionalism and representationalism.

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GENERAL CONCLUSIONS

1. Numbers and spatial attention

The first two papers of this thesis have provided new evidence on the relation between numbers and space. The idea of numbers semantics in the form of a mental number line oriented from left to right comes reinforced. Furthermore, they have characterized the processes underlying the shifts of attention after the perception of numbers in electrophysiological terms:

1. The perception of numbers generate a sensorial amplification in the perception of the subsequent congruent space location. As signaled by modulations in the sensory components P1 (first paper) and N1 (second paper), perception of numbers generates shifts of attention at the sensory level. The effects of numbers in the perception of spatial targets begins as soon as 80-100 ms. after the perception of the number. This means that the sensorial processing in primary visual and auditory cortex is affected by numbers and therefore a numbers-space relationship is present in a stimulus elaboration phase.
2. When stimuli and target are presented visually, the cognitive P300 is modulated by number-space congruency. The larger P300 amplitude found for congruent trial signals that a trace of the relevance of a location may have been held in working memory. The perception of the digit could activate the spatial representation of the number. Then its position in the mental number line is held in working memory determining the relevance of a certain location in the external space. Thus, not only sensory but also cognitive components related with attention and working memory may be behind the congruency effects between numbers and space.

3. With regard to the comparison between the processes of attention towards the external and internal numerical-space, there are more similarities than differences if we attend to the behavioral data and the data from neglect (fifth paper). In fact, numbers have early effects on the attention to external stimuli and attention to external motion has an impact in the spatial representational biases experienced in neglect. Nevertheless, some differences arise when we attend to the scalp distribution of ERP components. We interpreted this as top down modulation from representational space into sensory and cognitive processes. Different neural generators could therefore be acting when cues are numbers instead of external input.

Models that suggest spatial characteristics of the semantic representation of numbers are supported by the present data (Dehaene, 2003; Walsh, 2003). The Triple Code Model (Dehaene, 1992; Dehaene and Cohen, 1995, 1997) suggests that the analog magnitude representation is linked to space. The perception of a visual Arabic form of a verbal auditory number activates this representation and interactions with spatial parameters should be found. According to Walsh, there are common cortical metrics between space, quantity and time with neural intersections both in the posterior parietal cortex and in the prefrontal cortex. The posterior system is used for estimation of 'how much, how many, how far, how long, and how fast'. The anterior system is important for complex calculation, memory and longer term planning. The data presented in the first part of the thesis thus, agrees with these proposals in the sense that processes of attention to space are influenced by number processing. Likely similar, although not identical, attentional processes operating over external stimuli also operate over the "mental number line".

2. Sensory modalities and numbers semantics.

Magnitude estimation has been shown to be independent of modality (Barth et al., 2003; Brannon, 2003). Several studies have obtained SNARC effects both when numbers were presented as Arabic digits or as written words (e.g., Fias, 2001; Dehaene et al., 1993; Nuerk et al., 2003). The SNARC effect has been used to index automatic access to a central semantic and amodal magnitude representation. This assumption of modality independence has been recently tested in other modalities. Some authors (Nuerk et al., 2005; Castronovo and Seron, 2007a) showed that the SNARC effect is a general index of a central semantic and amodal number magnitude representation.

Nevertheless, using ERP methodology, other authors (Szücs and Csèpe, 2004) have shown electrophysiological differences between written and auditory number words during mental addition. A global view of the first two papers of this thesis may suggest actual differences across modalities in the pattern of shifts of attention in the auditory versus visual modality. From the comparison between the first two papers we can conclude that:

1. Perception of numbers generates shifts of attention both in the auditory and in the visual modality in sighted individuals. This is signaled by lower reaction times in congruent trials and by the amplitude modulation of the sensory N1/P1 depending on this space-number size congruency.
2. In sighted population numbers modulate attention to the external space also through higher level processes, as reflected by the amplitude modulations of the cognitive P3. This component is interpreted as the reflection of the process of holding the relevance of a location in

working memory. This modulation does not appear in the auditory modality.

3. In blind individuals, only the P3 and not the sensory N1 is modulated by congruency in the auditory modality.

As we explained at the end of the first part, the absence of a modulation by congruency in the P300 in the auditory modality can be explained as the link between space and number having a preference for the visual modality (Thinus-Blanc & Gaunet, 1997). The P3 is only modulated in attended versus unattended targets when the target appears at the attended modality (Teder-Sälejärvi et al.1999; Nager et al 2006; Eimer and Schroger, 1998; Eimer, 2001). The N1 is modulated both in unimodal and cross-modal situations. Taking it further, this would mean that the mental number line is linked more to vision than to other modalities: the perception of a numbers activates numbers representation and a part of it is attended in the representational space, which in turns has an effect on attention to external space. These dissociations found in the P3 suggest the activation of a visual image rather than an amodal mental number line. The absence of visual input in blind individuals would have generated a different way of representing numbers independent of the modality or, dependent on the auditory modality. This explains that space-number congruity only modulates the P300 in this population in a preferred modality.

The only modulation by congruity on the P3 and not on the N1 in the blind population may be due to different treatment of a number-spatial representation. Exposition to numbers and magnitude is restricted to an iterative auditory or tactile input, differing from a parallel processing of space in vision. This may have led the blind population to manipulate numbers in a more controlled way, dependent on working memory resources.

3. Motion in numbers.

The second part of the thesis aimed to explore a possible relationship between numbers and motion. The hypothesis about this link is based on the possibility of a relationship between neural networks processing motion and numbers in the parietal cortex. The space-numbers link is partly based on this kind of neural connection (Dehaene, et al. 2003; Walsh, 2003). Numbers, attention to space and attention to motion rely on the dorsal pathway therefore it seemed plausible to extend the processes operating over numbers to motion processes.

Very recently, other authors have suggested that this link exists and they have compared calculation processes to an operational momentum (McCrink et al, 2007). This proposal comes from the idea of an operational momentum effect, whereby addition problems are overestimated and subtraction problems are underestimated. In our opinion, our data go further in the exploration of motion processes in numbers because motion perception and numbers are jointly manipulated. Data from the fourth and fifth papers provide evidence of interference between motion perception and number comparison and of one possible neural intersection between the two processes in VIPS. Overall, these studies add important new information about numbers representation:

1. When a comparison has to be done on a number, the comparison time is influenced by the direction of perceived coherent motion.
2. Rightward and upward concurrent motion facilitate the number comparison in agreement with left-to-right and down-to-up SNARC patterns.
3. RDK is a stimulus classically used to study selective attention to motion. Thus, it can be proposed that these kind of processes actually occur over the mental number line. Exploring the number continuum allude to processes of

selective attention to motion. The exact mechanism of these processes cannot be described neither from the present results, nor from the data of McCrink et al. (2007). But we can suggest that motion occurs over the mental number line; otherwise, the capture of selective attention to motion in a certain direction would not alter the comparison process.

4. The number comparison task is thought to access the core representation of numbers, the analog magnitude continuum. As number comparison is affected by processes of attention to motion, we can conclude that motion processes operate on the core numbers representation, that is, on the semantic, analogue magnitude representation.
5. Motion processes are independent of spatial processes over the mental number line. This is the case because no interaction between the size of the number and the direction of motion occurred.
6. The TMS data provide convergent evidence to the described relationship between numbers and motion: an area related to motion processing (VIPS) has been shown to be implied also in number comparison. Number parietal areas and motion perception areas are likely functionally related showing neural overlaps as the one find in VIPS. Probably other motion areas could show the same number-motion association than the one showed here.

4. Number space in hemispatial neglect is affected by the perception of motion.

In the pathological case of an altered attentional system, as is the case in neglect, the perception of motion has a compensatory effect. In this case, leftward motion has an impact in the altered mechanisms of attention over representational stimuli such as numbers. The impact of leftward motion has a double effect:

a) It alleviates the rightward bias that neglect patient present in their numbers representation. Without concurrent leftward motion neglect patients have longer comparison times on numbers that precede the reference number. This is interpreted as a problem in the access to numbers located on "the left" (i.e. number 4) of the reference number (i.e. number 5), left of the center in the numbers representation. When leftward motion concurs with these numbers this difficulty is alleviated. Thus motion has a compensatory effect

b) Distance effect is recovered as compared to when rightward or noisy motion concurred with the number to be compared. Both rightward and noisy motion could be aggravating neglect, as they either direct attention to the hyper-attended right side (as happens with rightward motion) or confound an already altered attentional system (noisy motion).

In general the present data link representational and attentional accounts of neglect: an external stimulus has an impact in the internal re-direction of attention over an spatial representation. This, at least at the behavioral level, entails similarities between mechanism of attention operating over external and internal stimuli. As we mentioned before, ERPs can also uncover some differences.

5. Some suggestions for future research

Numbers and spatial attention in other modalities

The comparison between the auditory and visual modalities in our ERP studies raised some questions on the preferred modality for the mental number line. An exploration of a similar cueing paradigm in the tactile modality both in sighted and blind individuals would provide important information for our proposal. From the interpretation given to our data, it follows that tactile targets would generate an electrophysiological response similar to the one found in audition in sighted and blind population. Controlled processes in blind individuals would master the processing of congruency. Thus early sensory processes should not be affected. In sighted individuals tactile targets would behave similarly to auditory targets and further processing of the stimulus would not be present. In this sense it would also be interesting to explore motion processes on the mental number line in the auditory modality.

A description of the exact motion processes in the mental number line

Other studies carried out in our lab have tested the electrophysiological correlates of the interferences from motion to number comparison. ERP components like the *selection negativity* (SN), related to selective attention to motion (i.e. Hillyard and Anllo-Vento, 1998) have been shown to parallel the behavioral data. This component is affected when the detection of an attended direction of motion is requested. Thus, as it is happening with space, the external capture of attention by motion has an effect on the motion processes happening on the mental number line. Further experiments showing “what is moving” in the mental number line are required.

Besides, the operational momentum proposal (McCrink et al, 2007) should be explored with the direct manipulation of motion while a subtraction or an addition is being performed. If the hypothesis is correct, leftward motion should facilitate subtraction while rightward motion should facilitate addition. So far, we have developed a paradigm in which subtraction is concurrent with coherent motion, finding in fact, a leftward motion facilitation.

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