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Mental number line disruption in a right-neglect patient after a left-hemisphere stroke

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ABSTRACT

A right-neglect patient with focal left-hemisphere damage to the posterior superior parietal lobe was assessed for numerical knowledge and tested on the bisection of numerical intervals and visual lines. The semantic and verbal knowledge of numbers was preserved, whereas the performance in numerical tasks that strongly emphasize the visuo-spatial layout of numbers (e.g. number bisection) was impaired. The behavioral pattern of error in the two bisection tasks mirrored the one previously described in left-neglect patients. In other words, our patient misplaced the subjective midpoint (numerical or visual) to the left as function of the interval size. These data, paired with the patient's lesion site are strictly consistent with the tripartite organization of number-related processes in the parietal lobes as proposed by Dehaene and colleagues. According to these authors, the posterior superior parietal lobe on both hemispheres underpins the attentional orientation on the putative mental number line, the horizontal segment of the intraparietal sulcus is bilaterally related to the semantic of the numerical domain, whereas the left angular gyrus subserves the verbal knowledge of numbers. In summary, our results suggest that the processes involved in the navigation along the mental number line, which are related to the parietal mechanisms for spatial attention, and the processes involved in the semantic and verbal knowledge of numbers, are dissociable.

1. Introduction

1.1. A neurocognitive model of number-related process in the parietal lobes

Based on significant behavioral, neuropsychological, and neuroimaging evidence, a neurocognitive model of number-related processes in humans as set in the parietal lobes has been proposed (Dehaene, Piazza, Pinel, & Cohen, 2003; Piazza & Dehaene, 2004). It is stated that the brain network is distributed into three subsystems: the bilateral horizontal intraparietal sulcus (hereinafter referred to as HIPS) should be a quantity-based domain-specific system; the posterior superior parietal lobe (hereinafter referred to as P-SPL) on both hemispheres with the possible involvement of the most posterior portion of the intraparietal sulcus (hereinafter referred to as P-IPS) and Precuneus (hereinafter referred to as PRE), should underpin the spatial processing of numbers; finally, the left angular gyrus (hereinafter referred to as AG) should be associated with the manipulation of numbers in verbal form. Dehaene and coworkers (2003, 2004) argued that the core semantic system of numerical quantity (HIPS) can be likened to a continuous, left-to-right oriented, mental number line with smaller quantities located to the left of larger ones (see also Hubbard, Piazza, Pinel, & Dehaene, 2005). The navigation along the mental number line depends on the attentional system (P-SPL). However, this latter system is known to be essential in various visuo-spatial tasks (e.g. reaching, grasping, eye, and/or attention-orienting, mental rotation, and spatial working memory) rather than being number-specific. Therefore, it is conceivable that the same process of covert attention that operates to select locations in space can also be engaged when attending to specific quantities on the number line. Clear evidence that numbers are coded spatially in the brain comes from the SNARC effect (Spatial Numerical Association of Response Codes), in which responses to small numbers are faster when executed in the left-hemispace, whereas responses to large numbers are faster when executed in the right-hemispace, indicating a spatial correspondence effect (Dehaene, Bossini, & Giraux, 1993). Nonetheless, "hemispace" is a relative concept, given that the SNARC effect has been reported even when "left" and "right" response positions have been defined within the same hemispace (right), using as effectors the index and middle fingers of the right-hand (Priftis, Zorzi, Meneghello, Marenzi, & Umilta, 2006).

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According to the model of Dehaene and coworkers (2003, 2004), we can expect anatomo-functional dissociations between the types of numerical tasks that brain-damaged patients should or should not be able to perform depending on the lesion site. Specifically, damage to the HIPS should mainly affect those tasks that require a genuine manipulation of both symbolic and non-symbolic numerical quantities, including approximation, subtraction, comparison, or estimation of numerosity. Damage to the P-SPL, and perhaps to P-IPS and PRE, should affect those tasks that place a strong emphasis on the visuo-spatial layout of numbers, such as, for example, the number bisection task (i.e. indication of the number is halfway between two spoken number words defining a numerical interval) and other tasks where the spatial sense of numbers is particularly relevant. Finally, damage to the left AG should result in the inability to retrieve arithmetical facts, which are mainly stored in verbal format, such as multiplications.

1.2. Neuropsychological evidence for the neurocognitive model of the number-related process in the parietal lobes

Support for the dissociation between attention-orienting process and the two other systems (i.e. the semantic and verbal ones) is provided for by the joint deficits of space and numbers processing that can be observed in patients that are affected by left unilateral neglect. These patients, following damage to the right-hemisphere, more frequently affecting the posterior inferior parietal lobe and parieto-frontal connections in the underlying white matter (see Bartolomeo, Thiebaut de Schotten, & Doricchi, 2007 for a review) are not aware of the left side of the perceived and/or internally generated space. When these patients are asked to judge whether a number is larger or smaller than a reference one, they are much slower with smaller than with larger numbers, demonstrating a representational deficit for numbers located to the left of a reference point along the mental number line (Priftis et al., 2008; Vuilleumier, Ortigue, & Brugger, 2004). For the same reason, when they are administered a number bisection task, they can progressively misplace their subjective midpoint number to the right as the interval grows (e.g. Question: interval 1–7, Answer: 5; Q: interval 1–9, A: 8), along with a paradoxical crossover effect (i.e. a leftward misplacement) for smaller intervals (e.g. Q: interval 1–5, A: 2). Several studies reported such a pattern of error (Cappelletti, Freeman, & Cipolotti, 2007; Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005; Priftis et al., 2006; Rossetti et al., 2004; Zamarian, Egger, & Delazer, 2007; Zorzi, Priftis, Meneghello, Marenzi, & Umilta, 2006; Zorzi, Priftis, & Umiltà, 2002). Due to damage to the non-dominant hemisphere, left-neglect patients are not acalculic and do not show any deficit in other numerical tasks such as simple arithmetic fact retrieval. Interestingly, Vuilleumier and Rafal (1999) found that in left-neglect patients the mere quantitation of a small number of items is preserved; patients could estimate numerosity with sets of up to four objects even when some of the enumerated items fell in the neglected hemispace. This again suggests that attentional and numerical systems are dissociable.

1.3. The nature of the mental number line

Despite the fact that nowadays, it is widely accepted that the mental number line is spatially organized and can be disrupted in left-neglect patients its nature is still an object of scientific debate. Two main proposals have been put forward. First, since left-neglect patients can show the above-mentioned pattern of spatial bias when bisecting both numerical intervals and horizontal visual lines, it has been proposed that spatial attention might be oriented along the mental number line, as it is oriented along visual lines (Zorzi et al., 2002, 2006). The proposed similarity between visual and numerical space is supported by the fact that pseudoneglect, namely the slight leftward bias showed by healthy participants (Jewell & McCourt, 2000), can also be detected in numerical bisection (Loftus, Nicholls, Mattingley, & Bradshaw, 2008; Longo & Lourenco, 2007; Zamarian et al., 2007), in which errors are correlated between the line and number bisection (Longo & Lourenco, 2007). The anatomical evidence in favor of this number/space analogy come from studies reporting that repetitive transcranial stimulation (rTMS) over the right posterior parietal cortex induces left-neglect in both line (Fierro et al., 2000) and number (Göbel, Calabria, Farne, & Rossetti, 2006) bisections. In contrast, a second account claims that leftward biases in visual and numerical space are two relatively independent phenomena dissociated both on functional (Doricchi et al., 2005; Rossetti et al., 2004) and anatomical (Doricchi et al., 2005) grounds. More specifically, mechanisms allowing for navigation along the mental number line might be related to an impairment in the spatial working memory underpinned by the right ventrolateral prefrontal cortex (Doricchi et al., 2005).

1.4. Aims of the present study

Since unilateral neglect is more frequent, severe, and persistent after right-brain damage, a relative low number of patients with right visual and/or representational neglect after left-brain damages has been reported (for a review see Beis et al., 2004). Here we examined a left brain-damaged patient with both visual and representational neglect due to a lesion to the P-IPS, P-SPL, and PRE but sparing AG and HIPS. The patient was assessed for numerical knowledge and administered a number bisection task as well as an extensive investigation of line bisection errors. Previous studies on mental number line disruption in neglect have examined right-brain damaged patients with large lesions (Cappelletti et al., 2007; Doricchi et al., 2005; Priftis et al., 2006; Rossetti et al., 2004; Zamarian et al., 2007; Zorzi et al., 2002, 2006), whereas our patient had a very selective left-hemisphere lesion. This allowed us to make predictions about his spared and impaired abilities more accurately. First, in accordance with Dehaene and coworkers' model (2003, 2004) we expected preserved performances on tasks strongly based on verbal (e.g. multiplication facts) or semantic (approximation, subtraction, comparison, and estimation of numerosity) knowledge of numbers. On the contrary, tasks enhancing the visuo-spatial components of the numerical representation, such as number bisection, counting, and continuing numerical series, should be relatively more impaired. It is noteworthy that the only available fMRI study on the forward and backward recitation of numbers (Zhou et al., 2006) showed that the mental storage of number sequences do not reside in the same brain region as number facts. Therefore, both number bisection and number sequences tasks could be processed mainly at the visuo-spatial level without accessing to the domain-specific knowledge of numbers. Second, we predicted a pattern of number bisection errors that mirrored the one reported in left-neglect patients (Cappelletti et al., 2007; Doricchi et al., 2005; Priftis et al., 2006; Rossetti et al., 2004; Zamarian et al., 2007; Zorzi et al., 2002, 2006): the longer the interval, the stronger the leftward shift of the subjective midpoint. Third, we investigated the relationship between line and number bisection errors in order to contribute to the discussion on the neurocognitive mechanisms underlying numerical and visual space.

2. Case history

DM is a 70-year-old female, right-handed, with 5 years of education (which is a normal educational level for Italians of her age). A modified *t*-test to compare an individual score with a control sample (Crawford & Howell, 1998) showed that age was not significantly different (two-tailed $p = .8$) to that of a control group (mean age 69, $SD = 3.39$) of five healthy females with the same educational level (mean educational level 5, $SD = 0$)

In March 2005, DM sustained a left-hemisphere hemorrhagic stroke. At the end of the same month, she came to our attention and she gave informed consent to participate in our study as approved by the Local Ethical Committee.

2.1. Neuroimaging examination

Two senior neuroradiologists, who were blind as to the purposes of the study, carefully described the whole CT scan performed 20 days after the stroke (in Fig. 1 for brevity only four representative slices are displayed). The left-hemisphere lesion involved the middle occipital lobe (hereinafter referred to as MOL), the superior occipital lobe (hereinafter referred to as SOL), the PRE, the P-IPS, the P-SPL, and superior longitudinal fasciculus (SLF). One experimenter (F.C.), without knowledge of the results and clinical features, mapped the lesion (Fig. 2) with Brain Voyager QX 1.8 software (Brain Innovation, Maastricht, Holland) according to the neuroradiologists' description (see figure legends for details on the mapping method).

2.2. Background

DM appeared oriented in space and time. The Mini Mental State Examination (Measso et al., 1993) resulted as adequate for her socio-educational background (adjusted score = 26, cut off = 24). Verbal short-term memory skills (Orsini et al., 1987) were preserved (adjusted score 4, cut off 3.5) and categorical thinking abilities (Laiacona, Inzaghi, De Tanti, & Capitani, 2000) were normal (adjusted score = 4, cut off 3). DM showed a mild receptive aphasia in the Aachen Aphasia Test (Luzzatti, Willmes, & De Bleser, 1994). However, this deficit did not affect the evaluation because she was clearly able to understand and follow each verbal instruction.

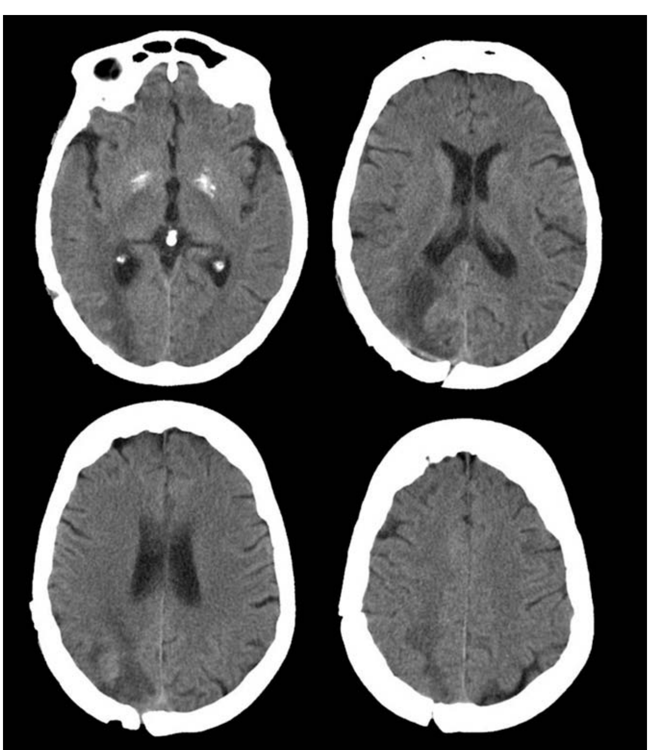

Fig. 1. CT scans. Data acquisition covering the whole brain was performed on a Siemens Sensation 10 scanner (Sensation Cardiac, Siemens, Erlangen, Germany). The radiological parameters were 120 kV, 360 mA, Pitch = 1, Acq. Matrix = 512 × 512.

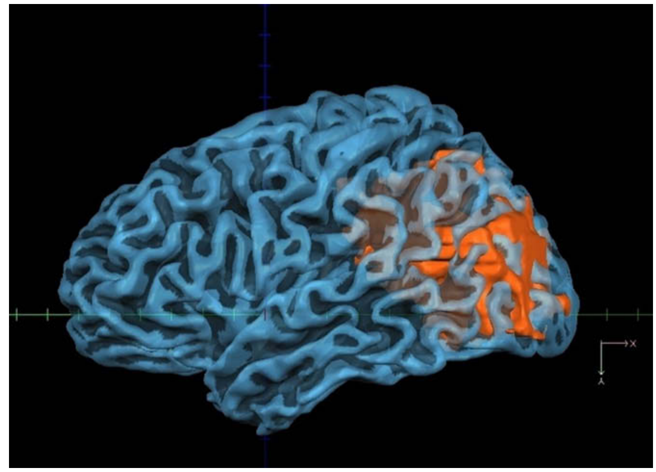

Fig. 2. Lesion reconstruction. The CT scans were analyzed using the Brain Voyager QX 1.8 software (Brain Innovation, Maastricht, Holland). To enable the following transformations, the 2D CT scans where converted in a 3D volume, and then a series of steps were followed in order to allow for the precise anatomical location of the lesion. First, the datasets where transformed into Talairach space (Talairach & Tournoux, 1988): the cerebrum was translated and rotated into the anterior–posterior commissure plane and then the borders of the cerebrum were identified, in which finally using the determined Talairach reference points, the dataset was transformed into Talairach space. Second, the CT scan was co-registered on a 3D high-resolution template (Colin 27, Montreal Neurological Institute). This process involved a mathematical co-registration exploiting slice positioning, as well as fine adjustments computed by comparing the data sets based on their intensity values; if needed, manual adjustments were also performed. Third, 3D Voi representing the lesion was created using intensity-based criteria. Finally, for display purposes, the maps were projected onto an average volumetric image.

DM expressed a 100% right-hand preference on the Edinburgh handedness questionnaire (Oldfield, 1971). Visual, sensory, and motor functions were assessed through the standard confrontation technique and a Goldman perimetry that revealed a complete right homonymous hemianopia but no other sensory-motor deficits.

2.3. Neglect assessment

2.3.1. Perceptual neglect

2.3.1.1. Line bisection. DM were required to mark the midpoint of a series of ten 180 mm long and 1 mm thick black horizontal lines printed at the center of A4 (210 × 297 mm) landscape-oriented sheet of white paper and presented in turn on a desk. The pages were horizontally centered on the sagittal midline of the patient's trunk. Errors were measured with an approximation to the nearest mm. A record was taken of the mean bisection error and *SD* (see Table 1).

2.3.1.2. Diller cancellation task (Diller & Weinberg, 1977). DM was presented with six rows of letters (104 Hs and 208 distracting letters) distributed in 52 columns, printed on an A3 (297 × 420 mm) landscape-oriented sheet of white paper, and asked to cross out all the Hs. The paper was centered on the patient's sagittal midline. The letters measured approximately 4 mm in height by 4 mm in width, and the style was capital Times New Roman. A record was taken of the number of omitted Hs in the left and right side of the array of stimuli (see Table 1).

2.3.1.3. Albert cancellation task (Albert, 1973). The patient was presented with a modified version of the Albert cancellation task,

Table 1
Neglect assessment

Visual												Representational			
Line bisection (mean rightward deviation)	Cancellation				Words and non-words reading		Sentences reading (number of sentences read incorrectly)	Copy of daisies (mean three judges' score)				Mental clock (mean three judges' score)		Spontaneous drawing (mean three judges' score)	
	Diller (omissions)		Albert (omissions)		Words (neglect-related errors)	Non-words (neglect-related errors)		Separate stem		Same stem					
	Left	Right	Left	Right				Left	Right	Left	Right	Left	Right	Left	Right
24.18 (*SD* = 17.03)	24/52	51/51	0/25	3/25	4/10	5/10	1/4	0	1	0	1	0	2	0	3

which was composed of 50 short black segments (20 mm long and 0.5 mm thick) printed on an A4 landscape-oriented sheet of white paper in front of the participant at a reading distance. The segments, which were distributed in 10 columns and five rows, were randomly oriented and grouped by proximity in two sets of 25 lines each, separated by an empty gap, vertically oriented and 4 cm wide. The participant's task was to cross out all the segments by means of a pencil with no limitation of time. A record was taken of the number of omitted lines in the left and right side of the array of stimuli (see Table 1).

2.3.1.4. Words reading (Vallar, Guariglia, Nico, & Tabossi, 1996). The patient was presented with a series of 10 Italian words printed at the center of A4 landscape-oriented sheet of white paper and presented in turn on a desk. The letters measured approximately 4 mm in height by 4 mm in width, and the style was capital Times New Roman. The patient's task was to read aloud each stimulus, with no time constraint. A record was taken of the neglect-related errors, namely omissions, substitutions, or additions of letters in the right-hand side of the letter string (see Ellis, Flude, & Young, 1987 for details).

2.3.1.5. Non-words reading (Vallar et al., 1996). The patient was presented with a series of 10 Italian non-words printed at the center of A4 landscape-oriented sheet of white paper and presented in turn on a desk. The size of the letters was approximately 4 mm both horizontally and vertically, and the letter style was capital Times New Roman. The patient's task was to read aloud each stimulus, with no time constraint. A record was taken of the neglect-related errors, namely omissions, substitutions, or additions of letters in the right-hand side of the letter string (see Ellis et al., 1987 for details).

2.3.1.6. Sentences reading (Pizzamiglio et al., 1992). DM was presented with a series of four Italian sentences ranging from 5 to 10 words printed at the center of A4 landscape-oriented sheet of white paper and presented in turn on a desk. The size of the letters was approximately 4 mm both horizontally and vertically, and letter style was capital Times New Roman. The patient's task was to read aloud each stimulus, with no time constraint. A record was taken of the number of sentences read incorrectly (see Table 1).

2.3.1.7. Copy of daisies (Marshall & Halligan, 1993). DM was presented with two separate daisies and two other daisies originating from the same stem printed upright in the center of two different A4 sheets of paper. The task was to copy the given drawing without any time constraints. Three judges search for omitted details attributing separately to each drawn half a score on a four-point scale: 0 = no omissions; 1 = 1 or 2 omissions, 2 = 3 or 4 omissions, 3 = 5 or more omissions (see Table 1). A record was taken of the mean score in the left and right side of the draw.

Perceptual neglect was defined according to the following criteria: (1) mean leftward bisection error exceeding 10 mm; (2) right side minus left side omissions on both Diller (Diller & Weinberg, 1977) and Albert (1973) cancellation tasks equal to 5 or more and (3) mean score of the right part of the copy of daisies (Marshall & Halligan, 1993) equal to 1 or more.

2.3.2. Representational neglect

2.3.2.1. Mental clock (Paivio, 1978). DM was presented with an 80 mm diameter circle representing a clock drawn in the center of an A4 sheet and asked to add digits from memory. A record was taken of the mean score in the left and right side of the drawn obtained through the afore-mentioned three judges' procedure (see Table 1).

2.3.2.2. Spontaneous drawing. DM was presented a white sheet of paper and asked to draw spontaneously whatever she wanted. A record was taken of the mean score in the left and right side of the drawing obtained through the afore-mentioned three judges' procedure (see Table 1).

Representational neglect was defined according to the following criteria: (1) mean score of the right part of the mental clock (Paivio, 1978) and spontaneous drawing equal to 1 or more.

As shown in Table 1, DM displayed signs of both perceptual and representational right-neglect in several conventional tests: line bisection, cancellation, word reading, copy of daisies, mental clock, and spontaneous drawing.

3. Experiment 1—arithmetical and number skills

DM and the control group were assessed for arithmetical and number skills by means of the following tasks. For each task a record was taken of the number of incorrect trials (see Table 1).

3.1. Number sequences

3.1.1. Forward counting

Participants were given a series of 10 spoken number words as cues (range 1–30) and then they were asked to recite forward a sequence without any time constraints. The participant did not recite beyond 30 (e.g. "would you please recite forward from 1 until you reach 20?").

3.1.2. Backward counting

Participants were given a series of 10 spoken couple of number words as cues (range 1–30) and then they were asked to recite backward a sequence without any time constraints. Participant did not recite beyond 1 (e.g. "would you please recite backward from 20 until you reach 10?").

3.1.3. Forward continuing of numerical series

Participants were presented a series of 10 spoken couple of number words as cues (range 1–30) and then they were asked to continue reciting forward a sequence without any time constraints. The participant did not recite beyond 30 (e.g. "would you please continue reciting forward the series 11–13–? until you reach 30?").

3.1.4. Backward continuing of numerical series

Participants were presented a series of 10 spoken couple of number words as cues (range 1–30) and then they were asked to continue reciting a sequence backward without any time limit. The participant did not recite beyond 1 (e.g. "would you please continue reciting backward the series 30–27–? until you reach 11?")

3.2. Repetition of numbers

Participants were given a series of 10 spoken number words as cues (range 1–30) and then they were asked to repeat them aloud.

3.3. Reading numbers

Participants were given a series of 10 visually presented numbers (range 1–30) and then asked to read them aloud.

3.4. Number comparison

3.4.1. Two numbers

Participants were given a series of five couple of numbers (range 1–30) and were required to identify the highest one.

3.4.2. Three numbers

Participants were given a series of five triplets of numbers (range 1–30) and were required to identify the highest one.

3.5. Arithmetical knowledge

3.5.1. Identification of odds

Participants were presented with a series of five triplets of numbers and had to identify which ones were odds.

3.5.2. Identification of evens

Participants were presented a series of five triplets of numbers and had to identify which ones were evens.

3.6. Mathematical operations

3.6.1. Additions

Participants had to perform five additions.

3.6.2. Subtractions

Participants had to perform five subtractions.

3.6.3. Multiplications

Participants had to perform five multiplications.

3.6.4. Divisions

Participants had to perform five divisions.

4. Experiment 2—number bisection and line bisection

DM and the control group were tested on number and line bisection tasks.

4.1. Number bisection

The stimuli and procedure were obtained following the Zorzi and colleagues study (2002). Participants were presented with two spoken number words that define a numerical interval. The size of the interval could be three (e.g. 1–3), five (1–5), seven (1–7), or nine (1–9) units. The magnitude of the two numbers could be units (e.g. 1–3), teens (11–13) or first teens (21–23). The order of presentation could be ascending (e.g. 1–3) or descending (3–1). The total number of stimuli was 96 randomly administered. Participants were asked to state the midpoint number without any calculation.

4.2. Line bisection

Participants were required to mark the midpoint of a series of five 1 mm thick black horizontal lines of seven different lengths (20, 40, 80, 100, 160, 200, and 240 mm). Stimuli were printed at the center of A4 landscape-oriented sheet of white paper and randomly presented on a desk. The pages were horizontally centered on the sagittal midline of the participant's trunk.

5. Results

5.1. Experiment 1—arithmetical and number skills

The control group performed 100% correctly in all numerical and arithmetical tasks, whereas DM resulted impaired in the number sequences tasks, namely the counting and continuing numerical series (see Table 2). She did not complete eleven series of the counting task (five forward and six backward) and eight of the continuing of the numerical series (four forward and four backward). Interestingly, the incorrect trials were due to omissions of the highest numbers of the series. For instance, in the counting tasks, she stopped at 5 when she had to recite from 1 to 10, whereas she started from 7 when she had to recite numbers from 10 to 1. Similarly, in the continuing of numerical series tasks, she stopped at 25 when she had to continue the couple 11–13 until 30, whereas she started from 21 when had to continue the couple 30–27 until 11. In the other tests, she made only one more error, namely she said that 5 was higher than 3 and 7 in the number comparison task.

5.2. Experiment 2—number bisection and line bisection

5.2.1. Number bisection

A multiple regression analysis (independent variables: size, magnitude, and order of the interval) on bisection errors (units) revealed that DM's performance was significantly ($\beta = -.448$, $p < .0001$) affected by the interval size (the longer the numerical interval, the stronger the leftward shift of the subjective midpoint number), whereas magnitude ($\beta = -.115$, $p = .263$) and the order ($\beta = -.136$, $p = .186$) were not significant. The performance at each of the four interval sizes resulted significantly different from the veridical midpoint (3 units: mean −1, SD = 0.83, $p < .0001$; 5 units: mean −1, SD = 1.15, $p = .0001$; 7 units: mean −1, SD = 0.46, $p < .0001$; 9 units: mean −2, SD = 0.81, $p = .0018$) as well as from the performance of the control group (3 units: no controls made errors, whereas DM had a mean of −1 (*SD* = 0.83); 5 units: $t = -17.38$, two-tailed $p < .0001$; *7 units* $t = -9.41$, two-tailed $p = .001$; 9 units: no controls made errors, whereas DM had a mean of −2 (*SD* = 0.81) on a modified *t*-test to compare an individual score with a control sample (Crawford & Howell, 1998).

In Fig. 3a (upper part) the mean bisection errors (units) and SE as a function of the interval size for DM and for the control group are shown.

5.2.2. Line bisection

A simple regression analysis on bisection errors (percentage of the deviation from the true midpoint) revealed that DM misplaced her subjective midpoint to the left as a function of the line length

Table 2
Experiment 1—arithmetical and number skills

Number sequences (number of incorrect trials)				Repetition of numbers (number of incorrect trials)	Reading numbers (number of incorrect trials)	Number comparisons (number of incorrect trials)		Arithmetical knowledge (number of incorrect trials)		Mathematical operations (number of incorrect trials)			
Counting		Completion of numerical series				Identification of the highest number		Identification of odds or evens		Additions	Subtractions	Multiplications	Divisions
Forward	Backward	Forward	Backward			Two numbers	Three numbers	Odds	Evens				
5/10	6/10	4/10	4/10	0/10	0/10	1/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5

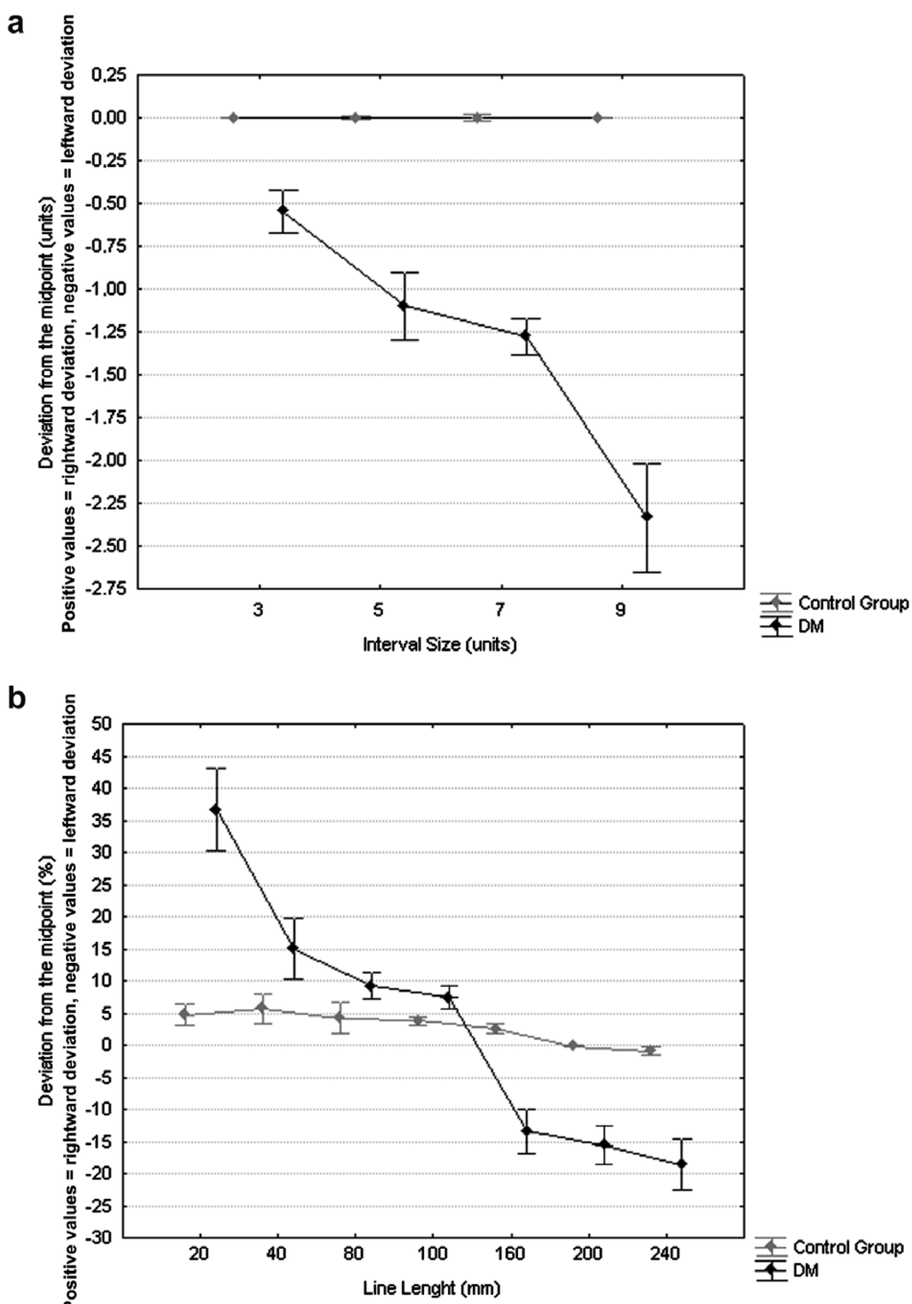

Fig. 3. Mean deviation (units) and standard error on number bisection as a function of the interval size (a) and mean deviation (percentage) and standard error on line bisection as a function of the line length (b).

($\beta = -.908$, $p < .001$) along with a crossover effect with the shortest lines (20, 40, 80, and 100 mm). The performance at each of the seven line lengths resulted in significantly different result from the veridical midpoint (20 mm: mean 36.37, $SD = 11.54$, $p = .002$; 40 mm: mean 15, $SD = 8.66$, $p = .01$; 80 mm: mean 9.17, $SD = 3.81$, $p = .0058$; 100 mm: mean 7.4, $SD = 0.001$, $p < .0001$;

160 mm: mean −13.33, SD = 6.29, $p = .0091$; 200 mm: mean −15.6, SD = 0.001, $p = < .0001$; 240 mm: mean −18.61, SD = 7.28, $p = .0046$) as well as from the performance of the control group (20 mm: t = 221.76, two-tailed $p < .0001$; 40 mm: $t = 103.36$, two-tailed $p < .0001$; 80 mm: $t = 58.42$, two-tailed $p < .0001$; 100 mm: t = 59.83, two-tailed $p < .001$; 160: $t = -9.48$, two-tailed $p = .001$; 200 mm: t = −6.86, two-tailed $p = .002$; 240 mm: t = −3.78, two-tailed $p = .019$) on a modified *t*-test to compare an individual score with a control sample (Crawford & Howell, 1998).

In Fig. 3b (lower part) the mean bisection errors (percentage) and SE as a function of the line length for DM and for the control group are shown.

5.2.3. Comparison between number bisection and line bisection

In order to examine the relationship between numerical and visual intervals in DM, we tested whether the slopes and intercepts of the two tasks were significantly different (indeed, we obtained the number bisection slope with a further linear regression analysis with interval size alone). The two coefficients of regression were not significantly different ($t = -0.01$; $df = 114$; $p = .959$) and the differences between the two intervals of confidence were rather small (mean line bisection = −0.101; mean number bisection = 0.205). Both the line bisection and number bisection slopes were significantly different (Crawford & Garthwaite, 2004) from the ones of the control group (line bisection: $t = -9{,}571$, two-tailed $p < .0001$; number bisection: $t = -4.84$, two-tailed $p < .0001$).

6. Discussion

This study reports a rare case of right spatial neglect following a left-hemisphere stroke in a right-handed patient. The patient also developed a mild form of aphasia that indicates preserved left-hemisphere dominance for language and, therefore, her spatial neglect seems to reflect a specific left-hemisphere variety of neglect (Beis et al., 2004), more than a form of inversed hemispheric asymmetry.

The assessment of numerical knowledge as well as the number bisection task revealed deficits of the visuo-spatial processing of numbers along with spared semantic and verbal numerical skills. DM was impaired as regards number sequence tasks (i.e. counting and continuing numerical series) and in the number bisection task. Both of these tasks require to sequentially attend to the enumerated objects on the mental number line rather than making numerical operations (Dehaene, Molko, Cohen, & Wilson, 2004; Dehaene et al., 2003; Zhou et al., 2006). Since DM's left-hemisphere damage involved P-IPS, P-SPL, and PRE but spared AG and HIPS, these data are strictly consistent with the neuropsychological predictions of the tripartite organization of the number-related processes in the parietal lobes (Dehaene et al., 2003; Piazza & Dehaene, 2004) as well as with left-neglect patients data (Cappelletti et al., 2007; Doricchi et al., 2005; Priftis et al., 2006; Rossetti et al., 2004; Zamarian et al., 2007; Zorzi et al.,2002, 2006). Therefore, our results support the idea that the processes involved in the navigation along the mental number line might be dissociable by the semantic and verbal knowledge of numbers and are related to the parietal mechanisms for spatial attention. In a broader sense, these conclusions are suggestive of the fact that much of the human capacity for number processing relies largely on representations and processes that are not specific to the number domain.

Our patient showed both visual and representational neglect, which is a well documented phenomenon in right-brain damaged patients (Bisiach & Luzzatti, 1978). Indeed, the orientation of attention in representational space activates areas that extensively overlap those that are involved in spatial attention (Nobre et al., 2004). More distinctively, DM displayed a novel behavioral pattern that mirrored the one reported in left-neglect patients (Cappelletti et al., 2007; Doricchi et al., 2005; Priftis et al., 2006; Rossetti et al., 2004; Zamarian et al., 2007; Zorzi et al., 2002, 2006); when asked to bisect numerical intervals, she misplaced her subjective midpoint leftward, as a function of the interval size. The absence of any effect of the order of presentation (i.e. 1–9 or 9–1) is consistent with the idea of a canonical left-to-right orientation of the mental number line (Cappelletti et al., 2007; Doricchi et al., 2005; Priftis et al., 2006; Rossetti et al., 2004; Zamarian et al., 2007; Zorzi et al., 2002). Such a conclusion is supported by the fact that in the number sequence tasks of the arithmetical and number skills assessment, incorrect trials were due to the omissions of the highest numbers of the series, independent of direction (forward vs backward) of the to-be-produced number sequence (this cannot be due to a general impairment of oral counting, since numbers on the leftmost were produced correctly). Interestingly, Baxter and Warrington (1983), reported a patient affected by neglect dysgraphia who made spelling errors at the beginning of words irrespective of whether words were spelled in a forward or backward direction. This might suggest that serial tasks, such as the oral spelling of a specific sequence of graphemes or oral production of a specific sequence of numbers might require a left-to-right spatial representation of graphemes and numbers, respectively. All in all, these data corroborate the idea that the mental number line is spatially organized along a continuous, quantity-based analogical format (see also Hubbard et al., 2005), which can be selectively disrupted according to the side of the damaged attention-orienting processes.

The above-mentioned progressive leftward misplacement of the subjective numerical midpoint was mimicked in the line bisection task. Indeed, when DM had to bisect the shortest visual lines, she showed a crossover effect, namely she displaced her subjective midpoint rightward rather than leftward (see Fig. 3). Such an effect of line length manipulation (Marshall & Halligan, 1989), although in the opposite direction (i.e. progressive rightward displacement with increasing visual lengths and paradoxical leftward shift for very short lines) is a well-known phenomenon in left-neglect patients. On the contrary, such a mirror-like behavior has been rarely reported in right-neglect patients (Mennemeier, Rapcsak, Pierce, & Vezey, 2001; Mennemeier et al., 2005). The functional association between the performances in the two bisection tasks (i.e. numerical and physical) prompts the event that spatial attention operates similarly in visual and numerical space (Zorzi et al., 2002, 2006); bisection errors would result from damage to a common attention-orienting process underpinned by left P-IPS and P-SPL. However, due to the atypical nature and rarity of these patients, no definitive conclusions about the neural basis of right-neglect in the left-hemisphere can be claimed at present (see Husain & Nachev, 2007 for a discussion). In addition, a CT scan can underestimate the extent of the subacute disruptive effects that are produced by a stroke on areas surrounding the lesion and, therefore, the functional association between the line and number bisection could be a consequence of damage to two different, although close, brain areas. Because of these reasons, we must take into account some possible alternative interpretations of these results. First, right-neglect here might follow damage to the AG and the supramarginal gyrus, namely the left inferior parietal lobe areas that are very close to P-IPS, and P-SPL and are homologous to those most frequently damaged in left-neglect after right-hemisphere damage (see Halligan, Fink, Marshall, & Vallar, 2003). Second, right-neglect might be due to damage to the SLF (the most important intrahemispheric fiber tract connecting the posterior parietal lobe and frontal lobe (Makris et al., 2005) whose interruption in the right-hemisphere contributes to left-neglect (see Bartolomeo et al., 2007 for a review). Third, we cannot exclude the fact that the pattern of numerical errors might be due to a functional diaschisis of the ventrolateral prefrontal cortex, which is a brain area that could be crucially involved in disrupting the mental number line in left-neglect patients after right-hemisphere damage (Doricchi et al., 2005).

In conclusion, our data support the view that navigating along the mental number line necessarily requires the normal functioning of spatial attention mechanisms, whereas the integrity of verbal and domain-specific knowledge of numbers is not a sufficient condition. Additionally, the association between the two bisection tasks is in line with the idea that spatial attention operates similarly in visual and numerical space. However, we acknowledge that single case studies consistently limit any generalization and, as we pointed out above, several cautions should be taken regarding the anatomo-functional relationship between numerical and visual space in this case report. To conclude, further evidence is necessary in order to disentangle whether representations of physical and numerical space are systematically associated in neglect and whether or not they share common neural structures.

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