Neuropsychology
2011, Vol. 25, No. 2, 193–200

0894-4105/11/$12.00 DOI: 10.1037/a0021304

Time Perception in Spatial Neglect: A Distorted Representation?

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Objective: It has been proposed that time, space, and numbers share the same metrics and cortical network, the right parietal cortex. Several recent investigations have demonstrated that the mental number line representation is distorted in neglect patients. The aim of this study is to investigate the relationship between time and spatial configuration in neglect patients. ***Method:*** Fourteen right-brain damaged patients (six with neglect and eight without neglect), as well as eight age-matched healthy controls, performed a time discrimination task. A standard tone (short: 700 ms and long: 1,700 ms) had to be confronted in duration to a test tone. Test tone differed of 100, 200, and 300 ms respect to the standard tone duration. ***Results:*** Neglect patients performed significantly worse than patients without neglect and healthy controls, irrespective of the duration of the standard tone. ***Conclusion:*** These results support the hypothesis that mental representations of space and time both share, to some extent, a common cortical network. Besides, spatial neglect seems to distort the time representation, inducing an overestimation of time durations.

Keywords: time perception, spatial neglect, brain damaged patients, theory of magnitude, parietal cortex

Converging evidence for similarities in the processing of space, numbers, and time has recently led to the Theory of Magnitude (ATOM) (Walsh, 2003). This theory suggests that these three domains share similar mechanisms, including a common metric for action, the same accumulator principles and the same neural basis, the inferior parietal cortex. The relation between numbers and space is well established and has been demonstrated both in healthy volunteers and in brain damaged patients (for a review see Hubbard et al., 2005). In general, healthy participants tend to have a spatially oriented number representation. This "mental number line" is typically organized such that small digits are represented toward the left side of the imagined space, while large digits are represented toward the right side. Previous findings strongly suggest that number magnitude is represented with a spatial orientation that develops progressively from left to right.

To date, less attention has been dedicated to the link between spatial processing and time perception. In behavioral studies, subjects who observe downscaled environments (i.e., a miniature version) undergo systematic shifts in their experience of time (De Long, 1981; Mitchell & Davis, 1987). Specifically, they experience a compression in temporal estimation that is proportional to the scale-model environments being observed.

Recently, researchers have proposed a spatial-temporal association of response codes (STEARC), as a 'mental time line,' or a systematic relation between spatial and time codes for action (Ishihara, Keller, Rossetti, & Prinz, 2008). In this work, Ishihara and colleagues (2008) asked participants to estimate the onset time of the last click of a given sequence. In the congruent condition, left-sided responses indicated 'early,' whereas right-sided response indicated "later" appearance of the probe. In the noncongruent condition, the stimulus-response contingency was reversed. The authors identified a facilitatory effect for compatible responses ("left"–"early," "right"–"late") compared to noncompatible responses (left–late, right–early), which suggests a space-time representation relationship that has the potential to influence perception and action. The STEARC is an analogous of the SNARC effect (spatial-numerical association of response codes), such as in the parity judgment task, participants are quicker to respond to smaller numbers (e.g., 1 and 2) with the left hand and to larger numbers (e.g., 8 and 9) with the right hand.

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Vicario, Caltagirone, and Oliveri (2007) showed that optokinetic stimulation can influence time estimation. Subjects were required to make time comparison of time intervals before and after optokinetic stimulation (leftward or rightward). They found a directional bias in time perception with only rightward stimulation inducing an overestimation of time perception compared with baseline and leftward optokinetic stimulation, suggesting a mental linear representation of time intervals.

Also neuropsychological research on hemispatial neglect has considered this issue. Hemispatial neglect is a syndrome characterized by a deficit in interpreting and processing stimuli presented to the left hemispace, which follows damage to the right hemisphere, and in particular to the inferior parietal lobule (Husain & Nachev, 2006). Studies with neglect patients have demonstrated impaired temporal dynamics of spatial attention (Becchio & Bertone, 2006), but few studies to date have investigated time discrimination or interval-production tasks. Basso and colleagues (1996) tested a patient with hemispatial neglect on short-duration estimation tasks (300 vs. 700 ms). The patient overestimated durations of stimuli presented in the leftward space of the right space and underestimated durations of stimuli presented in the non-neglected field. More recently, Danckert et al. (2007) investigated the ability of neglect patients to estimate time intervals of seconds.

They found that, compared to healthy controls (HCs), neglect patients grossly underestimated all durations for intervals greater than one second. Right-hemisphere damaged patients without neglect also tended to underestimate durations, but their responses were less inaccurate than those of patients with neglect.

Recently, Cappelletti, Freeman, and Cipolotti (2009) described a patient, with a right hemisphere lesion. This patient showed important deficit of time estimation (underestimation), but not of number and space processing. Nevertheless, an interaction in his behavior between numbers and time representations as well as between numbers and space representations was present. Once again, these results suggest that space, numbers, and time partially overlap even if they could be impaired selectively.

More recently, some evidence for the spatial representation of time has been presented in studies that use prism adaptation (Frassinetti, Magnani, & Oliveri, 2009). Prism adaptation is a technique to rehabilitate spatial deficits in neglect patients (e.g., Luaute, Halligan, Rode, Jacquin-Courtois, & Boisson, 2006). Neglect patients are initially biased to the right, but after sensorimotor adaptation to the rightward prismatic displacement of the visual field, this symptom can improve markedly (Rossetti et al., 1998). Frassinetti et al. (2009) used this technique to shift time perception in healthy participants. They found that, after prism adaptation, participants reported an underestimation (if exposed to leftward deviation) or overestimation (if exposed to rightward deviation) of time durations, suggesting that time perception may be modified after sensorimotor adaptation.

The aim of the present study is to investigate the possible relationship between time and space processing in neglect patients. We used a time discrimination task, involving a comparison of duration between a standard auditory stimulus and a test tone. Two groups of right brain-damaged patients were tested, one with hemispatial neglect, and the other without hemispatial neglect. In addition, we tested a group of healthy controls. We compared the responses to two different durations of standard stimulus (700 or 1,700 ms). Because it has been reported that suprasecond durations are processed by cortical structures (Mauk & Buonomano, 2004), we expected that, for durations longer than one second, a larger bias would be present in neglect patients, similar to what happens for spatial elaboration. In particular, if the time representation follows the same rules as the spatial one it is expected that the magnitude of the over- or underestimation bias of is linearly related to the length of the stimulus. As in line bisection has been shown the longer the line to bisect, the greater the magnitude of the neglected space (e.g., Halligan & Marshall, 1988).

Moreover, to test the presence of specific lateralization effects in time discrimination, the presentation of auditory stimuli was lateralized. Standard and test tones were randomly presented contralaterally (e.g., standard at right ear and test at left ear, or vice versa). At this regard, we expected that time discrimination in the left space would be more severely impaired than in the right space, for neglect patients as compared to non-neglect patients and HCs.

Method

Apparatus and Stimuli

Tones were delivered at a suprathreshold level using earphones. The first stimulus, termed the 'standard,' was presented to one ear, and the second stimulus, termed the 'test,' was presented to the other ear. Presentation order was counterbalanced between the two sides. Each trial comprised a series of two stimuli, a standard and a test tone. Standard tones could be of two durations: "short" or "long" (700 vs. 1,700 ms, respectively). Test tones were presented at multiple offsets from the standard tones, using differences of 100, 200, or 300 ms. In other words, given a standard of 700 ms, the test tone could be any of 400, 500, 600, 800, 900, or 1000 ms. The interstimulus interval was 500 ms and the intertrial interval was 800 ms. The experiment comprised four blocks of 48 trials each, for a total of 192 trials, of which 96 featured short and 96 featured long tones.

Participants were required to decide whether the test tone was shorter or longer than the standard tone. Responses were recorded via a response-box. Participants used the right hand to respond, or in the case of motor deficits, the experimenter recorded the responses (for five patients with neglect). Accuracy was stressed as being of greatest importance, and there were no response time restrictions. Stimuli were created using the Test Tone Generator and presented with Presentation software package, version 11.0 (http://www.neurobs.com). This software was used both to deliver tones and to record subjects' responses.

Participants

Eight right-brain damaged patients without hemispatial neglect (N−) (mean age = 70.0 ± 10.9 years; mean education = 6.9 ± 2.4 years) and six right-brain damaged patients who exhibited hemispatial neglect (N+) (mean age = 60.3 ± 11.1 year; mean education = 9.3 ± 2.6 years) took part in our experiment. Patients were recruited at the Neurological Unit of the University of Brescia, Italy, and at the Service de Rééducation Neurologique, Hôpital Henry Gabrielle, Hospices Civils de Lyon, France. Eight age-matched healthy controls (HC) were also tested (mean age = 67.2 ± 4.5 years; mean education = 9 ± 3.2 years). Clinical details are listed in Tables 1 and 2. All participants were right-handed. All gave informed consent and the experimental

Table 1
Clinical and Demographic Characteristic of Patient Groups

Patients	Gender	Age (years)	Education (years)	Aethiology	Time from lesion (days)	Lesion site
Patients with spatial neglect (N+)						
RB	M	65	8	ISCHAEMIC	477	Fronto-parietal
CP	M	60	5	ISCHAEMIC	35	Territory of middle cerebral artery and basal ganglia
RF	M	80	13	ISCHAEMIC	150	Temporo-occipital
DO	F	49	10	HAEMORRAGIC + LOBECTOMY	328	Temporal and partial fronto-parietal
LMI	M	53	10	ISCHAEMIC	210	Fronto-temporo-parietal
VR	F	55	10	ISCHAEMIC	113	Fronto-parietal
Patients without spatial neglect (N−)						
MB	F	88	8	ISCHAEMIC	15	Frontal and basal ganglia
PG	M	72	5	ISCHAEMIC	19	Periventricular white matter
PM	F	68	11	HAEMORRAGIC	28	Capsulo-thalamic and basal ganglia
ZP	F	76	5	ISCHAEMIC	27	Anterior foreharm of internal capsule
GS	M	49	8	ISCHAEMIC	350	Frontal
TM	M	67	8	ISCHAEMIC	16	Frontal
CF	M	73	5	ISCHAEMIC	172	Superior intraparietal lobule
MA	M	67	5	ISCHAEMIC	180	Fronto-temporale

protocol was approved by the Ethics Committee of IRCCS San Giovanni di Dio Fatebenefratelli, Brescia, Italy.

All right-brain damaged patients were assessed for visuospatial abilities (Lezak et al., 2004). The neuropsychological battery included:

A. Line bisection tasks. Line bisection of three different lengths (5, 10, and 25 cm) presented on A4 format paper and the Schenkenberg test were performed. The cut-off score for line bisection was calculated on the basis of an age-matched

Table 2
Neuropsychological Assessment and PSE of Patient Groups

	Neuropsychological assessment						Time discrimination task
Patients	Visual extinction	Auditory extinction[a]	Line bisection[b]	Shenkenberg[c]	Albert test[d]	Star cancellation[d]	PSE right side[e]
Patients with spatial neglect (N+)							
RB	+	+	26	17 (4)	2	37	55
CP	+	−	13	28 (4)	3	31	24
RF	+	+	42	31 (8)	3	35	15
DO	+	+	13	35 (2)	6	29	74
LMI	+	+	28	26 (2)	3	37	89
VR	+	−	14	18 (5)	4	18	171
Patients without spatial neglect (N−)							
MB	−	−	−1	3	0		1
PG	−	−	−2	5	0	0	−44
PM	−	−	−3	2	0	1	−20
ZP	−	−	−3	5	0	1	−30
GS	−	−	2	4	0	0	11
TM	−	−	2	3	0	0	−28
CF	−	−	−3	1	0	1	−24
MA	−	−	−1	3	0	1	−19

[a] Cuf-off <60% double tones detected. [b] Cuf-off <7 mm deviation ("+" indicates rightward bias, "−" indicates leftward bias). [c] Cuf-off <15 mm deviation ("+" indicates rightward bias, "−" indicates leftward bias); in parentheses the number of omissions. [d] Cuf-off <2 omissions on the left side of the sheet. [e] PSE: point of subjective equivalence; difference between PSE and standard tone duration is reported.

sample of 10 subjects (2 SDs below the mean of control subjects' performance). For the Schenkenberg test, we considered hemispatial neglect to be present when participants exhibited a mean rightward deviation of greater than 1.53 cm.

B. Cancellation tasks. The Albert Test and the Star Cancellation test were used. For both tests, we considered a cut-off score of two omissions on the left hemispace of the paper.

C. Drawing. A drawing-copy test and the Clock Test of drawing for memory were performed. A score was considered pathological when left-sided elements of the drawing were omitted.

D. Reading task. We asked participants to read aloud eight sentences of different lengths presented separately on a sheet of paper (cut-off score: 2 errors).

In addition, the Mini Mental State Examination Test was performed to assess possible cognitive decline. Patients were excluded if they scored below the cut-off of 24/30.

Clinical evaluation was supplemented by an assessment of motor, somatosensory, and visual deficit awareness, using the Bisiach, Vallar, Perani, Papagno, and Berti (1986) questionnaire. Auditory extinction was also assessed by delivering 10 tones unilaterally (right and left) and 10 tones under a dichotic listening condition. The tone duration was 500 ms, and auditory extinction was considered if the patient missed more than 60% of the left stimuli under the dichotic condition.

Statistical Analysis

Mixed repeated measure ANOVAs were performed on the percentage of correct responses. Within-subject factors included: Tone Series (short vs. long), Side of Standard Tone Presentation (right vs. left), Time Offset (100, 200, and 300 ms). The between-subjects factor was the Group (N+, N−, and HC).

For the point of subjective equivalence (PSE, for its calculation see below), it was conducted a mixed repeated measure ANOVA considering the standard tone (700 vs. 1,700) as within-subject factor and the Group (N+, N−, and HC) as between-subjects factor.

The assumption of sphericity was assessed using Mauchly's Test, and the Geisser-Greenhouse correction for the number of degrees of freedom was adopted when necessary. Size effects are reported as partial eta squared values (η_p^2).

Post hoc analyses were performed by applying the False Discovery Rate (FDR) together with the Benjamini and Hochberg (1995) procedure for multiple comparisons. This technique has the advantage of controlling for Type I errors and is applicable for both within- and between-subjects comparisons. Statistical analyses were performed with SPSS (SPSS, Inc., Chicago) and the alpha value for significance was set equal to 0.05.

Results

The correct response percentages were analyzed to compare between-group performance. We found a significant main effect of Group [$F(2, 19) = 52.52$, $p < .001$ $\eta_p^2 = 0.85$]. Post hoc analyses revealed that N+ patients (62.4 ± 18.4) scored significantly worse than N− (78.2 ± 15.2, $p < .0001$) and HC (85.2 ± 14.1; $p < .0001$); moreover, N− patients were significantly worse than HC ($p = .003$).

A main effect of Tone Series [$F(1, 19) = 36.23$, $p < .001$, $\eta_p^2 = 0.66$] was found. All participants exhibited better performances for the short Tone Series (81.1 ± 17.2) than for long ones (60.5 ± 17.4), but there was no difference between groups (no significant interaction of Tone series and Group). The main effect of Time Offset was also significant [$F(1.98, 37.66) = 49.28$, $p < .001$, $\eta_p^2 = 0.72$), demonstrating a linear effect as the Offset between standard and test tones increased.

Interestingly, the interaction between Side of Presentation × Time Offset × Group was statistically significant [$F(2.94, 27.97) = 4.51$, $p = .01$, $\eta_p^2 = 0.32$]. Post hoc analyses showed that the N+ patients recorded performances that were significantly weaker than HC for all the Time Offsets considered. Namely, for the right side: at 100 ms (N+ = 58.1 ± 15.6, HC = 73.2 ± 6.9; $p = .03$), 200 ms (N+ = 67.9 ± 16.6, HC = 93.2 ± 8.0; $p = .007$), and 300 ms (N+ = 66.7 ± 21.7, HC = 98.2 ± 5.1; $p = .0009$). For the left side: at 100 ms (N+ = 49.7 ± 9.7, HC = 76.9 ± 11.2; $p = .0006$), 200 ms (N+ = 57.8 ± 16.1, HC = 95.1 ± 5.8; $p < .0001$), and 300 ms (N+ = 77.6 ± 14.3, HC = 94.3 ± 7.8; $p = .002$). Even if the two groups (i.e., N+ and HC) performed similarly for both sides, higher differences were found on the left side; for this reason the Side of Presentation × Time Offset × Group interaction was significant. That is, the difference, on the right side, between N+ and HC was 15.1 ms at 100 ms Time Offsets, and 30.5 ms at 200 ms Time Offsets. While on the left side these differences were higher: 27.2 ms and 40.3 ms at 100 and 200 ms Time Offsets, respectively.

Moreover N+ individuals performed significantly worse than N− patients for all Time Offsets ($p < .05$), whereas the N− performance metrics were not significantly different in terms of Time Offset to those of HCs (see Figure 1).

Point of Subjective Equivalence (PSE)

We calculated the PSE, defined as the perceived duration (of the test tone) in relation to the reference duration (of the standard tone), for each participant. The PSE was calculated following this method. First, we calculated the probability of the "test longer" responses against the actual duration of the stimulus. The probability goes from 0 to 100%, where 50% stands for the subjective perception of the stimulus duration equal to the test duration. Then, data were fitted to a logistic function and PSE (in milliseconds) was estimated for each participant trough the regression × parameter (using the standard durations, such as 700 and 1,700 ms).

If the PSE is inferior to the standard tone duration it means that there is an underestimation of the perceived test tone, and if the PSE is longer an overestimation is assumed. So, the PSE estimates the subjective perception of each participant when the tone is 700 or 1,700 ms long. For instance, if the standard tone duration is 700 ms and the PSE is 650 ms, this means that participant had perceived the duration of the tone 50 ms shorter, indicating an underestimation.

For the standard of 700 ms and the test on the right, the PSE for the N+ patients was 772 (±81), 671 (±26) for N−, and 683 (±31) for HC. When the test was presented on the left the PSE, or

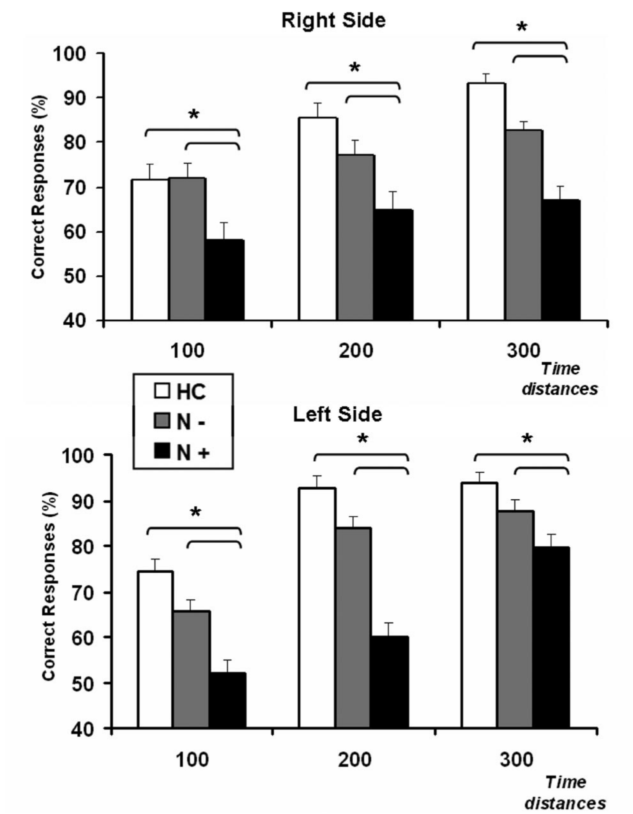

Figure 1. Percentage of correct responses in the time discrimination task, as a function of the side of test tone presentation. Bars display means and standard errors. N+ = patients with spatial neglect (n = 6); N− = patients without spatial neglect (n = 8); HC = healthy controls (n = 8).

the N+ patients was 692 (±81), 691 (±26) for N−, and 690 (±31) for HC. The analysis showed a significant overestimation of the duration (72 ms) of N+ patients compared to N− (−29 ms, p = .03) and HC (−17 ms, p = .04), when the test tone was on the right. No difference between groups was found when the test tone was presented on the left.

For the standard of 1,700 ms and the test on the right, the PSE for the N+ patients was 1769 (±94), 1628 (±91) for N− and 1638 (±105) for HC. When the test was presented on the left the PSE, or the N+ patients was 1667 (±110), 1638 (±126) for N− and 1634 (±65) for HC. The analysis showed a significant overestimation of the duration (69 ms) of N+ patients compared to N− (−72 ms, p = .04) and HC (−62 ms, p = .04), when the test tone was on the right. No difference between groups was found when the test tone was presented on the left (see Figure 2).

Correlations

Spearman's rank correlation coefficients were calculated considering the spatial bias in line bisection and the N+'s performance in time discrimination task. For line bisection it was considered the spatial rightward bias from the geometric midpoint for the three length of lines (5, 10 and 25 cm). It was considered the percentage of correct responses for the three time offsets (100, 200, and 300 ms), when the test tone was delivered on the right and the left side, respectively. Positive correlations between the percentage of correct responses for the time offset of 300 ms on the right and the rightward bias in bisection of 10 cm (r = .87) and of 25 cm (r = .93) lines were found. Negative correlations between the percentage of correct responses for the time offset of 300 ms on the left and the rightward bias in bisection of 10 cm (r = −0.82) and of 25 cm (r = −0.81) lines were found. These results indicate that in N+ larger the spatial bias poorer the performance in the time discrimination task when the test tone was delivered on the left, but not on the right.

In N+ patients, PSE negatively correlated with the magnitude of the rightward bias only when the test tone was presented on the left ($r > -0.71$). This indicates that the larger is the spatial bias on line bisection, the larger is the underestimation of the time duration on the left side.

Discussion

Recent evidence has suggested that numbers, space, and time share a common cognitive mechanism and neural substrate in the parietal cortex (Walsh, 2003). Distortion of space and numbers has been previously demonstrated in brain damaged patients by several studies (e.g., Hubbard et al., 2005; Zorzi, Priftis, & Umilta, 2002) strengthening the idea of a direct relationship between the two.

Conversely, to the best of our knowledge, the relationship between time and space has not been widely investigated in patients with visuospatial deficits, such as hemispatial neglect patients (Basso et al., 1996). In the current study, a time discrimination task was performed with a group of neglect patients, and the data were compared to a group of right-brain damaged patients without spatial neglect and a group of HCs. In general, we concluded that neglect patients were more severely impaired in terms of time discrimination compared to both HCs and right-brain damaged patients without visuospatial deficits. These results are consistent with previous studies that investigated temporal processing in neglect patients (for a review see Becchio & Bertone, 2006). These studies have suggested that neglect patients have deficits in processing time information because of their inability to integrate information across time or in temporal processing (e.g., Husain, Shapiro, Martin, & Kennard, 1997).

It was not found any effect of tone series between groups. All the groups had a lower performance in processing long tones (1,700 ms) in comparison to short tones (700 ms), but this effect was of the same size in all groups.

Neglect patients performed worse than controls both when the test tone was presented on the left and when it was presented on the right. Only small differences in effect-size were found: neglect patients performed worse when the test tone was on the left than on the right for short time intervals (i.e., 100 and 200 ms). It is known that, in neglect patients, left-side stimuli are often not reported or undetected (Heilman, Watson, & Valenstein, 2005) because of the right parietal damage and its consequential attentional impairments. By assuming a parallelism between space and time representation, we hypothesized that time discrimination might be more severely impaired when the target stimuli were presented on the left side, as left-sided targets are impaired in spatial processing. Space and time processing are thought to share the same neural network, namely the right parietal region (Bueti & Walsh, 2009; Walsh, 2003), which is one of the typical lesion sites associated

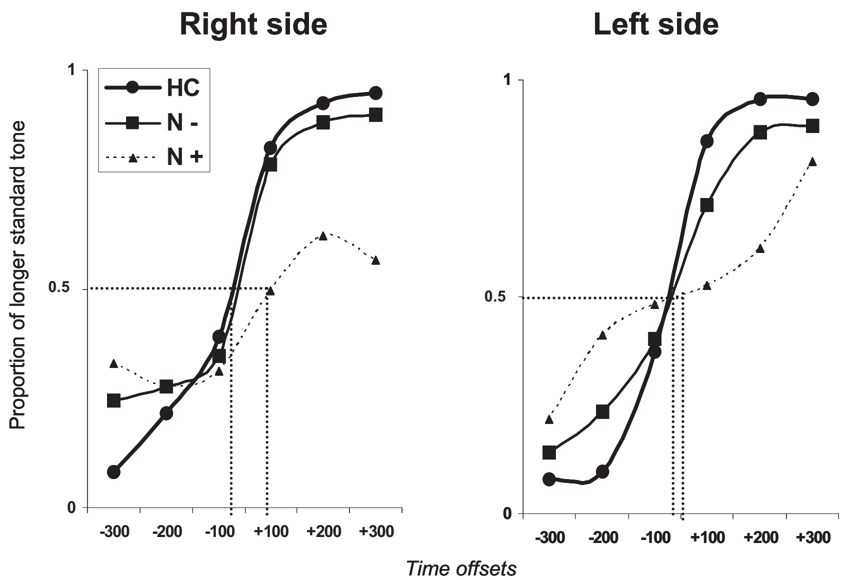

Figure 2. PSE for each group in the time discrimination task, as a function of the side of test tone presentation. N+ = patients with spatial neglect (n = 6); N− = patients without spatial neglect (n = 8); HC = healthy controls (n = 8).

with spatial neglect (Husain & Nachev, 2006). Conversely, our behavioral results suggest that time discrimination is always impaired irrespective of the side of presentation.

However, when we looked at the qualitative aspect of the time distortion, such as under- or overestimation, interesting results were found. We calculate the PSE for each participant to see the subjective estimation of the perceived time duration of the test tone. It is supposed that shorter PSE respect to the standard tone is consistent with an underestimation and vice versa. It was found that N+ patients have an overestimation of about 70 ms whereas N− and controls showed underestimation, when the test tone was presented on the right. Conversely, when the test tone was presented on the left the slope function of the PSE changed (it was flatter than HC group), and no difference to HC for the PSE was observed for N+.

These results could be compatible with an impaired clock mechanism (Gibbon, Church, & Meck, 1984). The internal clock is an accumulator that sums pulses produced by a pacemaker. The output of the accumulator is compared to reference in the memory, and time estimation is made. In this case, impaired attentional resource in N+ affects the accumulation resulting in a higher production of the pulses, and consequently an overestimation. This overestimation was observed when the test tone was on the right, so not in the neglected space. So, it is not the case. How can this overestimation on the right be explained? Beside the accumulator, in the model of Gibbon et al. (1984) reference memory and working memory are included. Reference memory is related to the representation of the time and permits the comparison with the output of the accumulator, while working memory allows the temporal storing of the information. It is likely that one of these two systems is affected in the N+ patients. When the standard tone is in the memory and its representation is distorted (i.e., smaller in N+) the consequence is an overestimation of the test tone perception, as showed by present results. The distortion of the standard tone occurred in the neglected space and consequently the test tone perceived on the right was altered, inducing an overestimation on the right side, as our results shown. Interestingly, the underestimation in controls mimics what it is classically found in line bisection. Neurologically normal subjects bisect space during line bisection systematically on the left of the geometrical midpoint, a phenomenon called "pseudoneglect" (Jewell & McCourt, 2000). The same bias for time perception and spatial representation suggests, to some extent, a common mechanism already in healthy participants.

Basso et al. (1996) found an overestimation in the leftmost part of right space, in which neglect was present as well. These opposite results could be explained by the different methodology. We presented the stimuli each to one ear, whereas Basso et al. (1996) required classifying a shorter or longer stimulus after a phase of training. Moreover in Basso et al. (1996) the stimuli were presented in the visual modality, while in our study we used auditory modality. Alternatively these different results could be because of the organization of the sensory modalities, that is, the time discrimination of N+ for auditory material is less specific to one hemisphere because a less lateralized representation of time is present in the auditory space.

Even if different pattern of time estimation has been found in our participants, it appeared that N+ showed lower performance in time discrimination compared to N− and HC. So, our results may also be explained in terms of a general deficit in temporal dynamics (see Husain et al., 1997). When healthy participants are required to detect two serially presented targets, they need about 400 ms between the two targets to be able to report both. When neglect patients are confronted with the same task, they exhibit a longer attentional blink effect than HCs (Husain et al., 2001; Husain et al., 1997). This suggests that neglect patients suffer from a deficit in detecting stimuli over time. Neglect patients fail to correctly retain the representation of the stimuli, and in turn they fail to compare the various interval durations presented in the task. This may lead to deficits in the estimation of time duration, as shown by our results.

Battelli, Walsh, Pascual-Leone, and Cavanagh (2008) also suggest different role of the parietal lobe, the so called "when" pathway. According to these authors the parietal lobe is involved in the spatial attentional processing and this function is strongly contralateral. Conversely, the control of the right parietal lobe over temporal attention is bilateral. This bilateral control could be impaired in N+ patients, reflecting a lower performance in time discrimination both in the right and in the left side of the space.

In general, we found that right-brain damaged patients without neglect performed significantly worse than HCs but better than spatial neglect patients. However, when the presentation side was taken into account in our analyses, patients without neglect performed as well as HCs did. This again confirms the interdependence of spatial and time codes in perception. Moreover, the correlational analysis support that the larger is the rightward bias in N+ the larger is the impairment in time discrimination.

We cannot specifically determine whether the lesion site was related to performance, because only general data of structural imaging are available of our patients. However, almost all our neglect patients exhibited damage involving those temporo-parietal regions that are related to spatial functions (Husain & Nachev, 2006). Even though right hemisphere involvement in time processing remains under debate (Funnell, Corballis, & Gazzaniga, 2003; Handy, Gazzaniga, & Ivry, 2003; Kagerer, Wittmann, Szelag, & Steinbuchel, 2002), imaging studies in brain damaged patients (Harrington & Haaland, 1999) have identified a right hemispheric superiority in time perception, specifically involving the fronto-parietal network. From a speculative point of view, this could support he notion that time and space are not only functionally linked, but they also share the same neural network.

In conclusion, the results of the present study support the existence of an overlapping perception of time and space. Neglect patients, who are known to be impaired in spatial processing, also exhibit impairment in terms of time discrimination. These data support the hypothesis of a "distortion" of the representation in the reference memory or impaired working memory in time processing that is potentially located in the right parietal cortex, a neural network involved in spatiotemporal processing of perception and action.

References

Basso, G., Nichelli, P., Frassinetti, F., & di Pellegrino, G. (1996). Time perception in a neglected space. *Neuroreport, 7*(13), 2111–2114.

Battelli, L., Pascual-Leone, A., & Cavanagh, P. (2007). The 'when' pathway of the right parietal lobe. *Trends in Cognitive Science, 11*(5), 204–210.

Battelli, L., Walsh, V., Pascual-Leone, A., & Cavanagh, P. (2008). The 'when' parietal pathway explored by lesion studies. *Current Opinions in Neurobiology, 18*(2), 120–126.

Becchio, C., & Bertone, C. (2006). Time and neglect: Abnormal temporal dynamics in unilateral spatial neglect. *Neuropsychologia, 44*(14), 2775–2782.

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society: Series B* (57), 289–300.

Bisiach, E., Vallar, G., Perani, D., Papagno, C., & Berti, A. (1986). Unawareness of disease following lesions of the right hemisphere: Anosognosia for hemiplegia and anosognosia for hemianopia. *Neuropsychologia, 24*(4), 471–482.

Bueti, D., & Walsh, V. (2009). The parietal cortex and the representation of time, space, number and other magnitudes. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1525), 1831–1840.

Cappelletti, M., Freeman, E. D., & Cipolotti, L. (2009). Dissociations and interactions between time, numerosity and space processing. *Neuropsychologia, 47*(13), 2732–2748.

Danckert, J., Ferber, S., Pun, C., Broderick, C., Striemer, C., Rock, S., & Stewart, D. (2007). Neglected time: Impaired temporal perception of multisecond intervals in unilateral neglect. *Journal of Cognitive Neuroscience, 19*(10), 1706–1720.

De Long, A. J. (1981). Phenomenological space-time: Towards an experiential relativity. *Science, 213,* 681–683.

Frassinetti, F., Magnani, B., & Oliveri, M. (2009). Prismatic lenses shift time perception. *Psychological Science, 20*(8), 949–954.

Funnell, M. G., Corballis, P. M., & Gazzaniga, M. S. (2003). Temporal discrimination in the split brain. *Brain and Cognition, 53*(2), 218–222.

Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. *Annals of the New York Academy of Sciences, 423,* 52–77.

Halligan, P. W., & Marshall, J. C. (1988). How long is a piece of string? A study of line bisection in a case of visual neglect. *Cortex, 24*(2), 321–328.

Handy, T. C., Gazzaniga, M. S., & Ivry, R. B. (2003). Cortical and subcortical contributions to the representation of temporal information. *Neuropsychologia, 41*(11), 1461–1473.

Harrington, D. L., & Haaland, K. Y. (1999). Neural underpinnings of temporal processing: A review of focal lesion, pharmacological, and functional imaging research. *Reviews in the Neurosciences, 10*(2), 91–116.

Heilman, K. M., Watson, R. T., & Valenstein, E. (2005). Neglect and related disorders. In K. M. Heilman & E. Valenstein (Ed.), *Clinical neuropsychology* (4th ed., pp. 296–346). New York: Oxford University Press.

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews Neuroscience, 6*(6), 435–448.

Husain, M., Mannan, S., Hodgson, T., Wojciulik, E., Driver, J., & Kennard, C. (2001). Impaired spatial working memory across saccades contributes to abnormal search in parietal neglect. *Brain, 124,* 941–952.

Husain, M., & Nachev, P. (2006). Space and the parietal cortex. *Trends in Cognitive Sciences, 11*(1), 30–36.

Husain, M., Shapiro, K., Martin, J., & Kennard, C. (1997). Abnormal temporal dynamics of visual attention in spatial neglect patients. *Nature, 385,* 154–156.

Ishihara, M., Keller, P. E., Rossetti, Y., & Prinz, W. (2008). Horizontal spatial representations of time: Evidence for the STEARC effect. *Cortex, 44*(4), 454–461.

Jewell, G., & McCourt, M. E. (2000). Pseudoneglect: A review and meta-analysis of performance factors in line bisection tasks. *Neuropsychologia, 38*(1), 93–110.

Kagerer, F. A., Wittmann, M., Szelag, E., & Steinbuchel, N. (2002). Cortical involvement in temporal reproduction: Evidence for differential roles of the hemispheres. *Neuropsychologia, 40*(3), 357–366.

Lezak, M. D., Howieson, D. B., Loring, D. W., Hannay, H. J., & Fischer, J. S. (2004). *Neuropsychological assessment*. New York: Oxford University Press.

Luaute, J., Halligan, P., Rode, G., Jacquin-Courtois, S., & Boisson, D. (2006). Prism adaptation first among equals in alleviating left neglect: A review. *Restorative Neurology and Neuroscience, 24*(4–6), 409–418.

Mauk, M. D., & Buonomano, D. V. (2004). The neural basis of temporal processing. *Annual Reviews of Neuroscience, 27,* 307–340.

Mitchell, C. T., & Davis, R. (1987). The perception of time in scale model environments. *Perception, 16*(1), 5–16.

Rossetti, Y., Rode, G., Pisella, L., Farne, A., Li, L., Boisson, D., & Perenin, M. T. (1998). Prism adaptation to a rightward optical deviation rehabilitates left hemispatial neglect. *Nature, 395*(6698), 166–169.

Vicario, C. M., Caltagirone, C., & Oliveri, M. (2007). Optokinetic stimulation affects temporal estimation in healthy humans. *Brain and Cognition, 64*(1), 68–73.

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7*(11), 483–488.

Zorzi, M., Priftis, K., & Umilta, C. (2002). Brain damage: Neglect disrupts the mental number line. *Nature, 417*(6885), 138–139.

Received February 17, 2010
Revision received August 11, 2010
Accepted August 12, 2010 ■