Frames of Reference for Mapping Tactile Stimuli in Brain-Damaged Patients

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Abstract

■ Twelve normal controls, twelve left-brain-damaged patients, and thirty-six right-brain-damaged patients with or without tactile extinction or tactile neglect were asked to report light touches delivered to the left or the right hand or simultaneously to both hands. The hands could be in anatomic position or one hand could cross over the other. Moreover, the two hands could be in the left or the right hemispace or across the corporeal midline. Controls and nontactile-extinction groups performed better when the hands were in anatomical than in crossed position. By contrast, patients with tactile extinction detected contralesional stimuli with higher accuracy in crossed than in anatomical position. This result suggests that, in these patients, impairments in detecting contralesional stimuli can be due not only to sensory but also to spatial factors contingent upon the position of the hands. There was no interaction between the effect of crossing the hands and the hemispace where the crossing took place. This suggests that coding the position of a hand as left or right does not necessarily occur in relation to the bodily midline, but it may arise from the computation of the position of the other hand. ■

INTRODUCTION

The process of coding sensory signals in space (and acting toward them) can take place in reference to different systems of coordinates. Stimuli mapped according to egocentric frames of reference are defined in relation to the viewer's body. Egocentric codes stem from continuously updated static and dynamic somatosensory signals that tune the motor apparatus. They correspond to a sensorimotor mode of processing spatial information and benefit from a direct dialogue with the physical world (Paillard, 1991). Stimuli mapped in allocentric frames of reference are defined in terms of objects or other landmarks in the external world. Allocentric representations include both world- and object-centered frames of reference (Andersen, Snyder, Li, & Stricanne, 1993; Behrmann & Moscovitch, 1994; Driver, Baylis, Goodrich, & Rafal, 1994; Olson & Gettner, 1995). These representations can be described as memory based, internal constructs that extract features of the visual world that remain stable when the body moves (Paillard, 1991). Although visual stimuli may be coded in terms of ego- or world-centered frames of reference (Blouin et al., 1993; Gentilucci, Chieffi, Daprati, Saetti, & Toni, 1996), somatic stimuli are more likely to be coded in terms of egocentric reference frames. Within the egocentric frame of reference, however, different anchors for coding a given stimulus (or for implementing a given motor act toward the stimulus) may be used. In different experimental conditions, for example, the center of the egocentric system may be localized at different loci within the body architecture. Thus, it may be head-, shoulder-, trunk-centered, and so on (Colby, 1998). The position of the body relative to gravitational forces, the status of the systems monitoring the position of the body in space (e.g., vestibular system and proprioceptive receptors) or subserving corporeal awareness, the position of the locus where a stimulus is delivered in relationship to the corporeal midline, or other corporeal segments, may be other relevant variables (Pizzamiglio, Vallar, & Doricchi, 1997; Vallar, 1997). Insights into the type of coordinate systems for spatial analysis of sensory signals come from studies of unilateral brain lesions inducing behavioral disorders like neglect for the contralesional space. It has been shown, for example, that visual neglect may arise in reference to several coordinate systems such as the corporeal midline, the relative position of head and eyes with respect to the trunk, or the retinal position with respect to gaze direction (Calvanio, Petrone, & Levine, 1987; Farah, Brunn, Wong, Wallace, & Carpenter, 1990; Karnath, Schenkel, & Fischer, 1991; Làdavas, 1987; Mennemeier, Chatterjee, & Heilman, 1994). Most of the studies, however, have investigated what reference frames are used for building complex spatial maps of the extrapersonal space from visual information. By contrast, the issue of what reference frames are used for transforming tactile and proprioceptive signals in spatial higher-order maps of peripersonal and personal space have hitherto been largely unaddressed.

In patients with neglect and tactile extinction, Moscovitch and Behrmann (1994) delivered somatic stimuli to the ulnar (on the side of the little finger) and the radial (on the side of the thumb) surface of the left or the right wrist. The hand, always kept on the same side of the corporeal midline, was tested in both the palm up and the palm down position; thus, each stimulated point was coded as ipsilesional or contralesional according to the palm down or palm up position. Stimuli delivered to the point coded as contralesional were omitted regardless of palm orientation position, suggesting a role for higher-order frames of reference in tactile extinction. We have previously shown that the capability of right-brain-damaged (RBD) patients with neglect and tactile extinction to detect somatic stimuli delivered to the left hand changed according to its location (Smania & Aglioti, 1995). The number of correct detections for stimuli delivered to the left hand was higher when this hand crossed the corporeal midline than when it was in anatomical position. The effect turned out to be quite clear under both single and double stimuli conditions and suggested that, in these patients, somaesthetic deficits are linked not only to sensory factors but also to a defective computation of body-centered coordinates, perhaps based upon the sagittal midplane. Although egocentric codes for left and right hemispaces are typically defined in terms of the corporeal midline, this may not be the only anchor for coding as left or right the stimuli delivered to the body. An interesting issue is whether or not the increase in accuracy of the contralesional hand is related to the bodily midline or if it also occurs when the hands are crossed within one hemispace. In this condition, coding the position of a stimulated hand may take place in relation to the other hand and not only in relation to the bodily midline.

Both somatotopic and spatial components may underlie the somatosensory deficits observed in brain-damaged patients. If these deficits are related uniquely to an impairment of processing in primary areas (somatotopic hypothesis), they should not change according to the relationship between the hands and their spatial location. In contrast, if these deficits are also related to a damage of supramodal areas involved in higher-order information processing, like integration and coding of stimuli in the extrapersonal and personal space (spatiotopic frame-of-reference hypothesis), a consistent difference of accuracy in the different experimental situations should be observed. We attempted to tell these two components apart by testing whether or not the accuracy of left- and right-brain-damaged patients in detecting tactile stimuli delivered to their contralesional hand changed according to the relationships of the two hands and the hemispace in which the hands are positioned. We used different stimulation conditions whereby single or double light touches delivered to the left or right hand or both hands had to be detected (1) when the hands were in anatomical (Figure 1, right column) or in crossed position (Figure 1, left column) and (2) when the hands were on opposite sides of the corporeal midline (Figure 1, upper part) or in the right or the left hemispace (Figure 1, middle and lower parts, respectively).

In particular, we examined whether crossing the hands brought about any changes in accuracy and if such changes were related to the corporeal midline or also to other anchors for segmenting the personal space; finally, we tested whether the presence of the crossing effect was specifically related to the presence and degree of tactile extinction. To do so, we examined five groups of experimental subjects: non brain-damaged subjects (C), left-brain-damaged patients (LBD), RBD patients without tactile extinction (RBD TE minus), RBD patients with tactile extinction (RBD TE), and RBD patients with more severe tactile extinction (RBD TE plus).

RESULTS

Nonbrain-Damaged Control Patients

Under single stimuli conditions, C scored 100% of the hits. Their performance in double stimulation condition, however, was not errorless (Table 1). Correct reports in the double stimulation condition were entered in a 3 (hemispace: left hemispace, right hemispace, across the bodily midline) × 2 (hand: left and right) × 2 (position of the hands: anatomical and crossed) repeated measures analysis of variance (ANOVA). The significance of the position ($F(1, 11) = 7.95$, $p = 0.017$) was due to the higher accuracy in anatomical than in crossed position (percentage of the hits, 98 and 89.8, respectively). Neither hemispace nor hand were significant ($F(1, 11) < 1$ in both cases). The number of correct detections, in fact, was comparable in the three space conditions (93.8% left hemispace, 93.9% across the midline, and 94.1% right hemispace) and for the two hands (left 93.1% and right 94.7%). The insignificance of any interaction suggests that the difference between anatomical and crossed position was comparable for the two hands and in the different hemispatial conditions (Table 1).

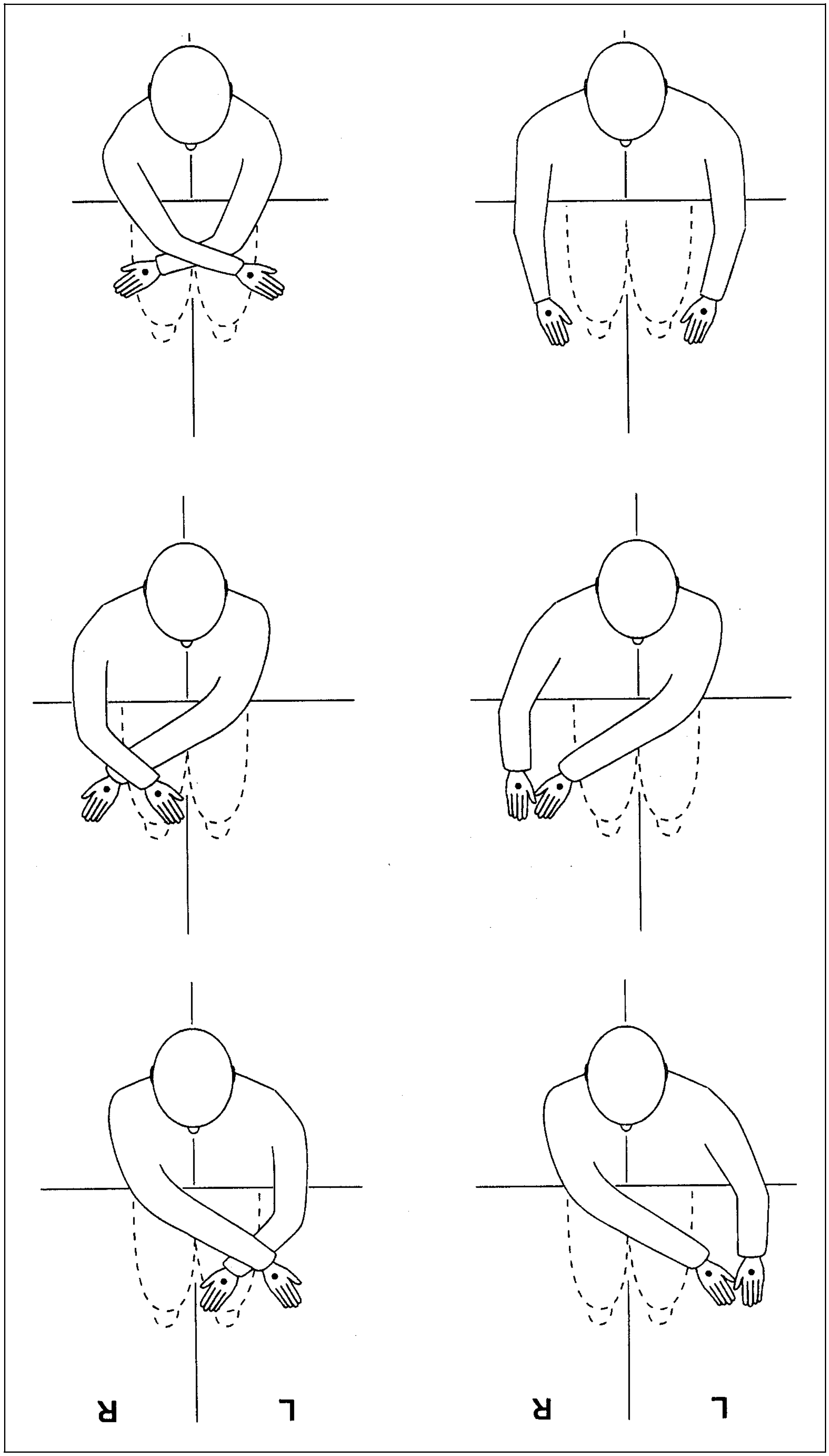


Figure 1. Schematic drawing of the relative positions of the hands (anatomical or crossed) in the left hemispace (lower part), in the right hemispace (middle part), and across the bodily midline (upper part). The small circles on the dorsum of the hands indicate the sites of stimulation. Letters L and R refer to patients' left and right hemispaces.

Table 1. Correct Detections of Stimuli for Control Subjects, LBD Patients, and RBD Patients without Tactile Extinction. Values in parentheses represent standard errors.

Group		Left Hemispace[a]				Across Midline[a]				Right Hemispace[a]			
		LH An.	*LH Cr.*	*RH An.*	*RH Cr.*	*LH An.*	*LH Cr.*	*RH An.*	*RH Cr.*	*LH An.*	*LH Cr.*	*RH An.*	*RH Cr.*
C	Single	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	99 (1)	100 (0)	100 (0)	100 (0)	100 (0)
C	Double	98 (1)	88 (4)	98 (1)	91 (4)	97 (1)	89 (4)	99 (1)	90 (3)	98 (6)	89 (14)	98 (3)	98 (11)
LBD	Single	100 (0)	100 (0)	97 (3)	100 (0)	100 (0)	100 (0)	98 (2)	98 (2)	100 (0)	100 (0)	98 (2)	99 (1)
LBD	Double	100 (0)	95 (3)	93 (5)	69 (8)	100 (0)	94 (3)	91 (7)	71 (8)	99 (1)	95 (2)	92 (4)	71 (8)
RBD TE–	Single	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)	98 (2)	98 (2)	100 (0)	100 (0)
RBD TE–	Double	96 (2)	68 (9)	99 (1)	98 (2)	95 (2)	69 (8)	99 (1)	98 (2)	89 (5)	70 (9)	99 (1)	98 (2)

[a] An. = hands in anatomical position; Cr. = hands in crossed position; LH = left hand; RH = right hand.

LBD Patients

Eleven out of twelve patients performed perfectly under single stimulation conditions. One patient, although perfect in detecting single stimuli delivered to his left hand, missed 11 out of 120 (9.2%) single stimuli delivered to his right, contralesional hand. Under double stimulation conditions LBD patients were far from perfect (Table 1). The same type of three-way ANOVA carried out in controls showed the following: The factor hand was significant ($F(1, 11) = 6.5$, $p = 0.027$) because patients detected stimuli delivered to the ipsilesional, left hand much more accurately than stimuli delivered to the contralesional, right hand (97% vs. 81% of the hits); the position of the hands was significant ($F(1, 11) = 20.72$, $p = 0.001$) because fewer stimuli were omitted in anatomical than in crossed position (96% vs. 83% of the hits); the interaction of hand by position of the hands was significant ($F(1, 11) = 10.25$, $p = 0.008$). This result occurred because the difference of accuracy between anatomical and crossed position was higher for the right than the left hand (21.4% vs. 4.6%).

RBD TE Minus

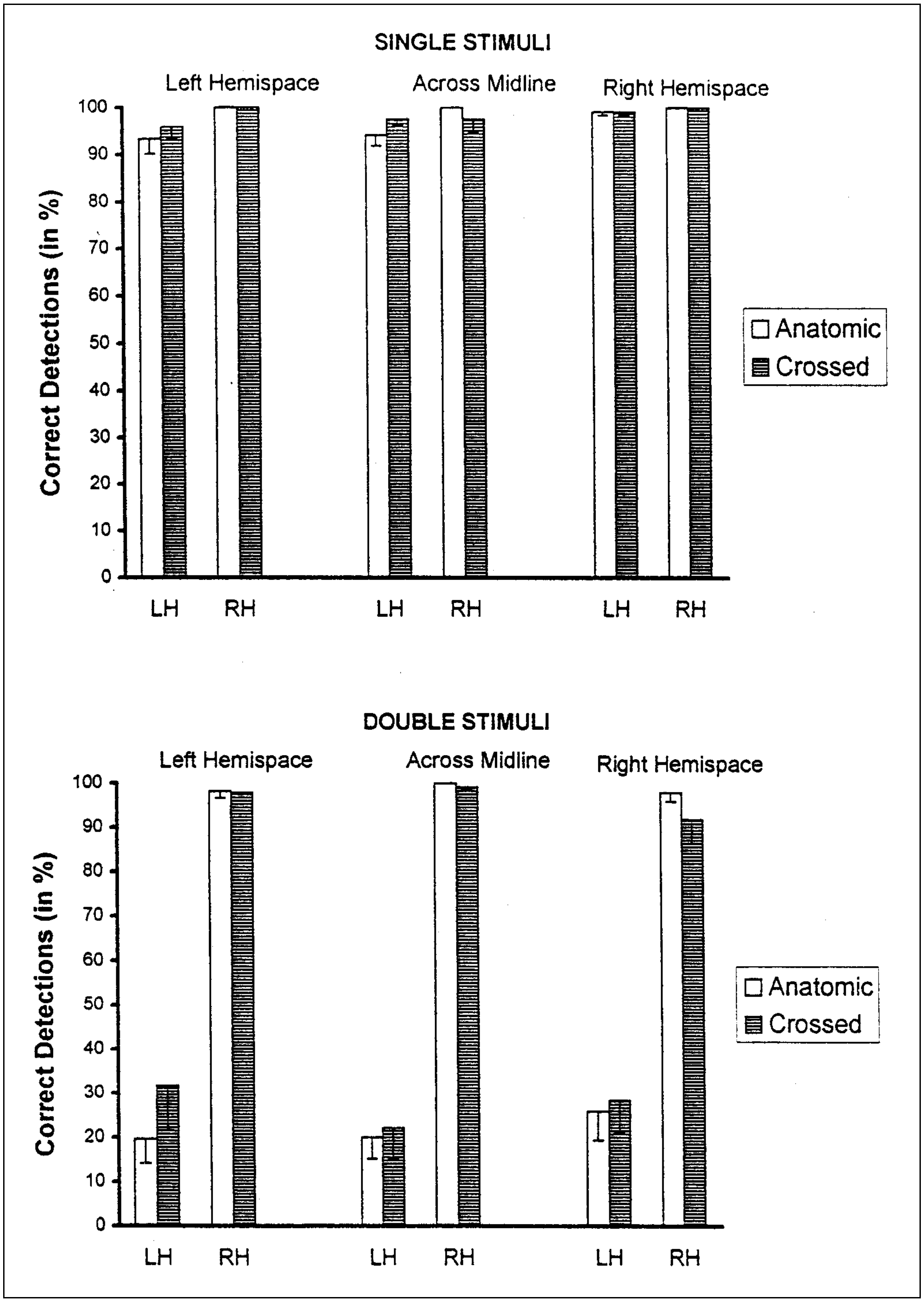
Under single stimulation conditions, performance was perfect in 11 out of 12 patients. Only 1 patient, omitted 4 single stimuli (out of 120), 2 in anatomic and 2 in crossed positions. Also in this group more omissions occurred under double stimulation conditions (Table 1). The three-way ANOVA described above showed that the factor hand was significant ($F(1, 11) = 11.7$, $p = 0.007$) because patients detected stimuli delivered to the ipsilesional, right hand much more accurately than stimuli delivered to the contralesional, left hand (98.5% vs. 81.2% of the hits). The position of the hands ($F(1, 11) = 15.08$, $p = 0.003$) was significant because fewer stimuli were omitted in anatomical than in crossed position (96.3% vs. 83.5% of the hits); the interaction of hand by position of the hands was significant ($F(1, 11) = 11.91$, $p = 0.005$). This result occurred because the difference between the anatomical and crossed position was higher for the left than the right hand (24.6 % vs. 1%).

Unlike the other groups, RBD TE and RBD TE plus patients also omitted stimuli to the contralesional, left hand under single stimulation condition. Thus, their performance was analyzed by means of the following $2 \times 2 \times 2 \times 3$ ANOVAs where number (single or double), hand (left or right), position of the hands (anatomical or crossed), and hemispatial condition (hands in left hemispace, in right hemispace, across the midline) were the main factors.

RBD Patients with Tactile Extinction (TE)

The factor number was highly significant ($F(1, 11) = 161.1$, $p < 0.0001$) due to the lower percentage of the hits in the double than in the single stimulation condition (61% vs. 98.1%). The factor hand was highly significant ($F(1, 11) = 199.4$, $p < 0.0001$) because accuracy for stimuli on the ipsilesional, right hand was much higher than for stimuli on the contralesional hand (98.5% vs. 60.5 %). The number by hand interaction ($F(1, 11) = 138.3$, $p < 0.0001$) was significant because the higher accuracy in detecting single stimuli was dramatic only for the left hand (the difference of accuracy between single and double stimulus conditions was 72% for the left and 2% for the right hand). Unlike the other groups described hitherto, a slightly higher accuracy in crossed (27.3% of the hits) than anatomical (22% of the

Figure 2. Accuracy of RBD TE patients in the different experimental conditions. Results from single and double stimulation conditions are reported in the upper and lower graph respectively. Legend: LH = left hand; RH = right hand.



hits) conditions was observed (Figure 2), even though the factor position of the hands did not reach the statistical significance. The interaction hand by position of the hands, however, was marginally significant ($F(1, 11) = 3.51, p = 0.08$) because correct responses for stimuli to the left hand tended to be higher in the crossed than in the anatomical position. No other factors or interactions were significant.

RBD TE Plus

In this group, stimuli to the contralesional left hand were also omitted in a consistent number of trials under single stimulation conditions (Figure 3). The $2 \times 2 \times 2 \times 3$ ANOVA showed the following: The factor number was highly significant ($F(1, 11) = 147.8, p < 0.0001$) due to the lower number of hits in the double than in the single stimulation condition (53% vs. 71.1%). The factor hand

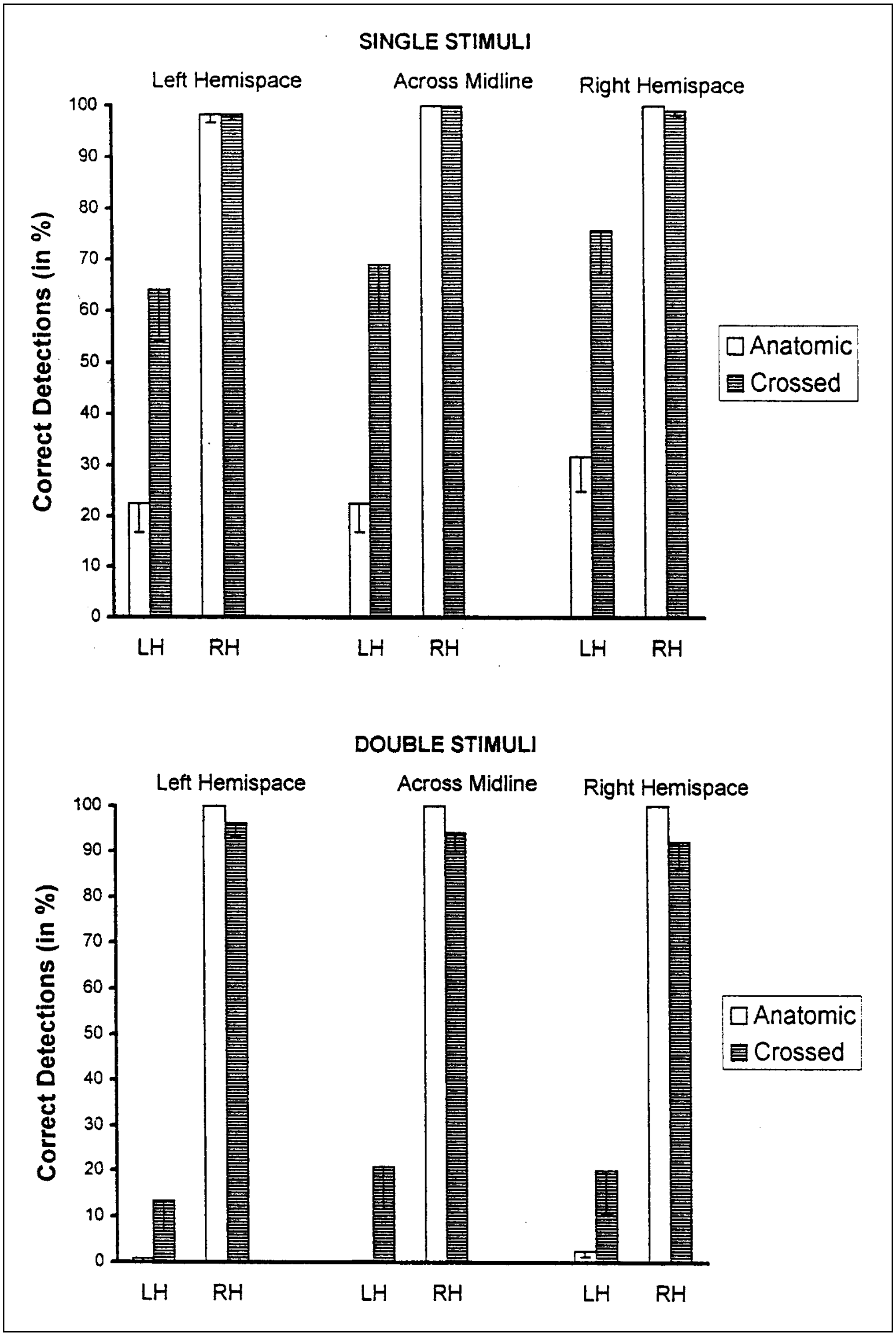


Figure 3. Accuracy of RBD TE plus patients in the different experimental conditions. Results from single and double stimulation conditions are reported in the upper and lower graph, respectively. Legend as for Figure 2.

was highly significant ($F(1, 11) = 228.9$, $p < 0.0001$) because accuracy for stimuli on the ipsilesional, right hand was much higher than for stimuli on the contralesional, left hand (98.1% vs. 28.6%). The factor position of the hands was significant ($F(1, 11) = 19.9$, $p < 0.001$) because accuracy was higher in the crossed (hits 70.2%) than in the anatomical (hits 56.5%) position. The interaction number by hand ($F(1, 11) = 66.8$, $p < 0.0001$) was significant because the difference of correct detections in single and double stimulation conditions was dramatic for the left hand (37.9 %) and virtually absent for the right hand (2%). The significance of the interaction number by position of the hands ($F(1, 11) = 9.5$, $p = 0.01$) occurred because the increase of accuracy in crossed position was higher for single than for double stimuli conditions (accuracy in crossed minus accuracy in anatomical position was 31.3% for single stimuli; this difference was 5.4% for double stimuli). Finally, the significance of the interaction hand by position of the hands ($F(1, 11) = 15.6$, $p = 0.002$) is explained by the fact that whereas stimuli to the left hand were detected better in crossed than anatomical position (increase of hits of 30.5% in crossed position), the opposite was true for stimuli to the right hand (reduction of hits of 3% in crossed position). No other factors or interactions were significant.

To sum up, the effect of crossing the hands was as follows: Like control subjects, LBD and RBD TE minus patients were more accurate when the hands were in the anatomic than in the crossed position; this effect was no longer present in TE patients. In TE plus patients, stimuli to the left hand were detected much more accurately in the crossed than in the anatomical position (Figure 4); this was true under both single and double stimulation conditions; by contrast, the accuracy in detecting stimuli to the right hand was slightly but significantly lower when this hand was in the crossed position (Figure 3). This deleterious effect was present only under double stimuli condition (the percentage of the hits in the anatomic and crossed position was 100 and 94.1; two sample t test; $p = 0.025$). Finally, the "crossing effect" was comparable in the three spatial positions.

In TE and TE plus groups, we attempted to correlate the amount of the crossing effect under both single and double stimulation conditions, with the severity of personal neglect and visual neglect. The only significant correlation was found in the TE plus group where the crossing effect under double stimulation conditions was positively correlated with the severity of personal neglect ($r = 0.72$, $n = 12$, $p = 0.008$).

DISCUSSION

The apparently simple task of reporting somatic stimuli is likely to rely upon complex interactions of low and higher levels of processing. An optimal performance in these tasks requires that information about primary sensory attributes (e.g., sharpness, roughness, temperature) is matched with additional, more complex information (e.g., the representation of the stimulated body part). The analysis of basic sensory attributes is probably accomplished comparatively early, for example, in the primary somatic cortex or even upstream in the somatosensory system. A further step toward a conscious awareness and a full linguistic description of a sensory event is the combination of basic features of each stimulus with information about the numerosity of the stimuli, the body part stimulated and its position in relationships to other body parts, and the extrapersonal space. The analysis of different attributes of a sensory stimulus is also related to the frames of reference in which it is mapped. The transformation of a sensory stimulus from the coordinates of its sensory epithelium to the coordinates for implementing appropriate motor acts is a fundamental aspect of behavior. There are several representations of extrapersonal and personal space interposed between sensory and motor output. A number of coordinate systems have been described: eye-, cranio-, body-, and world-centered representations (Andersen et al., 1993; Andersen, Snyder, Bradley, & Xing, 1997; Colby, 1998; Stein, 1992).

The experimental variables manipulated in the present research were the number of stimuli to be detected (one or two), the positional relationship between the stimulated body parts (anatomical or crossed), and the hemispace where the hands were positioned (left hemispace, right hemispace, across the corporeal midline). Because sensory analysis is probably more complex for double than for single stimuli, a more accurate detection for single than for double stimuli in all experimental groups is not surprising. Under daily life conditions, the anatomical position may be optimal for a compatible mapping of somatotopic and spatial signals leading to a correct performance. On the other hand, the somewhat incompatible matching of somatotopic and spatiotopic information required in crossed position should be more difficult and consequently more resource demanding.

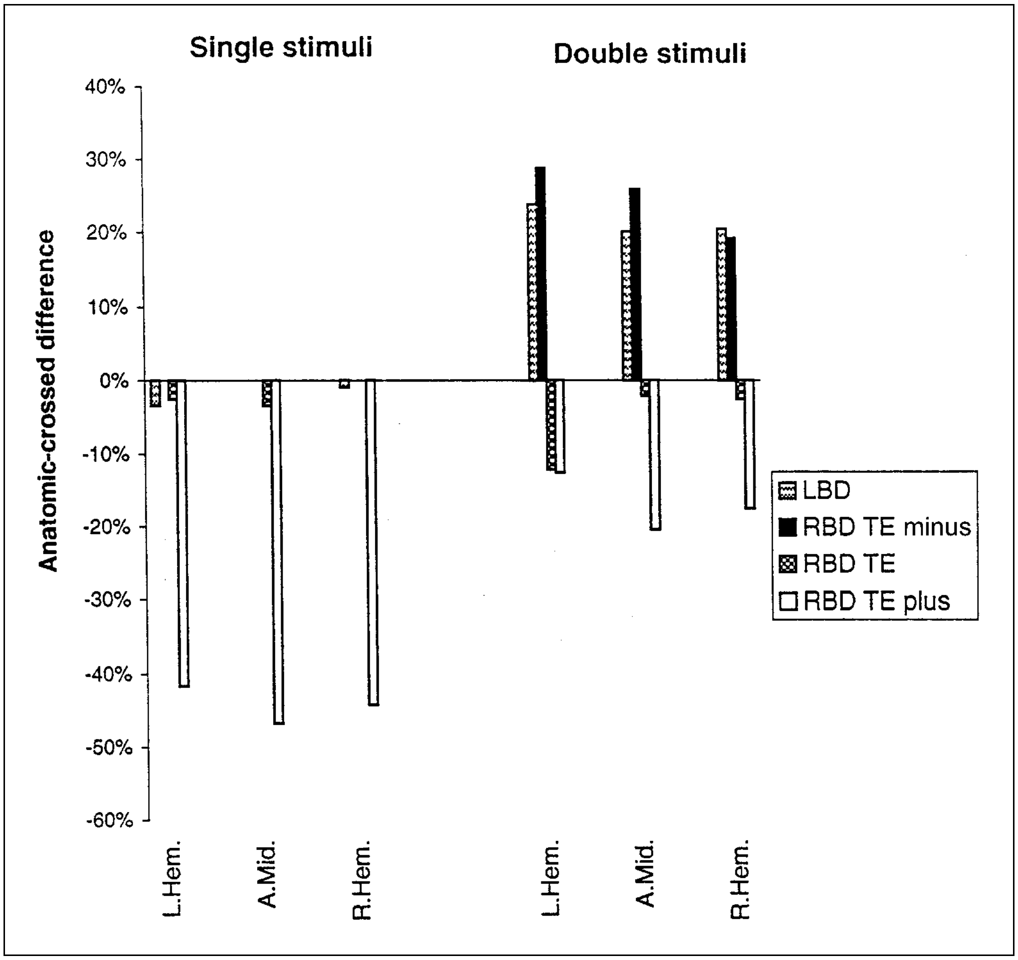
Behavioral Changes Contingent upon the Relative Position of the Two Hands and Cerebral Lesion per se

A modulation of performance related to the spatial position of the hands has previously been reported by testing RBD patients with tactile extinction and nonbrain-damaged controls (Smania & Aglioti, 1995). Thus, it was not known from that study whether or not the effect was simply due to the presence of a cerebral lesion. In the present research a much finer analysis has been performed by studying nonbrain-damaged subjects, LBD patients, and three groups of right-brain-damaged patients.

Nonbrain-damaged patients, who were almost perfect under single stimuli conditions, detected both left- and right-sided stimuli less accurately in the crossed than in the anatomical position under double stimuli conditions. The comparatively inaccurate performance of nonbrain-damaged patients in the most demanding condition (i.e., double stimulation in crossed position) obviously cannot be attributed to somaesthetic deficits, but it may ensue from higher-order factors such as, for example, a mismatch between codes describing the stimulated body part (e.g., the hand) and its position in space.

The detection of somatic stimuli delivered to the contralesional hand in LBD and RBD TE minus patients turned out to be significantly lower in the crossed than in the anatomical position, regardless of the hemispace in which the hands were located; this effect was not observed in the TE group and reversed in the TE plus

Figure 4. Difference of accuracy (anatomic minus crossed) of the contralesional hand in the four brain-damaged groups. Negative values indicate that accuracy was higher in crossed than anatomical positions. Legend: L.Hem= left hemispace; A.Mid = across midline; R.Hem = right hemispace.



patients who showed, in crossed position, a dramatic amelioration ("crossing effect," for short) in detecting stimuli delivered to their left hand. Thus, the lack of a disadvantage in crossed position and even a clear improvement in detection of contralesional stimuli has to do with the presence of tactile extinction.

The failure to report a single stimulus after cerebral lesions has been classically related to lesions of somatosensory areas where processing of information is of a comparatively low level and attentional modulation is scarce. It is worth noting that patients with "pure" somatosensory deficit due to a lesion centered upon the right somatosensory cortices do not show any advantage of crossing the hands. Thus, the modulation of performance underlying the crossing effect suggests that even the detection of single stimuli in the anatomic position may be due, at least in part, to spatial rather than to sensory defects. This result is in keeping with previous studies by Vallar and coworkers (Vallar, Bottini, Rusconi, & Sterzi, 1993; Vallar, Sterzi, Bottini, Cappa, & Rusconi, 1990), who reported that vestibular stimulation can induce a temporary remission of hemianaesthesia and tactile extinction in brain-damaged patients with signs of neglect.

Omissions of contralesional stimuli under double stimulation condition basically reflect tactile extinction, a phenomenon that is particularly frequent after right parietal lesions (Schwartz, Marchok, Kreinick, & Flynn, 1979; Sterzi et al., 1993) and that has been linked to the dominance of the right brain in spatial attention (Corbetta, Miezin, Shulman, & Petersen, 1993; Heilman, Watson, & Valenstein, 1993). The increased accuracy in the crossed position observed in extinction patients was significantly higher in single than in double stimuli conditions, thus supporting nonsensory explanations for the crossing effect. For example, the attentional overload in the latter conditions may prevent the compensation that is possible under single stimulation conditions. It is also noteworthy that the amount of the crossing effect was positively correlated with the amount of personal neglect but not of visual neglect. This result supports the notion of a tight relation between somatosensory inputs, representation of one's own body in space, and corporeal awareness (Vallar, 1997). Our behavioral study does not allow us to draw any conclusions about the neural basis of the crossing effect. However, it is plausible to postulate, somewhere in the cortex, the presence of somatic neurons that change the response properties (e.g., size or position of their receptive field) in relationships to the position in space of a given body part. No such studies have been hitherto carried out. Neurons coding the peripersonal space in a rather dynamic way have been reported in the monkey inferior premotor area, putamen, and although in much smaller numbers, area 7b. These are visuotactile bimodal neurons with tactile receptive fields on the hand and tridimensional visual receptive field in the peripersonal space around the face (Graziano, Yap, & Gross, 1994). Remarkably, changes in the position of the hand displace the visual receptive fields in a direction congruent with the displacement of the hand. Also striking is the fact that these neurons continue to fire in the dark if the animal believes that the stimulus is there (Graziano, Hu, & Gross, 1997). In other words, these neurons maintain a memory trace of the previous position of an object. Because the crossing effect reported in the present study is not related to visual but rather to personal neglect, we do not want to imply that such an effect bears a straightforward relation with these bimodal neurons. However, the presence of neurons dynamically coding objects in space would suggest that "somatosensory" neurons dynamically coding the spatial position of body parts may also exist.

Coordinate Systems for Mapping Tactile Stimuli in Patients with Extinction

The importance of the bodily midline for computing egocentric coordinates has been repeatedly shown in visual neglect patients (Karnath, 1996; Karnath et al., 1991). In the tactile domain, neither the study by Moscovitch and Behrmann (1994) nor our previous study (Smania & Aglioti, 1995) clarified whether or not the corporeal midline is crucial for mapping a tactile stimulus. Thus, a novel result of the present study is that the beneficial effect of crossing the hands is not only linked to the bodily midline, but it may rely on the process of coding the position of one hand in relation to the other.

Under double stimuli condition, TE plus patients detected stimuli delivered to the right hand less accurately when it was in crossed position, no matter which hemispace the crossing procedure took place in; these patients, however, detected right-hand stimuli in crossed position with an accuracy comparable to that of controls and the other two RBD groups. Moreover, in anatomical positions under double stimuli condition, TE plus patients outperformed all the other groups in detecting right touches. Thus, the slightly lower detection of right stimuli when the right hand was coded as leftward may be related to the presence of a bias toward the "right" space. A similar bias has already been reported in right-brain-damaged patients with visual neglect (De Renzi, Gentilini, Faglioni, & Barbieri, 1989; Gainotti, D'Erme, & Bartolomeo, 1991; Làdavas, Petronio, & Umiltà, 1990).

MATERIALS AND METHODS

Subjects

Twelve subjects (seven women and five men) with chronic low-back pain served as controls; none of them presented with brain lesions. Twelve subjects had lesions to the left hemisphere and 36 subjects had lesions to the right hemisphere. All subjects were right-handed according to a modified version of the Briggs and Nebes (1975) laterality inventory. Visual neglect was assessed in each subject by cancellation and reading tests and by examining the orientational bias toward the ipsilesional hemispace (Peru, Moro, Avesani, & Aglioti, 1996, 1997). For each test, a defective performance was scored 1 point. Thus, a neglect severity score ranging from 0 (no deficit) to 3 (deficit in all three tests) was defined. Personal neglect was assessed by asking subjects to touch the contralesional hand with their ipsilesional hand. The degree of impairment was scored according to the following four-point scale: 0 = no deficits; 1 = target reached with hesitation and search; 2 = search interrupted before reaching the target; 3 = no movement towards the target (Bisiach, Vallar, Perani, Papagno, & Berti, 1986). Visual extinction was assessed by a standard confrontation technique (Bisiach et al., 1986) in which the examiner moved in the left, in the right, or in both visual hemifields one or both index fingertips. Tactile extinction was tested by delivering single or double simultaneous light touches to the dorsum of the hands. Series of 30 stimuli (10 unilateral left, 10 unilateral right, and 10 bilateral) were used for both vision and touch.

Subjects were considered to have visual or tactile extinction when they omitted at least 30% of double stimuli but detected at least 80% of single contralesional stimuli. Although no LBD patient (six men and six women) presented with visual extinction or visual neglect, one of them showed tactile extinction (patient 5). Based on their performance on the preliminary test for assessing tactile extinction, three subgroups of RBD were selected:

1. Seven men and five women without any sign of tactile extinction (RBD TE minus). No patient in this group presented with visual extinction or visual neglect.
2. Eight men and four women in whom the contralesional stimulus was omitted in at least 30% of double stimuli but detected in at least 80% of single stimuli. These patients belonged in the category of tactile extinction (TE). Three patients in this group showed signs of visual hemispatial neglect.
3. Seven men and five women in whom the contralesional stimulus was omitted in more than 70% of the double stimuli conditions and at least 50% of the single stimuli conditions. This group will be hereafter referred to as TE plus (Table 2). Ten patients from this group showed signs of visual extinction and visual neglect. In

Table 2. Clinical and Lesion Information on the Brain-Damaged Patients.[a]

Groups	Pts.	Contr. Om. Sin. (%)	Contr. Om. Dou. (%)	VE	Alb.	Read.	Orien.	PN	Lesions Site
LBD									
	1	0	0	–	–	–	–	0	T-P
	2	0	0	–	–	–	–	0	Caps-Th
	3	0	0	–	–	–	–	0	BG
	4	0	0	–	–	–	–	0	F-T-Ins
	5	0	40	–	–	–	–	0	T-Th
	6	0	20	–	–	–	–	0	Caps.
	7	0	10	–	–	–	–	0	BG Th Ins
	8	0	10	–	–	–	–	0	T-P
	9	0	0	–	–	–	–	0	P-Caps-BG
	10	0	0	–	–	–	–	0	F-T-P
	11	0	0	–	–	–	–	0	F-P
	12	0	0	–	–	–	–	0	F-P-Ins
RBD TE–									
	1	0	10	–	–	–	–	0	Caps-Th
	2	0	10	–	–	–	–	0	F-T-Ins
	3	0	10	–	–	–	–	0	Caps-Th
	4	0	0	–	–	–	–	0	Caps-Th
	5	0	0	–	–	–	–	0	F
	6	0	0	–	–	–	–	0	Caps-Th
	7	0	20	–	–	–	–	0	P-O
	8	0	0	–	–	–	–	0	Caps-Th
	9	0	20	–	–	–	–	0	F-P
	10	0	10	–	–	–	–	0	F-T-Ins
	11	0	20	–	–	–	–	0	F-T
	12	0	0	–	–	–	–	0	BG

Continued on next page

principle, the performance of these patients under single stimulus conditions can arise from two, at least partially independent, factors, namely, a primary somatosensory deficit or a representational and/or attentional deficit (tactile neglect, for short) so severe that it prevents any explicit processing of stimuli (even when single) delivered to the contralesional personal space. Were the first factor crucial, no changes in the accuracy of detection related to the spatial position of the hands should be expected. By contrast, possibly significant modulations of the performance contingent upon the spatial position of the stimulated body parts can be observed (Smania & Aglioti, 1995). Two separate one-way ANOVAs showed that the five groups did not differ in terms of age (C = 61.8 years; LBD = 65.5 y.; RBD TE minus = 62.9 years; RBD TE = 60.7 years; RBD TE plus = 64.6 years) or education (C = 7.1 years of school; LBD = 5.6; RBD TE minus = 5.5; RBD TE = 5.7; RBD TE plus = 7.4) ($F(4, 55) < 1$ in both cases). Time since onset was shorter in the TE plus patients (1.9 months) than in the other groups (LBD = 6.4, RBD TE minus = 8.53, RBD TE = 14.6). For each brain-damaged patient the unilaterality of the lesion was ascertained by means of radiological investigations. Additional clinical and radiological information is reported in Table 2.

Stimuli and Procedure

Subjects were seated in front of the examiner with the palms in contact with the plane of a table and with their corporeal midline aligned with the center of the table. By using his second fingertips, the examiner delivered light and brief (about 0.5 sec) touches to the dorsal surface of the patients' left or right hand or both hands. All subjects, previously informed that stimuli could be single or double, were requested to report verbally if the left or the right hand or both hands were stimulated. Subjects were blindfolded throughout the testing sessions. The comprehension of the instructions was checked by giving a few practice trials while subjects

Table 2. Continued.

Groups	Pts.	Contr. Om. Sin. (%)	Contr. Om. Dou. (%)	VE	Alb.	Read.	Orien.	PN	Lesions Site
RBD TE									
	1	0	70	−	−	−	−	0	T
	2	0	80	+	−	−	−	0	BG
	3	10	80	−	−	−	−	0	T-P
	4	0	90	−	−	−	−	0	T-P
	5	20	80	+	+	+	+	1	T-P
	6	10	60	−	−	−	−	1	F-T-P
	7	0	90	+	−	−	−	0	F-T-P
	8	20	60	+	−	−	+	0	F-T-P
	9	10	60	+	−	−	−	1	F-T-P
	10	0	90	−	−	−	−	1	F-T-P
	11	0	100	+	+	+	+	0	F-T-P
	12	0	100	+	−	−	−	0	P
RBD TE+									
	1	90	100	+	+	+	+	2	T-P-Ins
	2	60	100	+	+	+	+	3	T-P-Ins
	3	100	100	+	+	+	−	0	T-P
	4	50	100	+	−	+	+	1	F-T-P
	5	50	100	+	−	+	+	0	T
	6	90	90	+	−	+	+	1	T-P
	7	70	100	+	−	+	−	0	T-P
	8	90	100	+	−	−	−	2	T-P
	9	80	100	−	−	−	−	1	F-T-P-O
	10	90	100	−	−	−	+	1	F-T-P
	11	100	100	+	+	+	+	1	T-P
	12	70	100	+	−	−	+	1	BG

[a] Omissions (in %) of tactile stimuli delivered to the contralesional hand (Contr. Om.) during the preliminary test for assessing tactile extinction are reported under headings 3 and 4 for single (Sin.) and double (Dou.) stimulation conditions, respectively. A + indicates an impaired performance; a − indicates a normal performance; VE = visual extinction; Alb. = Albert Cancellation Test; Read. = reading test; Orien. = orientational bias toward the ipsilesional side; PN = personal neglect; F = frontal; T = temporal; P = parietal; I = insular; Caps = internal capsule; BG = basal ganglia; Th = thalamus. The lesion mapping was based on CT or MRI scans.

kept their eyes open. Patients were instructed to ask for pauses every time they felt tired. The area of contact between examiner's fingertips and dorsum of subjects' hand was about 1 cm^2. The average weight impressed during each stimulation condition was inferred by stimulating two digital letter scales (with identical calibration and 1-g precision) following the same sequence and the same procedure used in the experiment. The average weight of stimuli delivered in single stimulation condition was 32.8 g (*SD* 13.7) for the left hand and 29.2 g (*SD* 9.2) for the right hand. Under double stimulation condition, the average weights were 34.7 g (*SD* 8.9) for the left hand and 30.4 g (*SD* 10.34) for the right hand.

Each subject was tested in six experimental blocks. In each block 10 single left, 10 single right, and 20 double simultaneous stimuli were delivered according to a fixed random sequence. In three blocks the subjects' upper limbs were in anatomical position; thus the left and right hand were, respectively, in leftmost and rightmost positions (Figure 1, left column). In the remaining three blocks, the hands were in a crossed position, that is, the right hand was in the left hemispace (or leftward with respect to the other hand) and the left hand was in the right hemispace (or rightward with respect to the other hand) (Figure 1, right column).

Independently from their relative position (anatomical or crossed), the hands could be in one hemispace (the left or the right, Figure 1, upper and middle part) or could be positioned across the corporeal midline (Figure 1, lower part). In the across-body midline conditions the hands were positioned about 20 cm laterally to the corporeal midline. When the hands were both in the left or right hemispace, the hands in medial and lateral position were, respectively, about 10 and 30 cm from the corporeal midline. Each group consisted of 12 individuals because this number allowed us to perfectly counterbalance across subjects the order of the different experimental blocks. Half C subjects crossed the left over the right limb; the opposite was true for the other half. For patients' comfort, the ipsilesional limb was always crossed upon the contralesional limb. Correct detections were scored 1 point and omissions were scored 0 points. Given the different number of trials in the single and double stimulation conditions, percentages of correct detections instead of raw scores were entered into the analyses. All subjects knew that the experimental sessions were not part of any rehabilitation program and gave their informed consent to participate in the study.

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