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Temporal Dynamics of Visuo-Tactile Extinction Within and Between Hemispaces

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The ability to detect left-sided stimuli (visual or tactile) was studied in visual and tactile extinction (RBD) patients and in healthy (C) subjects. Stimuli were single or double; double stimuli were always cross-modal and could be released across the 2 hemispaces or within the same hemispace. Moreover, the stimuli could be either simultaneous or separated by 1 of 3 different asynchronies (105, 505, 905 ms). C subjects were perfect in all conditions. RBD patients omitted the contralesional tactile stimulus in bilateral trials (across space, classical extinction). They also omitted the tactile stimulus in unilateral left trials (within hemispace). Both effects showed the same temporal modulation with lower extinction rates at longer stimulus onset asynchronies. Results suggest that attentional processing of a visual stimulus inhibits processing of a tactile one, even if both are delivered in the same contralesional hemispace.

Keywords: cross-modal integration, visuo-tactile extinction, patients with brain damage, temporal attention, temporal order judgment

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Patients with unilateral brain damage may fail to report a stimulus presented briefly on the contralesional side of space if it occurs simultaneously with a more ipsilesionally located stimulus even though they are able to report either stimulus when it is presented alone. It is relevant to the present study that patients with visual extinction omit one of two simultaneous stimuli not only when delivered in opposite hemispaces but also when delivered in the same contralesional hemispace (Vuilleumier & Rafal, 2000). Competitive models of selective spatial attention provide a possible explanation of extinction (Behrmann, Moscovitch, & Mozer, 1991; Bundesen, 1990; Duncan, 1996). According to this view, when two simultaneous stimuli are delivered in opposite hemispaces they compete with one another for limited-capacity attentional resources. A unilateral cerebral lesion, particularly when involving the right hemisphere, may induce attentional *imbalances* that bias the competition in favor of the ipsilesional stimulus. Studies of patients with brain damage have reported that this competition may occur for both unimodal and cross-modal stimuli delivered to personal or extrapersonal space (Bueti, Costantini, Forster, & Aglioti, 2004; Di Pellegrino, Ladavas, & Farné, 1997; Ladavas, Di Pellegrino, Farné, & Zeloni, 1998; Mattingley, Driver, Beschin, & Robertson, 1997). Studies in healthy subjects show the existence of cross-modal links in spatial attention (Driver & Spence, 1998). Competition among stimuli may also depend on the timing of their respective occurrence. Studies in normal subjects show that once a visual stimulus is identified, the ability to discriminate a second stimulus, presented shortly thereafter (rapid serial visual presentation), is impaired for time lags of about 400 ms (Duncan, Ward, & Shapiro, 1994; Raymond, Shapiro, & Arnell, 1992; Shapiro, Raymond, & Arnell, 1994). This time lag has been called *attentional blink*. Husain, Shapiro, Martin, and Kennard (1997) showed that in neglect patients the temporal window of the attentional blink is 3 times longer than that of normal controls. These results are quite important as they provide evidence for a temporal dimension that is independent of any spatial dimension. Indeed, the second stimulus was in the same spatial location as the first, thus differences between patients and normals cannot be explained in spatial terms. Similar results have been replicated in the visual domain (Di Pellegrino, Basso, & Frassinetti, 1998) and reported for the first time also in the tactile modality (Guerrini & Aglioti, 2006). Several authors have shown that the temporal dimension of unimodal extinction extends to tasks involving presentation of two stimuli in opposite hemifields. Rorden, Mattingley, Karnath, and Driver (1997), for example, performed a "prior entry" study in right-brain-damaged patients with extinction. Patients watched two horizontal line segments appearing on the left and the right side of a fixation cross, separated in time by a range of stimulus onset asynchronies (SOAs). In a forced-choice task, subjects were asked to judge which segment appeared first (left–right, right–left). The interval at which an equal number of the two responses was obtained constituted an index of perception of simultaneity. Although this interval was 0 ms SOA in controls, in patients it corresponded to an SOA at which the left

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line preceded the right segment by 200 ms. This time lag was considered as the time it took neglect patients to become aware of the left stimulus. Di Pellegrino, Basso, and Frassinetti (1997) tested a patient with visual extinction using a modified version of attentional blink task that required the identification of two letters presented bilaterally and separated temporally by SOAs ranging from 0 to 1,000 ms. Detection of the contralesional stimulus increased with the temporal asynchrony interval regardless of which letters appeared first. These results suggest that extinction may be a condition in which attentional processing of the ipsilesional stimulus inhibits processing of the contralesional stimulus. We find it interesting that this inhibition was maximal for simultaneous stimuli but had an effect for hundreds of milliseconds. Therefore, extinction may derive from competition of individual stimuli for attentional spatial selection.

The present study expands current knowledge by exploring three main issues. The first concerns the effect of delivering pairs of cross-modal stimuli not only across the two hemispaces but also within the left or right hemispace. Although the process of merging different senses may rely on higher order neural structures, the specific properties of each sensory modality may influence the process itself. Vision, for example, is better at space, whereas touch is better at time. Thus, cross-modal integration within a single hemispace may in principle be different than across hemispaces, particularly when temporal variables play a role in this process.

The second issue concerns the influence of temporal variables on cross-modal visuo-tactile extinction. We have previously reported that detection of left contralesional tactile stimuli is higher when tactile or visual ipsilesional stimuli are presented with a lag of time (Bueti et al., 2004). However, performance was still defective with time lags of 305 ms. A precise time course estimation of the interferential effect of the first stimulus in one modality on the second in another modality may be potentially useful for rehabilitation. Indeed, training programs based on the fine tuning of temporal processing may reduce attentional deficits in patients with brain damage. With this aim, we explored interferential cross-modal effects across a much wider range.

The third issue regards the ability of patients with brain damage to judge the temporal order of cross-modal stimuli, again delivered within or across hemispaces. Unlike previous studies (Karnath, Zimmer, & Lewald, 2002; Rorden et al., 1997), subjects were asked to report which stimulus occurred first on the basis of the modality (visual or tactile) instead of verbal space labels (left or right). This procedure not only allowed us to have the same type of responses in trials between and within hemispaces but it also reduced possible linguistic biases toward the right space.

Method

Subjects

The patient group consisted of 7 subjects in whom site and extent of unilateral lesions affecting the right side of the brain were ascertained by means of neuroradiological examinations (see Figure 1). The patients' mean age was 65.1 years (SD = 4.6, range = 58–70), and their education was 8.7 years (SD = 3.5, range = 5–14). Signs of widespread mental deterioration, assessed by means of the Mini-Mental State examination (Folstein, Folstein, & McHugh, 1975), were absent in all patients.

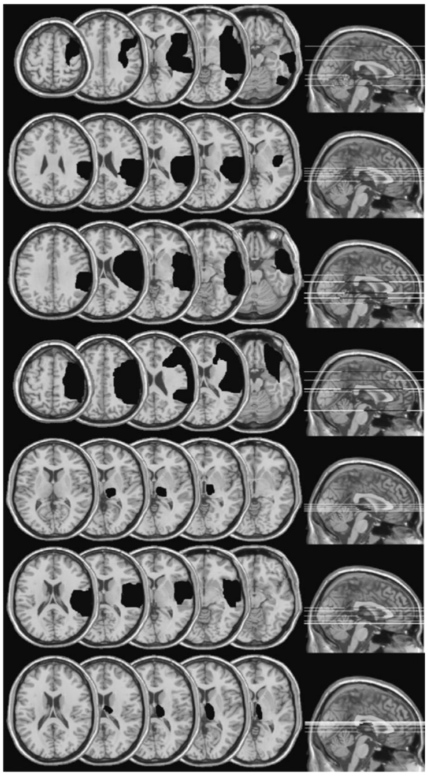

Figure 1. Lesion reconstruction for visual and tactile extinction (RBD) patients using MRIcro software (www.psychology.nottingham.ac.uk/staff/cr1/mricro.html). The figure shows the site and the size of the lesions (colored in black) for each RBD patient.

All patients were preliminarily submitted to a series of neuropsychological tests aimed at assessing visual and sensorimotor deficits and the presence of visual and tactile extinction and/or hemispatial deficits (Aglioti, Smania, & Peru, 1999; Bisiach, Perani, Vallar, & Berti, 1986; Peru, Moro, Avesani, & Aglioti, 1996). Visual extinction was assessed with a confrontation technique in which the examiner moved one or both index fingertips for about 1 s in the left, the right, or in both visual hemifields. Tactile extinction was tested by delivering a single or a double light touch with a flexible plastic stick (9.5 cm long, with a diameter of 2 mm) to the dorsum of the hands. Each stick was bent to obtain the same curvature. Thus, it was possible to deliver touches of 0.34 Newton on both sides. Visual and tactile extinction were tested in blocks of 20 unilateral (10 on the left and 10 on the right) and 10 bilateral trials. Subjects were considered to have visual and tactile extinction if they omitted at least 30% of the double stimuli but detected at least 70% of the single contralesional stimuli. Patients were selected on the basis of the presence of unimodal tactile and visual extinction. Further clinical details on the patients group are provided in Table 1.

Seven subjects without brain damage who were matched for age (M = 62.5 years, SD = 4.3, range = 58–71) and education (M = 5.7 years, SD = 1.3, range = 5–8) served as controls. All subjects gave their informed consent after being informed of the nontherapeutic nature of the experimental tests. The experimental protocol was approved by the local ethics committee. All subjects were naïve as to the purposes of the experiment.

Table 1
Demographical and Clinical Information About the Experimental Group

Pt	Age (years)	Sex	Education (years)	L-T (month)	Md	Ex	Pe	An	Extinction rate	
									Visual	Tactile
1	70	male	8	3	3	3	0	2	30	100
2	58	female	8	2	3	1	0	0	80	100
3	65	male	5	3	2	0	0	0	50	100
4	64	male	8	25	3	1	1	1	60	80
5	64	female	13	4	3	3	2	1	80	100
6	72	male	14	2	3	1	2	0	100	100
7	63	male	5	3	3	2	0	1	60	100

Note. Extinction rate was computed as the difference in accuracy between single and double stimulation. Pt = patient; L-T = interval between lesion and test; Md = motor deficit; Ex = extrapersonal; Pe = personal; An = anosognosia.

Materials and Procedure

The experimental stimuli consisted of series of single (tactile or visual, left [L] or right [R]) or double stimuli that were always cross-modal (1 visual and 1 tactile). Double stimuli could be delivered within a single hemispace (1 visual R/1 tactile R or 1 visual L/1 Tactile L) or across hemispaces (1 tactile L/1 visual R or 1 visual L/1 tactile R). Moreover, double stimuli could be delivered simultaneously (SOA 0) or sequentially (at three SOAs, namely, 105, 505, or 905 ms; see Figure 2).

In half of the asynchronous bilateral trials, left-sided stimuli preceded right-sided stimuli. The opposite was true in the other half. In half of the asynchronous unilateral trials, visual stimuli preceded tactile stimuli. The opposite was true in the other half. By convention, throughout the article negative SOAs on bilateral combinations indicate a trial in which the left stimulus was presented first, whereas a positive SOA indicates a trial in which the right stimulus was presented first. On unilateral combinations, negative SOAs indicate a trial in which the visual stimulus was presented first, whereas a positive SOA indicates a trial in which the tactile stimulus was presented first.

Visual stimuli consisted of two red parallelepipeds (1.5 cm high and 2 cm wide) comprising 12 square light-emitting diodes (LEDs; each with a 0.5 cm side) fixed on a table and positioned about 7 cm L and R of a central fixation point (thus subtending 7° of visual angle) and producing a flash with an overall luminance of 70 cd/m^2. A monophasic electric current stimulator (STM 140, High Technology Laboratory, Udine, Italy) was used for the tactile stimulation. Tactile stimuli were nonnoxious electric shocks delivered by electrodes (1 mm diameter) positioned on the palmar surface of the distal phalanx of the left and the right index finger. To ensure approximate intermanual perceptual equivalence, we defined stimuli intensity for each subject before starting the experimental session, separately for the left and the right hand, in relation to his or her sensitivity (Bueti et al., 2004; Guerrini & Aglioti, 2006; Guerrini, Berlucchi, Bricolo, & Aglioti, 2003). The criteria used to define intermanual subjective equivalence were the following: First, stimuli had to be perceived clearly; second, stimuli were not to be perceived as painful; third, stimuli intensity had to be referred as similar for both left and right hands. The intensity of single stimuli delivered to the contralesional hand was set at a value that allowed the detection of 5 of 10 stimuli (threshold level). Then, the intensity was increased so that at least 8 of 10 single stimuli were detected. Stimuli with this intensity delivered to the ipsilesional hand were typically perceived as too intense. Thus, the intensity of the stimuli on the ipsilesional side was reduced to ensure an approximate intermanual perceptual equivalence. The average stimulation intensities were as follows: (a) patients = right side: mean (standard deviation) = 10.0 (15.4) mA; left side: mean (standard deviation) = 28.0 (21.1) mA; (b) controls = 16 (9.3) mA for the right, and 13 (6.7) mA for the left side. Duration of visual and tactile stimuli was 5 ms. The visual and tactile stimuli in our study were presented at a clearly suprathreshold level. An IBM-compatible computer controlled the LEDs and the electric stimulators. MEL2 (Micro Experimental Laboratory; Schneider, 1995) software was used to control the presentation of the stimuli. Each experimental block consisted of 72 trials— 8 single (4 visual and 4 tactile), 16 double simultaneous (8 bilateral and 8 unilateral), and 16 double sequential stimuli (8 bilateral and 8 unilateral)—for each of the three SOAs. Each subject was tested in at least six experimental blocks, thus providing a minimum of 432 values for analysis. Patients performed no more than two sessions per day. The tactile threshold was reassessed on each block of 72 trials. Subjects were seated in a semidark room in front of the examiner with their corporeal midline aligned with a fixation point located 57 cm from the plane of their eyes, with their hands (palms down) on the table. Each hand was in its homonymous hemispace, close to each LED (see supplementary figure). Before the experimental session, all subjects were trained for at least 10 practice trials. In each trial, the following sequence of events occurred: Once the experimenter verified that subjects were fixating the central fixation point, he provided a verbal "ready" signal and pressed a computer button that initiated stimulus delivery. Maintenance of fixation throughout each perception–verbal response cycle was checked directly by one experimenter. The order of presentation of each combination of stimuli was randomized. All subjects, previously informed that stimuli could be single or double, were requested to verbally report the following: number (one or two), side (left, right, or bilaterally), modality (tactile, visual), and, when they reported two stimuli as asynchronous, also which stimulus appeared first. To minimize response biases, we made it necessary for patients to report the stimulus order by modality and not by side (visual first or tactile first). It is important to note that after a few trials both patients and controls spontaneously reported all the attributes of the response (i.e., number, side, sensory mo-

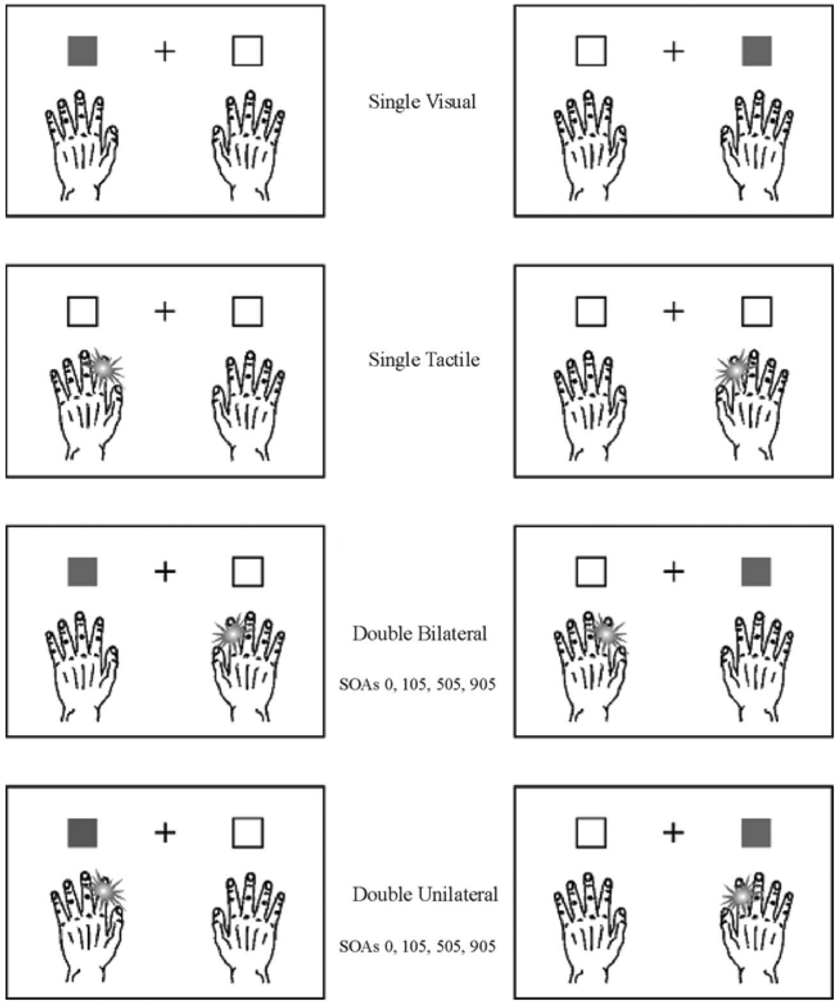

Figure 2. Schematic representation of experimental stimuli. SOAs = stimulus onset asynchronies.

dality, and temporal order). Verbal responses of the experimental subjects were keyed in the computer by one of the examiners. Subjects were instructed to wait for a verbal signal from the examiner before responding. The presence of unimodal tactile and visual extinction with the experimental stimuli (LEDs and electric shocks) was assessed in a preliminary test. This test consisted of series of single tactile or visual stimuli, left or right, or double unimodal stimuli (two tactile or two visual, L and R) always across hemispaces.

Results

Trials in which subjects failed to maintain fixation (less than 0.5%) or did not detect any stimulus under double stimulation conditions (less than 1.3 %) were discarded from the analysis.

Unimodal Test

Because the patients detected right-sided stimuli with high accuracy in single (98.6%) and double (98.6%) stimulation, an analysis was run only for the left-sided stimuli. Omissions of left-sided stimuli (in percentage of the number of trials for each combination) in the different stimulation combinations (single and double, visual and tactile) were entered in an analysis of variance (ANOVA) with Number (single vs. double) and Modality (touch vs. vision) as main factors. The significance of the Number factor, $F(1, 6) = 90.6$, $p < .0001$, partial eta square (η_p^2) = .93, was explained by the fact that patients omitted more double (78.1%) than single stimuli (8.3%). The significance of the Number $\times$ Modality interaction, $F(1, 6) = 21.2$, $p < .01$, $\eta_p^2 = .78$, was due to the fact that although no difference between visual and tactile single stimuli was found, patients omitted more double tactile (96.4%) than double visual (59.8%) stimuli, $t(6) = 3.2$, $p < .05$ (two tailed), effect size Cohen's $d = 1.7$.

Cross-Modal Test

In control subjects, detection and localization of visual and tactile stimuli in space were nearly perfect under single (98.5% of correct detections) and double simultaneous (97.3% correct responses out of the number of trials in that combination) and double sequential stimulation (98%) in both bilateral and unilateral trials.

Patients with right brain damage detected left and right single stimuli (visual: right = 97.8%, left = 84.9%; tactile: right = 93.6%, left = 90.1%) and double right stimuli (visual = 94.3%; tactile = 95.6%) with high accuracy. Previous analysis of single stimuli showed that there was no difference between them, suggesting that the salience of visual and tactile and left and right stimuli was comparable.

An important aim of the present study was to explore how detection of contralesional visual and tactile stimuli was temporally modulated by contralateral and ipsilateral stimuli in a different sensory modality. Visual and tactile extinction omissions of left-sided touches and of left-sided visual stimuli are plotted in Table 2.

Preliminary analyses showed that, in sequential stimulation conditions, omissions were independent from the stimulus that appeared first for both bilateral and unilateral stimulations. Thus, these values were averaged for further investigation.

Percentages of omissions of left-sided stimuli, on the total of either single trials or double trials in which the right-sided stimulus was detected, were entered in two separate ANOVAs, one for the tactile and one for the visual stimuli. Each analysis had the following main factors: Condition of Stimulation (single, double simultaneous, double at SOA 105, SOA 505, and SOA 905 ms) and Side of Stimulation (bilateral vs. unilateral).

The ANOVA on the left-sided tactile stimuli showed the significance of the main factor Condition of Stimulation, $F(4, 24) = 8.25$, $p < .001$, $\eta_p^2 = .57$. This was explained by the fact that fewer omissions occurred with single stimuli (9.9%) than with double simultaneous (26.0%), $t(6) = 3.36$, $p < .05$ (two tailed), $d = 0.79$, and double sequential stimuli at SOA 105 ms (24.5%), $t(6) = 3.32$, $p < .05$ (two tailed), $d = 0.47$. Moreover, omissions were significantly lower at SOAs 505 and 905 than SOAs 0 and 105, $t(6) = 3.62$, $p < .05$, $d = 0.72$; $t(6) = 2.67$, $p < .05$, $d = 0.58$; $t(6) = 3.03$, $p < .05$, $d = 0.57$; $t(6) = 2.72$, $p < .05$, $d = 0.45$, respectively. SOAs 505 and 905 did not differ from one another. The Condition of Stimulation × Side of Stimulation interaction was significant, $F(4, 24) = 3.33$, $p < .05$, $\eta_p^2 = .36$. Follow-up simple effect analysis revealed the following: In the bilateral combination, omissions at SOAs 0 (33.9%) and 105 (27.6%) were significantly higher than omissions in the single stimuli condition (9.9%), $t(6) = 2.90$, $p < .05$, $d = 0.86$; $t(6) = 2.58$, $p < .05$, $d = 0.59$, respectively. Moreover, omissions at SOA 0 were higher than at SOAs 505 (13.7%) and 905 (18.1%), $t(6) = 3.37$, $p < .05$, $d = 0.60$; $t(6) = 2.73$, $p < .05$, $d = 0.59$, respectively, which in turn did not differ from one another; in the unilateral combinations, omissions at SOA 0 (18.0%) and SOA 105 were significantly higher than in the single stimuli (9.9%) condition, $t(6) = 3.61$, $p < .05$, $d = 0.61$; $t(6) = 3.37$, $p < .05$, $d = 0.31$, respectively. It is important to note that at SOA 0 performance was significantly better under unilateral than bilateral combinations, $t(6) = 3.31$, $p < .05$, $d = 0.54$, and at SOA 105 performance tended to be significantly better under unilateral than bilateral combinations, $t(6) = 2.40$, $p = .06$, $d = 0.25$ (see Figure 3), thus suggesting that within this temporal window competition is maximal for stimuli delivered in opposite hemispaces but is also present for stimuli delivered within the contralesional hemispace.

The ANOVA on the left-sided visual stimuli showed no significant effect of both main factors and interaction. It is important to remember here that patients were selected for the presence of both visual and tactile extinction. The absence of modulatory effects of tactile on visual stimuli found in the current study suggests that the visual modality is more spatially capturing than the tactile one. This could be in agreement with the notion of visual capture, that is, the predominance of vision over other sensory modalities.

Comparison Between Unimodal and Cross-Modal Tests

With the aim of comparing the amount of unimodal (visual and tactile) and cross-modal (tactile L/visual R and visual L/tactile R) extinction, we ran an ANOVA on extinction rates (difference in accuracy between single and double stimulation) of the left-side stimuli in the unimodal test and in the double simultaneous bilateral conditions of the cross-modal test. The main factors were as follows: Extinction (unimodal vs. cross-modal) and Modality (tactile vs. visual). The factor Extinction was significant, $F(1, 6) = 35.7$, $p < .001$, $\eta_p^2 = .85$, because cross-modal extinction (19.3%) was lower than unimodal extinction (69.6%). The factor Modality, $F(1, 6) = 8.0$, $p < .05$, $\eta_p^2 = .71$, was significant because omissions of tactile (56.6%) stimuli were higher than omissions of visual (32.3%) stimuli.

Temporal Order Judgment in Patients and Controls

In trials in which two stimuli were reported, three possible temporal order responses—namely, simultaneous, right-first and left-first on bilateral trials and visual-first and tactile-first on uni-

Table 2
Patients' Percentage of Omissions (and Standard Errors) of Left-Sided (L) and Right-Sided (R) Visual (V) and Tactile (T) Stimuli in Double Bilateral and Unilateral Combinations

SOA	0		105		505		905	
	L	R	L	R	L	R	L	R
Lv-Rt	18.14 (6.66)	7.23 (3.51)	24.27 (10.64)	2.40 (1.42)	17.49 (5.40)	2.86 (2.35)	23.99 (6.39)	2.81 (1.91)
Lt-Rv	33.93 (10.42)	2.02 (1.46)	27.63 (9.61)	5.47 (2.52)	13.67 (5.57)	10.48 (6.73)	18.15 (8.48)	7.58 (2.89)
	V	T	V	T	V	T	V	T
Lv-Lt	8.54 (2.84)	18.03 (4.94)	10.49 (2.70)	21.42 (7.00)	14.94 (4.74)	9.44 (4.87)	15.38 (3.62)	12.66 (5.20)
Rv-Rt	3.23 (2.83)	5.71 (3.27)	5.68 (2.65)	3.98 (1.60)	5.53 (3.70)	4.45 (1.64)	11.13 (4.91)	1.79 (1.79)

Note. SOA = stimulus onset asynchrony; Lv = left visual; Rt = right tactile; Lt = left tactile; Rv = right visual.

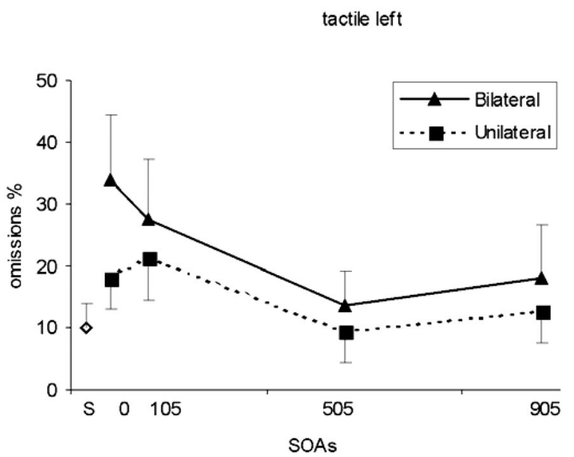

Figure 3. Percentage of omissions of left-sided tactile stimuli in bilateral (solid triangles) and unilateral (solid squares) combinations for visual and tactile extinction patients. An open diamond = single stimulus. Error bars indicate standard errors. SOAs = stimulus onset asynchronies.

lateral trials—were recorded. Theoretically, a performance that is completely congruent with the physical appearance of double stimuli should give the following reports: On bilateral trials, a simultaneous response is expected at SOA 0. Left-first and right-first responses are expected at negative and positive SOAs, respectively. On unilateral trials, a simultaneous response is expected at SOA 0. Visual-first and tactile-first responses are expected at negative and positive SOAs, respectively. For each SOA and each combination of stimuli, the actual distribution of the three possible types of temporal judgments (expressed as percentages of the total number of double trials in which two stimuli were detected) is shown in Figure 4 for control subjects and in Figure 5 for visual and tactile extinction patients (RBD patients). Series of chi-square tests were used to compare the different types of responses in each group.

Temporal Order Judgments of Patients and Controls on Bilateral Trials

Because no space- or modality-related imbalance was expected in controls, it was no surprise that their temporal order responses were comparable in the two stimulation combinations (1 tactile L/1 visual R or 1 visual L/1 tactile R); consequently, these values were collapsed. At SOA 0, the correct response "synchronous" was produced by controls in a high percentage of trials (65%; see Figure 4). However, a significant number of incorrect "synchronous" responses (59%) to asynchronous pairs of stimuli, which were separated by an SOA of 105 ms, was produced by controls, $\chi^2(1, N = 136) = 20.27$, $p < .001$, $\phi^2 = .15$ (see Figure 4).

The analysis of omissions shows that RBD patients' accuracy was influenced not only by space effects (contralesional stimuli being omitted more often than ipsilesional stimuli) but also by modality effects (combinations with tactile stimuli on the left being affected much more than combinations with visual stimuli on the left). Although temporal order judgments with an SOA of 905 ms were accurate in both stimulation combinations (see Figure 5), modality- and space-related variables appeared to influence temporal order judgments of RBD patients at SOAs of 0, 105, and 505 ms.

Temporal Order Judgments of Patients and Controls in Unilateral Trials

Temporal order judgment in control subjects was comparable in unilateral left and right combinations. Thus, these values

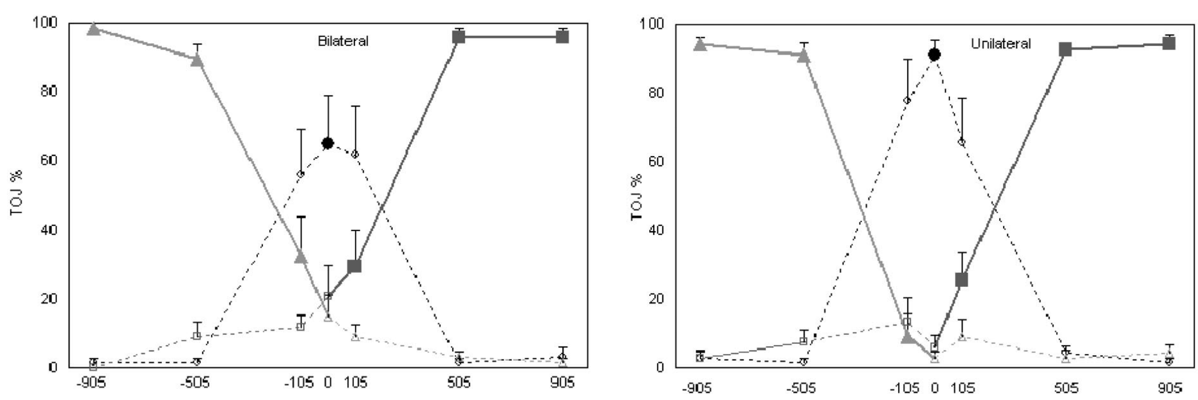

Figure 4. Representation for control subjects of the three possible temporal responses (in percentage of trials in which two stimuli were correctly detected). Error bars indicate standard errors. Bilateral trials (left panel): Negative stimulus onset asynchronies (SOAs) indicate trials in which the first stimulus in a pair was delivered to the left, and positive SOAs indicate trials in which the first stimulus in a pair was delivered to the right. An SOA of zero refers to the case wherein both stimuli were delivered simultaneously. A line (both solid and dotted) with triangles = left-first responses; a line (both solid and dotted) with squares = right-first responses; a dotted line with circles = simultaneous responses. Unilateral trials (right panel): Negative SOAs indicate trials in which the first stimulus in a pair was visual, and positive SOAs indicate trials in which the first stimulus in a pair was tactile. A line (both solid and dotted) with triangles = visual-first responses; a line (both solid and dotted) with squares = tactile-first responses; a dotted line with circles = simultaneous responses. For each curve, large filled symbols indicate responses corresponding to the actual physical order of the stimuli, that is, temporally correct responses. TOJ = temporal order judgment.

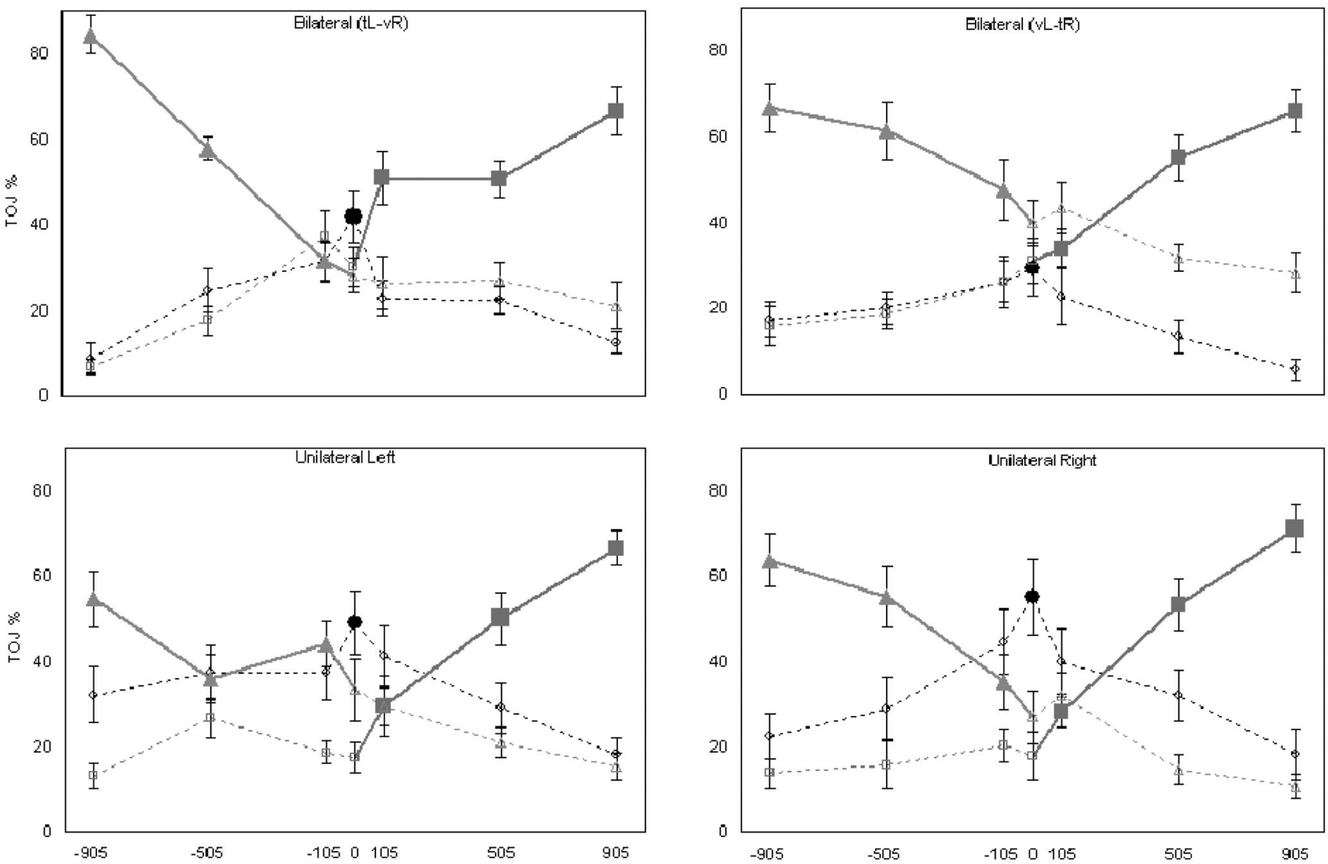

Figure 5. Representation for visuo-tactile extinction patients of the three possible temporal responses (in percentage of trials in which two stimuli were correctly detected). Bilateral trials (top panels): Negative stimulus onset asynchronies (SOAs) indicate trials in which the first stimulus in a pair was delivered to the left, and positive SOAs indicate trials in which the first stimulus in a pair was delivered to the right. An SOA of zero refers to the case wherein both stimuli were delivered simultaneously. A line (both solid and dotted) with triangles = left-first responses; a line (both solid and dotted) with squares = right-first responses; a dotted line with circles = simultaneous responses; tL = tactile left; vR = visual right; vL = visual left; tR = tactile right. Unilateral trials (bottom panels): Negative SOAs indicate trials in which the first stimulus in a pair was visual, and positive SOAs indicate trials in which the first stimulus in a pair was tactile. A line (both solid and dotted) with triangles = visual-first responses; a line (both solid and dotted) with squares = tactile-first responses; a dotted line with circles = simultaneous responses. For each curve, large filled symbols indicate responses corresponding to the actual physical order of the stimuli, that is, temporally correct responses. TOJ = temporal order judgment.

were collapsed. The actual distribution of the three possible types of responses is shown in Figure 4. The only error made by controls consisted of simultaneous report (72%) to sequential stimuli at SOA 105, $\chi^2(1, N = 134) = 78.06$, $p < .001$, $\phi^2 = .13$ (see Figure 4). In contrast, RBD patients were impaired in judging the temporal order of the stimuli in a time window ranging from –505 to +505 ms (see Figure 5). Moreover, in both unilateral left and right trials at SOA 0, visual-first responses were significantly higher than tactile-first responses—unilateral left: visual first = 33.3%, tactile first = 17.5%, $\chi^2(1, N = 58) = 6.65$, $p < .05$, $\phi^2 = .01$; unilateral right: visual first = 26.9%, tactile first = 17.9%, $\chi^2(1, N = 65) = 4.40$, $p < .05$, $\phi^2 = .01$—thus suggesting a bias toward the visual modality even in the ipsilesional hemispace.

Discussion

Classical studies of extinction have been typically carried out with pairs of simultaneous stimuli delivered in the same modality. However, on the basis of the notion that the brain merges multiple sources of sensory inputs into coherent percepts, cross-modal attention of extinction patients have been performed in patients with visuo-tactile (Bueti et al., 2004; Ladavas et al., 1998; Maravita, Spence, Clarke, Husain, & Driver, 2000; Mattingley et al., 1997), audio-visual (Frassinetti, Pavani, & Ladavas, 2002), and audio-tactile (Farné & Ladavas, 2002) extinction. Moreover, research on patients with unilateral brain damage and unimodal visual (Di Pellegrino, Basso, & Frassinetti, 1997, 1998), auditory (Karnath et al., 2002), or tactile extinction (Guerrini & Aglioti, 2006; Guerrini et al., 2003) has provided important information on the temporal course of awareness of bilateral stimuli.

The present study expands previous research by exploring the ability of RBD patients to detect contralesional visual and tactile stimuli paired with simultaneous or sequential stimuli delivered across hemispaces or within the same hemispace. Unlike our previous study in tactile extinction patients (Bueti et al., 2004), the patients of the present research presented with both visual and tactile extinction.

The first group of results of the current study concerns the spatial integration of visuo-tactile inputs. The left tactile stimulus was omitted also when the competing visual stimulus was delivered in the same hemispace, suggesting that competition for cross-modal attention occurs not only across hemispaces. The comparative independence of cross-modal competition from hemispaces is supported by the fact that in unilateral left-side stimulation, the time course of the "extinction-like" tactile effect was similar to that observed in classical extinction. Omissions of contralesional stimuli under double stimulation conditions were much more pronounced for tactile than for visual stimulation. It is worth noting that the visual-predominance effect is not accounted for by the higher amount of unimodal tactile than visual extinction. Indeed, this effect was comparable in 3 of the 7 patients (Patients 2, 5, and 6) who had a comparable amount of unimodal visual and tactile extinction. Moreover, this finding cannot be attributed to primary sensory factors because accuracy was high and comparable for the two modalities under single stimulation combinations. Thus, higher order processing of somatic stimuli may play a role in this phenomenon. Another somewhat unexpected finding is the absence of modulatory effects of tactile over visual stimuli in bilateral trials. However, it is worth noting that all the previous studies on visuo-tactile extinction have shown a modulatory effect of the visual ipsilesional stimulus on the tactile contralesional stimulus but not vice versa. Thus, attentional processing of the visual stimulus inhibits processing of the tactile one not only across hemispaces but even within the same contralesional hemispace, thus indicating that vision predominates over touch in tasks requiring bimodal integration in the space around the body.

All together, these results are in keeping with the notion of visual capture, that is, the predominance of vision over other sensory modalities, an effect classically reported for audio-visual (see for example the McGurk illusion; McGurk & MacDonald, 1976) and for complex visuo-tactile interactions (Botvinick & Cohen, 1998; Pavani, Spence, & Driver, 2000). Behavioral studies indicate that attentional processing in a given modality taps on specific phenomenal and neural systems (Duncan, Martens, & Ward, 1997). In these studies, normal subjects were presented with two streams of stimuli, either visual or auditory. Subjects had to report a target item in each stream. Attentional blink occurred when both streams were visual or auditory but not when they were audio-visual. This result indicates that when a visual target captures attentional resources it leaves resources available for an auditory task. Our finding that cross-modal extinction was lower than unimodal extinction, may be in keeping with this notion.

A second main finding of this research expands attentional blink studies on the temporal (Husain et al., 1997) and spatio-temporal (Cate & Behrmann, 2002; Di Pellegrino et al., 1998) factors underlying visual extinction by using cross-modal stimuli. A clear time-related decrease of cross-modal visuo-tactile extinction in both unilateral and bilateral conditions was found at time lags of 505 ms and similarly at 905 ms. This implies that any attention rehabilitation program based on asynchronous stimulation may use just the first of these two interstimuli intervals.

A third main finding of this research is the impairment of extinction patients in judging the temporal order of cross-modal stimuli delivered within the contralesional hemispace or in the two hemispaces. It is important to note that in both contralesional and ipsilesional unilateral trials at SOA 0, visual-first responses were higher than tactile-first responses. This result suggests that the bias toward the visual modality is exacerbated in patients with visuo-tactile extinction in both space and time. It has long been known that sensory events occurring at the location to which spatial attention is deployed tend to be perceived prior to physically synchronous events at unattended locations (Titchener, 1908; Zackon, Casson, Zafar, Stelmach, & Racette, 1999). Studies on unimodal extinction patients have shown that they perceive ipsilesional events earlier than synchronous contralesional stimuli. However, most of the previous studies used stimuli in the same sensory modality. Our study suggests that brain lesions may induce a bias of spatial attention not only toward the ipsilesional side but also toward the visual modality. This hypothesis is also supported by the evidence that the visual bias is not only present on the contralesional but also on the ipsilesional hemispace.

To sum up, our results suggest that attentional processing of a visual stimulus inhibits processing of a tactile one, even if both are delivered in the same contralesional hemispace, and that the visual stimulus seems to reach the consciousness earlier than the tactile one. Thus, brain lesions seem to alter both spatial and temporal aspects of the cross-modal merging of visuo-tactile inputs. A direct mechanism for cross-modal visuo-tactile integration is suggested by a single cell recording study (Graziano, Yap, & Gross, 1994) showing bimodal neurons driven by tactile stimuli on one hand and to visual stimuli delivered in a tridimensional area extending about 20–30 cm around the face ipsilateral to the same hand. Remarkably, when the hand was moved toward the contralateral space, the visual receptive field of these neurons followed the hand, thus maintaining a precise spatial register between touch and vision (Graziano & Gross, 1993; Graziano et al., 1994). Thus, it has been suggested that this type of neuron represents the neural basis of integrated representation of tactile and visual input in the peripersonal space (Rizzolatti, Fadiga, Fogassi, & Gallese, 1997). Although it is entirely plausible that disruption of visuo-tactile integration is related to lesions of neural structures where the above neurons are heavily represented, our patient group is much too small to allow us to draw any firm conclusion on this issue that, however, deserves further investigation.

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