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## Redundant target effect and intersensory facilitation from visual-tactile interactions in simple reaction time

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**Abstract** In a simple reaction time (RT) task, normal observers responded faster to simultaneous visual and tactile stimuli than to single visual or tactile stimuli. RT to simultaneous visual and tactile stimuli was also faster than RT to simultaneous dual visual or tactile stimuli. The advantage for RT to combined visual-tactile stimuli over RT to the other types of stimulation could be accounted for by intersensory neural facilitation rather than by probability summation. The direction of gaze (and presumably of visual attention) to space regions near to or far from the site of tactile stimulation had no effect on tactile RT. However, RT to single or dual tactile stimuli was fastest when observers could see the sites of tactile stimulation on their hands both directly and through a mirror at the same time. All these effects can be ascribed to the convergence of tactile and visual inputs onto neural centers which contain flexible multimodal representations of body parts.

**Keywords** Redundant target effect · Intersensory facilitation · Reaction time · Crossmodal integration · Human

### Introduction

The issue of how inputs from different sensory modalities cooperate in the control of behavior is of great interest to physiology and psychology alike. Recently, many studies have been devoted to the joint participation of visual and somatic information in the representation of extrapersonal and personal space, in the coding of the postures and movements of the body and its parts, and more generally in the construction and maintenance of the so-called body schema (e.g., Ettliger and Wilson 1990; Knudsen and Brainard 1995; Berlucchi and Aglioti 1997; Graziano 1999; Graziano et al. 2000; Kennett et al. 2001). Behavioral and psychophysical findings in normal observers have indicated the existence of a wide range of visuosomatic interactions in spatial perception and attention (Driver and Spence 1998a, 1998b; Johansen-Berg and Lloyd 2000). Specific interactions between vision and proprioception have been revealed by analyses of unilateral neglect and extinction in patients with selective brain damage (di Pellegrino et al. 1997; Mattingley et al. 1997; Ladavas et al. 1998, 2000) and by examining the representation of visuotactile space in the split brain (Spence et al. 2001). Animal experiments have provided ample evidence for the convergence of visual and somatic inputs onto single neurons in several cortical and subcortical brain areas (e.g., Rizzolatti et al. 1981a, 1981b; Graziano and Gross 1993; Graziano et al. 1994; Stein 1998). Neuronal activations resulting from such convergent bimodal inputs have proven to be maximal with, or totally contingent on, a precise spatial correspondence between simultaneous visual and somatic inputs (Stein 1998; Graziano 1999).

At an elementary behavioral level, it can be argued that bimodal integration may allow for a more efficient detection of near-threshold stimuli in either of the involved modalities (Stein and Meredith 1993). Reciprocal effects between different sensory modalities have been investigated with reaction time (RT) measurements (e.g., Bernstein et al. 1970, 1973; Bernstein 1970; Gielen et al. 1983; Schmidt et al. 1984; Miller 1982, 1986, 1991;

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Diederich and Colonius 1987; Giray and Ulrich 1993; Hughes et al. 1994; Plat et al. 2000) and event-related potential recordings (e.g., Schroger and Widmann 1998; Foxe et al. 2000). It has long been known that simple detection RT is faster with multiple compared to single-stimulus presentations (e.g., Raab 1962), and that the advantage for responses to multiple stimuli over responses to single stimuli is greater if the redundant stimuli are presented in different sensory modalities rather than in a single modality (see Nickerson 1973 for review of early RT studies). The advantage for RT to multiple stimuli over RT to single stimuli, called redundancy gain (RG), may be due either to a probabilistic race between signals transmitted along different neural channels (probability summation) (Raab 1962) or to a sensorimotor facilitation resulting from the convergence of the incoming signals onto one or more brain centers (Miller 1982; Colonius 1986, 1988; Ulrich and Giray 1986; Schwarz 1989; Mordkoff and Yantis 1991). The latter condition has been referred to with terms such as neural summation, or, in the case of multimodal stimulations, intersensory facilitation. Miller (1982) has proposed the most popular method to test between probability and neural summation: the so-called race-model inequality in which the RG exceeding that predicted by simple probability summation is taken as an index of neural summation.

While there have been several studies of RG effects resulting from visual-auditory interactions (e.g., Bernstein et al. 1970, 1973; Bernstein 1970; Gielen et al. 1983; Schmidt et al. 1984; Miller 1982, 1986, 1991; Diederich and Colonius 1987; Giray and Ulrich 1993; Hughes et al. 1994; Plat et al. 2000), little or no effort has been devoted to the assessment of RG effects from visual-somatic interactions (Gielen et al. 1983), in spite of the above-mentioned wealth of information on reciprocal influences between vision, touch and proprioception in cognition and behavioral control. The present study has addressed some as yet unexplored issues of the role of visual-tactile interactions in determining the performance of fast sensorimotor reactions. A first analysis has been aimed at establishing RG effects from double unimodal or bimodal stimuli compared to single visual or tactile stimuli. Since such RG effects, if present, would simply index the advantage for RT of redundant over single signals, we have tested the hypothesis of a specific intersensory facilitation of fast responses by comparing RT to bimodal visual-tactile stimuli with RT to double tactile or double visual stimuli. We have then examined whether RG effects from bimodal stimuli, if any, violate the race model, thus implying a neural summation of the redundant signals. Finally, we have assessed whether the location of the visual stimuli relative to the site of somatic stimulation can influence RG effects from bimodal stimuli, in an attempt to evaluate a possible role for visuospatial attention in such effects. A simple RT task to single and double unimodal (visual or tactile) and bimodal (visual and tactile) stimuli was employed. Tactile stimulation was applied to a fixed location on the hands while visual stimuli were positioned at

different locations in near personal or extrapersonal space. Since it has been shown that vision of a hand through a mirror influences reactivity to tactile stimulation of that body part (Tipper et al. 1998; Maravita et al. 2000), a condition in which the hands were seen both directly and through a mirror was also employed.

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## Materials and methods

### Participants

Eighteen right-handed subjects, nine females and nine males, were paid a modest fee for participating in the experiment. Their mean age was 25 years (range 19–30 years, SD 3.4 years). They were unaware of the purpose of the experiment. This experiment was carried out with subjects' signed informed consent and with approval of the Department's review board committee.

### Apparatus and stimuli

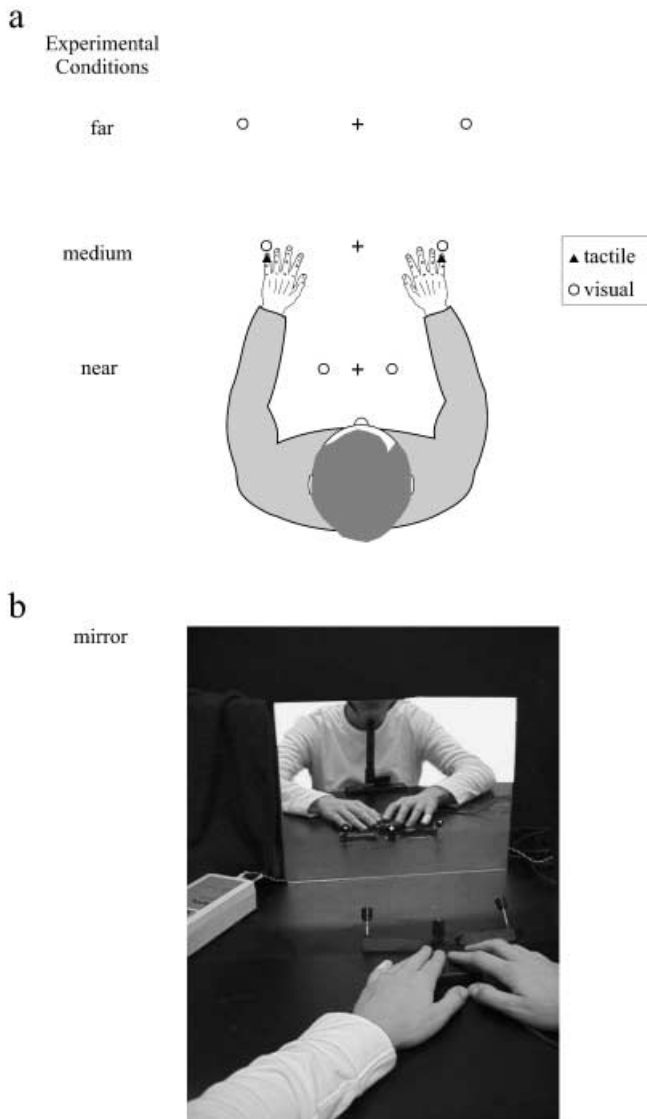
The experiment was run with the aid of a PC. The software package Micro Experimental Laboratory, MEL2 (Schneider 1995), was used to control stimulus presentation and response collection.

Visual stimuli were provided by two light emitting diodes (LEDs) with a diameter of 10 mm. These were activated by a 4-ms pulse which produced a flash with a luminance of 8 cd/m<sup>2</sup>. Tactile stimuli, consisting of trains of non-noxious electrical pulses generated by HTL stimulators (STM 140), were applied to the small finger of either hand with silver electrodes. Each train had a duration of 4 ms and included four 250- $\mu$ s pulses separated by 1 ms. All subjects perceived each train as a single tactile stimulus. For each subject the pulse current was set at a comfortable above-threshold magnitude, ranging from 2 to 18 mA among subjects.

### Procedure

Each subject sat in a dimly lit room with the head restrained by a head and chin rest. The forearms were rested on the top of a table with the hands in a pronated position and the electrodes attached to the little fingers. The mean distance between the extended fingertips and the body was about 57 cm (see below), and the hands were fully visible by the subject in all experimental conditions. A response key was placed under one forefinger. The two LEDs were placed on the same table, one on the right and one on the left, at a variable distance from the subject (see below); the separation between the two LEDs on the subject's frontal plane was 18° of visual angle, independent of the distance of the LEDs from the subject. A marker for fixation was placed halfway between the two LEDs. A trial involved fixating the marker and pressing a response key with the forefinger as fast as possible upon perceiving any stimulus from the LEDs and/or the electrodes. Stimuli were either single or double; double stimuli could be unimodal (two tactile or two visual) or bimodal (one tactile and one visual). Unimodal double stimuli were always presented bilaterally whereas bimodal stimuli were presented bi- or unilaterally. In the bimodal unilateral condition, stimuli were presented in one hemisphere (e.g., the left hand and the left visual field). In the bilateral condition, either unimodal or bimodal stimuli were presented in two hemispaces (e.g., the left hand and the right visual field). Single visual stimuli were presented in either hemifield and single tactile stimuli were presented to either hand. Because of the crossed organization of the visual pathways and the tactile pathways from the hands, stimuli in one hemisphere are projected to the contralateral cerebral hemisphere. Therefore, it is assumed that unilateral stimuli are initially processed by one hemisphere, whereas bilateral stimuli engage both hemispheres from the outset.

Each subject was run in four sessions, corresponding to four experimental conditions which were distinguished by different



**Fig. 1** Schematic design of the experimental setup showing the site of tactile stimulation and the four different positions of the visual stimuli in the near, medium, and far conditions (a) and the mirror condition (b)

distances between the LEDs and the subject's eyes (see Fig. 1). This distance was 28.5 cm in the near condition, 57 cm in the medium condition, and 85.5 cm in the far condition. In the fourth condition, the mirror condition, visual stimuli from the LEDs were seen after reflection from a mirror placed at about 71 cm from the subject's eyes, so that the apparent sources of the visual stimuli were located behind the mirror, at a distance approximately corresponding to that of the far condition. Forearms and hands were visible to the subjects in all conditions. A cap was used to equalize the retinal images of the LEDs across different distances. Specifically, the visual stimuli subtended a circle with a diameter of 3 mm in the near condition, 6 mm in the medium condition, and 9 mm in the far and mirror conditions. The LEDs were tilted by 70°, 45° and 30°, respectively, to ensure top on viewing. In all conditions, the subjects' arms and hands were placed on the table in front of them with the finger tips positioned at a distance of 54–60 cm from the body, depending on posture and arm length. Because the hands were positioned at a consistent distance from the body, the shortest distance between the site of tactile stimula-

tion and the source of visual stimulation was about 28 cm in the near condition, 0.5 cm in the medium condition, and about 18 cm in the far condition. In the mirror condition, the visual images of the hands, as reflected by the mirror, appeared to be adjacent to the apparent sources of visual stimuli, beyond the mirror surface (see Fig. 1b). On the assumption that the direction of visual attention coincided with the line of gaze, the four conditions were chosen in order to test whether this factor could influence RT to tactile stimulation of the hands. In the near and far conditions, visual attention was directed away from the site of tactile stimulation, closer to the body in the former condition, and farther from the body in the latter condition. In the medium condition, visual attention was aimed at a location very close to the locations of the hands. In the mirror condition, visual attention was directed at a location beyond the mirror that was very close to the locations of the reflected images of the hands. In all conditions the hands were visible to the subject, though in the near and far conditions they were seen within the peripheral visual field, while in the medium condition they were seen within the central visual field. In the mirror condition, the reflected images of the hands were seen within the central visual field, and the direct images of the hands were seen within the peripheral visual field. Each session included 8 blocks of 63 trials. In each block three trials in which no stimulus was presented were used as catch trials; in each block each of the ten possible stimulus configurations (left and right single visual stimuli, left and right single tactile stimuli, double bilateral visual stimuli, double bilateral tactile stimuli, left and right unilateral bimodal stimuli, left tactile stimulus and right visual stimulus, right tactile stimulus and left visual stimulus) was presented 6 times within a random sequence. There was a randomly generated inter-trial interval of 1000 up to 1800 ms, and a rest of some minutes was allowed between blocks, so that each session lasted between 20 and 40 min, depending on the requirement to arrive at a comfortable intensity of tactile stimulation. Each experimental block was initiated by the experimenter. Subjects responded with the left hand in half of the blocks and with the right hand in the other half, the order of responding hand being counterbalanced across subjects. The order of the four experimental sessions was similarly counterbalanced across subjects.

#### Analysis of the race model

Miller's (1982) inequality procedure was applied to test whether the advantage for RT to double unimodal stimuli or bimodal stimuli over RT to single stimuli could be accounted for by probabilistic or neural summation. This procedure sets an upper boundary for the cumulative probability of a correct response by any time  $t$  given redundant signals.

For redundant stimuli presented bilaterally and single stimuli presented to either the right or left visual hemifield or hand, the following inequality procedure was applied:

$$P(RT \leq t/T^L \text{ and } T^R) \leq P(RT \leq t/T^L) + P(RT \leq t/T^R) \quad (1)$$

with  $P(RT \leq t/T^L \text{ and } T^R)$  being the cumulative probability of a correct detection with bilateral targets,  $P(RT \leq t/T^L)$  being the cumulative probability of a response given a single target in the left hemispace, and  $P(RT \leq t/T^R)$  being the cumulative probability of a response given a single target in the right hemispace. When the upper boundary is violated, neural summation can be assumed because, in a race model, RTs to redundant signals cannot be faster than the fastest RT to single stimuli. Thus, violation of the race model is present when, at any point in time, the probability to respond to a bilateral stimulus is significantly higher than the joint probability to respond to the single stimuli.

**Table 1** Mean RTs (ms) (SE in parentheses) for responses to unimodal and bimodal stimuli in each experimental condition

Location of LEDs	Stimuli					
	Visual		Tactile		Visual-tactile	
	Single	Double	Single	Double	Bilateral	Unilateral
Mirror	295.6 (8.6)	286.1 (8.3)	263.9 (11.3)	253.4 (10.7)	251.0 (9.4)	253.5 (10.3)
Far	298.7 (7.7)	286.3 (7.8)	273.9 (10.7)	266.1 (11.3)	256.3 (9.7)	259.1 (9.3)
Medium	287.49 (12.2)	276.1 (11.4)	273.0 (15.4)	263.5 (14.6)	253.8 (13.3)	250.9 (14.1)
Near	289.21 (7.4)	280.1 (7.91)	274.3 (11.9)	263.8 (12.1)	250.2 (9.6)	251.2 (10.0)
Total	292.8 (9.0)	282.1 (8.8)	271.3 (12.3)	261.7 (12.2)	252.8 (10.5)	253.7 (10.9)

## Results

RTs faster than 100 ms or slower than 500 ms were considered as outliers and discarded. As a result, a mean of 1.9% of RTs per experimental condition were eliminated. Outliers were uniformly distributed among all conditions: 1.75% in the near condition, 1.98% in the medium condition, 1.88% in the far condition, and 1.97% in the mirror condition. On the basis of preliminary analyses which showed no systematic right-left differences related to the responding hand or the side of visual or tactile stimulation, RTs to each stimulation mode (single and double stimuli within each modality, unilateral and bilateral bimodal stimuli) were averaged separately across responding hands, and RTs to unilateral bimodal stimuli were also averaged across right and left stimulation sides. Further, for each subject RTs to single stimuli within each modality were averaged separately for the right and left stimulation sides, and whichever of the two RTs was faster was chosen for analysis. These averaging procedures yielded six basic data for each subject for each condition of visual stimulation: namely, RTs to single and double visual stimuli, RTs to single and double tactile stimuli, and RTs to unilateral and bilateral bimodal stimuli for the near, medium, far and mirror conditions. The corresponding group means are presented in Table 1.

A preliminary analysis was carried out to compare RTs to bimodal unilateral stimuli with RTs to bimodal bilateral stimuli, and thus to test for possible differences between intrahemispheric and interhemispheric stimulations. An ANOVA of RTs to bimodal stimuli with laterality (unilateral or bilateral) and condition (near, medium, far, mirror) as within-subject factors showed no significant effect from the two main factors [laterality:  $F_{(1,17)}=1.26$ , NS; condition:  $F_{(3,51)}=0.39$ , NS], as well as from the two-way interaction [ $F_{(3,51)}=1.90$ , NS]. Thus, given that RTs to bimodal unilateral stimuli and RTs to bimodal bilateral stimuli were statistically indistinguishable, in all subsequent analyses only the latter RTs were used for comparison with RTs to double unimodal stimuli, which were consistently bilateral.

## Analysis of redundant signal effects

We tested for the presence and extent of these effects by comparing, first, RTs to single stimuli of each modality with RTs to double stimuli of the same modality, and, second, RTs to single stimuli of each modality with RTs to bimodal stimuli. The first comparison was performed by running a repeated-measurements ANOVA with modality (visual, tactile), number of stimuli (single, double) and condition (near, medium, far, mirror) as main within-subjects factors. Significant effects were obtained for modality [ $F_{(1,17)}=23.0$ ,  $P<0.0001$ ] and number of stimuli [ $F_{(1,17)}=75.6$ ,  $P<0.0001$ ], but not for condition [ $F_{(3,51)}<1$ , NS]. Tactile RT (266.5 ms) was faster than visual RT (287.5 ms), and RT to double stimuli (271.9 ms) was faster than RT to single stimuli (282.0 ms). The interaction between modality and number of stimuli was insignificant [ $F_{(1,17)}<1$ , NS], indicating that the advantage for RT to double versus single stimuli did not differ between modalities. All other two-way interactions and the three-way interaction were also insignificant. The second comparison was performed by running a repeated-measurements ANOVA with type of stimulus (single, bimodal) and condition (near, medium, far, mirror) as main within-subjects factors.

In order to use a very conservative approach, the faster RT between the tactile RT and the visual RT for each subject for each condition was selected for analysis. Not surprisingly, given the results of the previous ANOVA, for 15 out of 18 subjects the mean tactile RT turned out to be the faster. Type of stimulus was significant [ $F_{(1,17)}=42.8$ ,  $P<0.0001$ ], RT to bimodal stimuli (252.8 ms) being faster than RT to single stimuli (267.8 ms), while condition [ $F_{(3,51)}<1$ , NS] and the two-way interaction [ $F_{(3,51)}=1.3$ , NS] proved insignificant.

One may argue that the RT advantage for double over single stimuli depended in part on the fact that with single stimuli half of the trials were performed with the hand contralateral to the stimulus, i.e., in a situation requiring a time-consuming interhemispheric transfer (Pollmann and Zaidel 1999, experiment 2). However, RT to bimodal and double unimodal stimuli was significantly faster than either ipsilateral or contralateral RT to single stimuli in both visual and tactile modalities ( $P<0.0001$  by  $t$ -tests for matched pairs in all cases: see Table 2).

**Table 2** Mean RTs (ms) (SE in parentheses) for responses to double stimuli (unimodal and bimodal) and single stimuli (ipsilateral and contralateral to the responding hand)

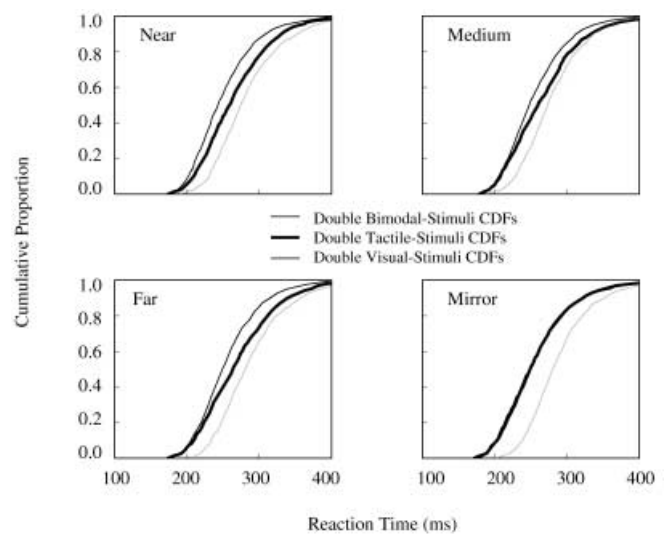
Stimuli	Single stimuli		Double stimuli	
	Ipsilateral	Contralateral	Unimodal	Bimodal
Visual	298.7 (8.4)	299.9 (8.6)	282.1 (8.3)	252.8 (9.7)
Tactile	276.6 (11.6)	280.6 (11.6)	261.7 (11.1)	252.8 (9.7)
Total	287.6 (10)	290.2 (10.1)	271.9 (9.7)	252.8 (9.7)

### Analysis of intersensory facilitation

The results described above indicate that double unimodal stimuli and bimodal stimuli alike produced RG effects relative to single stimuli. In order to assess whether bimodal stimuli facilitated RT more than unimodal double stimuli, we compared the RTs to the three types of stimuli. An ANOVA of RTs to double stimuli with modality (bimodal, visual, tactile) and condition (near, medium, far, mirror) as within-subject factors showed a significant main effect of modality [ $F_{(2,34)}=46.7, P<0.0001$ ]. RT to bimodal stimuli (253.7 ms) was significantly faster than RT to double tactile stimuli [261.7,  $t_{(17)}=-12.2, P<0.0001$ ], which in turn was faster than RT to double visual stimuli [282.1 ms,  $t_{(17)}=-4.8, P<0.0001$ ]. There was no significant effect of condition [ $F_{(3,51)}<1, NS$ ], but the interaction with modality was significant [ $F_{(6,102)}=4.1, P<0.001$ ]. The significance of the interaction is accounted for by the fact that, on average, RTs to bimodal stimuli were faster than RTs to unimodal double stimuli in either modality, but the advantage for RT to bimodal stimuli over RT to double visual stimuli was present in all conditions, while RT to bimodal stimuli was faster than RT to double tactile stimuli only in the near, medium and far conditions. In the mirror condition, RTs to bimodal and tactile stimuli were closely matched [ $t_{(17)}<1, NS$ ] (see Table 1). All other differences between RTs to bimodal stimuli and RTs to double visual stimuli, and between RTs to bimodal stimuli and RTs to double tactile stimuli, were significant at the  $P<0.0001$  level by  $t$ -tests for matched pairs. In order to provide an additional illustration of the RT differences between bimodal stimuli and unimodal double stimuli, cumulative distribution functions (CDFs) were calculated for each subject, for each combination of stimuli (two visual, two tactile and one visual and one tactile), and in each of the four conditions. Mean functions across subjects, obtained by Vincentizing (Ratcliff 1979), are plotted in Fig. 2.

### Redundancy gain versus intersensory facilitation

Both double unimodal stimuli and bimodal stimuli produced faster RTs than did single stimuli. Table 3 compares the RGs for double unimodal stimuli and bimodal stimuli in the four conditions. Inspection of the data in Table 3 suggests that in all conditions the RGs with uni-



**Fig. 2** Cumulative distribution functions (CDFs) for responses to double visual, double tactile and bimodal stimuli averaged across conditions

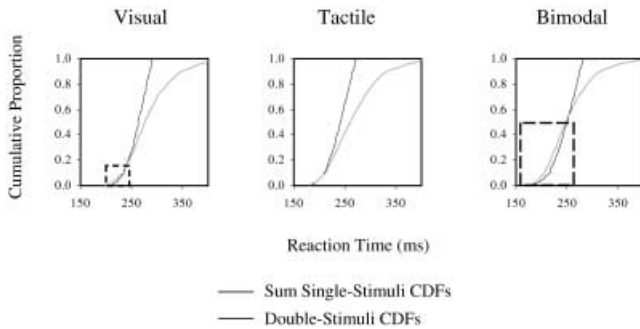
**Table 3** Mean redundancy gains (ms) (SE in parentheses) for responses to unimodal and bimodal stimuli

Location of LEDs	Stimuli		
	Visual	Tactile	Bimodal
Mirror	9.6 (1.6)	10.5 (2.5)	18.0 (2.5)
Far	12.5 (1.8)	7.8 (2.1)	21.9 (2.7)
Medium	11.4 (2.2)	9.3 (3.4)	20.3 (3.4)
Near	9.1 (2.6)	10.5 (3.4)	25.3 (3.2)
Total	10.7 (2.1)	9.5 (2.9)	21.4 (3.0)

modal stimuli were about the same in the visual and tactile modalities, but considerably smaller than the RGs for bimodal stimuli. In an ANOVA with RG (visual, tactile bimodal) and condition (near, medium, far, mirror) as main factors the only significant source of variation was the first main factor [ $F_{(2,34)}=23.0, P<0.0001$ ]. Bimodal RG was significantly greater than both unimodal RGs in all cases and in all conditions ( $P<0.0001$  by  $t$ -tests for matched pairs).

### Analysis of the race model

CDFs of RTs were calculated for single and double visual, tactile and bimodal stimulus presentations for all conditions in each subject. Insofar as condition (near, medium, far, mirror) had no significant main effects in all the above described ANOVAs, composite CDFs were then formed simply by averaging, across subjects and conditions, all the RTs at each percentile (2.5th, 5th, 7.5th and so on). Using this Vincentizing procedure (Ratcliff 1979), we obtained CDFs for the sum of single and double visual, tactile and bimodal stimuli. Figure 3 shows that viola-



**Fig. 3** Cumulative distribution functions (*CDFs*) for responses to double stimuli and for the sum of responses to single stimuli in visual, tactile and bimodal stimulation. The *dotted area* indicates statistically significant differences (*t*-tests)

tion of the race model was obtained for bimodal and unimodal visual stimuli, but not for tactile stimuli.

Since it is well known that race models are difficult to falsify based on this inherently conservative inequality (Miller 1982), when the upper boundary is violated one is fully justified to assume neural summation, but lack of violation does not exclude summation. Neural summation was much more pronounced with bimodal stimuli, being significant downwards of the 47.5th percentile ( $P < 0.05$  by *t*-tests for matched pairs), than for unimodal visual stimuli, for which neural summation was significant downwards of the 10th percentile.

#### Analysis of possible influences of the direction of the line of gaze on tactile RT

Insofar as condition (near, medium, far, mirror) had no significant main effects in all the above described ANOVAs, it must be concluded that it did not modulate the dependent variables in any systematic manner. However, it was noted that in the analysis of intersensory facilitation, RT to double tactile stimuli was slower than RT to bimodal stimuli in the near, medium and far conditions, but not in the mirror condition, contrary to RT to double visual stimuli, which was slower than RT to bimodal stimuli in all conditions. This resulted in a significant modality/condition interaction in the intersensory facilitation ANOVA; see above. Moreover, inspection of the data in Table 1 clearly shows that all tactile RTs, whether to single or double stimuli, were faster in the mirror condition than in the other conditions. This prompted us to perform a further ANOVA on RTs to single and double tactile stimuli. The main factors in the analysis were number of stimuli (single, double) and condition (two levels: mirror and non-mirror, the latter being the mean of the other three conditions). Both main factors proved significant [respectively:  $F_{(1,17)}=151.6$ ,  $P < 0.0001$ ;  $F_{(1,17)}=4.5$ ,  $P < 0.05$ ], but their interaction did not [ $F_{(1,17)} < 1$ , NS]. The significant effect from condition was accounted for by RT being faster in the mirror condition (262.8 ms) than in the non-mirror condition

(273.2 ms). The significant effect from number of stimuli was accounted for by RT to double stimuli (258.9 ms) being faster than RT to single stimuli (277.1 ms). The insignificance of the interaction was accounted for by the advantage for RT to double stimuli being the same in the mirror and non-mirror condition. This result, together with the above described lack of any difference between RT to double tactile stimuli and RT to bimodal stimuli in the mirror condition, suggests that in the latter condition there was a general facilitation of tactile RT.

## Discussion

Much previous work on redundant target effects from bimodal stimuli on speeded sensorimotor reactions has centered on interactions between vision and audition (e.g., Bernstein et al. 1970, 1973; Bernstein 1970; Gielen et al. 1983; Schmidt et al. 1984; Miller 1982, 1986, 1991; Diederich and Colonius 1987; Giray and Ulrich 1993; Hughes et al. 1994; Plat et al. 2000). The present results provide novel information about cross-modal interactions in redundant target effects by demonstrating that combined visual and tactile stimuli produce a robust effect of this kind in the performance of a simple detection RT task. A redundant target effect is conventionally defined as an advantage for RT to a dual stimulation over RT to a single stimulation. In agreement with Corballis (1998), we found that RT to two simultaneous visual stimuli, one on the right and the other on the left, is faster than RT to either visual stimulus alone, either right or left, independent of whether the responding hand is ipsilateral or contralateral to the single visual stimulus. Similarly, RT to two simultaneous tactile stimuli, one to the right hand and the other to the left hand, is faster than RT to either tactile stimulus alone, either right or left. The new finding is that the simultaneous presentation of a visual stimulus and a tactile stimulus, one on the right and the other on the left, elicits faster detection RTs than does the presentation of either stimulus alone, either on the right or on the left; and, more importantly, that RT to a combined visual stimulus on one side and a tactile stimulus on the other side is faster than RT to a dual bilateral tactile or visual stimulation. Therefore, in agreement with results of Bernstein and Peterson (1972) for two-choice RT, a double bimodal stimulus is more advantageous for RT than a double unimodal stimulus.

Redundant target effects that violate the race model can be attributed to the facilitatory convergence of dual stimuli onto some stage of the neural mechanisms translating inputs into outputs, rather than to response generation by the fastest of two signals engaging parallel processing channels. In the present data, RT facilitation by double stimulation, whether unimodal or bimodal, was found to be generally greater than that expected on the basis of probability summation. The evidence for the race model violation, presumably indexing neural summation, was much more systematic with bimodal stimulation than with double unimodal stimulation, suggesting

that the comparatively greater redundant gain effect from visual-tactile stimulation may depend on a more effective neural summation of intersensory compared to intrasensory redundant signals. The present violation of the race model indicates some degree of neural summation with double visual stimuli in normal subjects, in keeping with the findings of Reuter-Lorenz et al. (1995), Miniussi et al. (1998) and Cavina-Pratesi et al. (2001). Other studies have failed to reveal neural summation effects with double visual stimuli in normal subjects (Corballis 1998; Murray et al. 2001; Pollmann and Zaidel 1999), while such effects are consistently found in split brain subjects (Reuter-Lorenz et al. 1995; Corballis 1998; Corballis and Finlay 2000; Pollmann and Zaidel 1999; Iacoboni et al. 2000). In the present study on normal subjects, we found no evidence for neural summation with double tactile stimuli, possibly due to the greater variability of tactile RTs compared to visual RTs.

It may be argued that RT to visual-tactile stimuli was faster than RT to single or double visual stimuli simply because RT to tactile stimuli is usually faster than RT to visual stimuli, as indeed it was in the present study. However, this hypothesis does not account for the advantage of RT to bimodal stimulation over RT to single or double tactile stimuli, an advantage which is therefore best attributed to a genuine intersensory facilitation. Accordingly, we propose that in the present task the neural translation of input into output was facilitated by the convergence of visual and tactile signals onto common neural targets, and that this facilitation was more effective than any facilitation that may have resulted from the convergence of dual unimodal tactile or visual signals. Electrophysiological studies of primate brains, including human brains, have revealed a multitude of neural centers, both cortical and subcortical, where visual and somatic inputs can converge and interact, as indicated by the joint participation of both inputs in building up polysensory receptive fields of single neurons (Stein 1998; Graziano 1999). Whether the visual-tactile interactions effects reported here depend on all of these brain sites or part of them is still to be determined. The results also warrant some limited inferences about the relationships between the direction of gaze and the speed of reactivity to tactile stimuli. It has been shown that orienting toward a body site facilitates the processing of tactile stimuli delivered to that site relative to other body sites. Visual, proprioceptive and general attentional mechanisms have been shown to play distinctive roles in these effects (Honoré 1982; Honoré et al. 1989; Tipper et al. 1998; Johansen-Berg and Lloyd 2000). The present subjects did not orient toward one or the other hand, that is toward the site of tactile stimulation, but were to fixate their gaze, and therefore presumably their visual attention, on regions of space that could be relatively remote from both hands, or relatively close to both of them. In the near and far conditions, the gaze was directed on a fixation mark that was remote from the hands, in that it was closer to the body than were the hands in the former

condition, and farther from the body than were the hands in the latter condition. The medium and mirror conditions were designed in such a way that the direction of gaze fell between and close to the directly seen hands in the former condition, and between and close to the reflected images of the hands in the latter condition. One could have expected a faster tactile RT in the medium condition than in the other conditions, because of a possible facilitatory effect from the spatial contiguity of tactile stimuli and visual attention. Yet, tactile RT was not significantly different in the near, medium and far conditions, possibly because of the very simple nature of the task, which according to Posner (1978) may not be suitable for the assessment of attentional effects in tactile reactivity. An alternative possibility is that attentional effects on tactile RT emerge only when attention is selectively aimed at one of two or more potential sites of tactile stimulation, which was not the case in our study. The direction of visual attention, however, was not totally without influence on tactile RT in our experiment, insofar as in the mirror condition RTs to both single and double tactile stimuli were speeded up relative to the corresponding RTs in the near, medium and far conditions. This effect is akin to the finding that looking at body sites through a mirror expedites the processing of tactile information at those sites (Tipper et al. 1998; Maravita et al. 2000). Both the latter effect and the one described here are likely to depend on bimodal cortical and subcortical neurons that are able to realign their visual and somatic receptive fields throughout various conditions of observation, in such a way as to hold the two maps in register (Rizzolatti et al. 1981a, 1981b; Graziano and Gross 1993; Graziano et al. 1994; Stein 1998). In our specific case, it is reasonable to surmise that the somatosensory centers representing the hands received a double visual stimulation from viewing the hands both directly and after reflection from the mirror, with a resulting facilitation of tactile RT.

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