Binding personal and extrapersonal space through body shadows

Francesco Pavani[1] & Umberto Castiello[1,2]

Shadows in visual scenes can have profound effects on visual perception. Here we have found that visual distracters distant from the body interfere with human spatial discrimination of tactile targets at a hand, particularly when the shadow of the stimulated hand stretches toward them in extrapersonal space. These findings suggest that shadows cast by a person's own body parts can bridge the gap between personal and extrapersonal space.

We tested ten healthy individuals (mean age 28 years, s.d. = 6; experiment 1) in a visuo-tactile interference paradigm[1]. In this paradigm, spatial-discrimination times for tactile targets presented on the body (thumb or index finger of either the right or left hand) increase when spatially incongruent visual distracters flash in the vicinity of the body part that was touched, simultaneous to each tactile target. In our tests, visual distracters were presented 30 cm away from either hand, but the shadow of one of the two hands stretched towards the distracting lights, as if to 'reach' them (**Fig. 1a**). Although participants were instructed to ignore the extrapersonal distracting lights, spatially incongruent visual distracters (*e.g.*, flashes above the point of fixation—as seen from the participant's perspective—during touches down at the thumb) interfered with spatial discrimination for tactile targets. Visuo-tactile interference (the cost, in spatial-discrimination time or accuracy, of tactile targets with spatially incongruent flashes as compared with tactile targets with spatially congruent flashes) emerged reliably as assessed by both response time (overall mean 63 ms; significantly above zero by *t*-test, $t_9 = 5.84$, $P < 0.0001$) and percentage errors (overall mean 5%; $t_9 = 3.16$, $P < 0.01$).

Crucially, even though visual distracters were equidistant from both hands, visuo-tactile interference was significantly stronger when tactile targets were presented at the hand casting the shadow (mean 72 ms) than at the hand not casting a shadow (mean 54 ms; on paired *t*-test $t_9 = 2.64$, $P < 0.03$; a similar trend was also observed when visuo-tactile interference was measured as percentage error: 7% versus 4%, respectively, $t_9 = 1.69$, nonsignificant; **Fig. 2a**). This suggests that the hand shadow bound visual distracters in extrapersonal space to tactile targets presented at the hand.

Three further experiments examined the specificity of this result. We first considered whether any shadow stretching from the hand to the visual distracters could have produced the observed personal-extrapersonal binding. Participants ($n = 10$, mean age 32 years, s.d. = 9; experiment 2) wore a shaped glove that projected a polygonal shadow near the visual distracters (**Fig. 1b**). With this setup, any minimal movements of the cast shadow were still temporally correlated with hand movements, but the shadow had no resemblance to a hand. Visuo-tactile interference was almost identical for the hand projecting the shape shadow (mean 77 ms) and the hand not casting a shadow (mean 78 ms, on paired *t*-test $t_9 = 0.17$, nonsignificant; with no difference for errors, 7% versus, 6%, respectively, $t_9 = 0.99$, nonsignificant; **Fig. 2b**), suggesting that merely seeing a shadow stretching out from the body is not sufficient to produce a personal-extrapersonal binding. We next tried using a line drawing silhouette of a hand 'reaching' for the visual distracters ($n = 10$, mean age 28 years, s.d. = 6; experiment 3). The silhouette mimicked the shape of the hand shadow while bearing no resemblance to a shadow (**Fig. 1c**). In addition, no real shadows of the hand were visible. Again, visuo-tactile

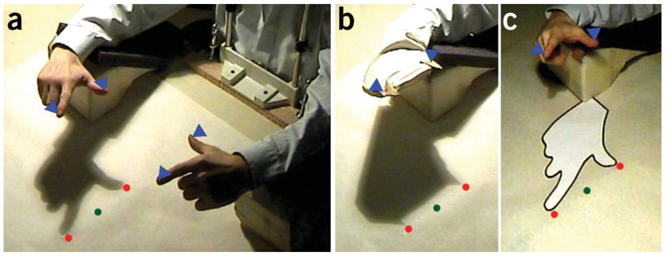

Figure 1 Experimental setup. (**a**–**c**) Participants sat with their chin on a rest, fixating on a green LED on the table surface (green circle). Computerized tactile targets consisted of three successive punctate 50-ms touches, separated by 50 ms, delivered by custom-made electromagnetic stimulators attached to the fingertips (blue arrows). Visual distracters consisted of three successive 50-ms flashes, separated by 50 ms, delivered by a pair of red LEDs equidistant from either hand (red circles). Participants performed a speeded discrimination of which finger was tactually stimulated (regardless of side), releasing a foot pedal under their toe to indicate stimulation at the index finger or a foot pedal under their heel to indicate stimulation at the thumb. In all experiments, participants saw (**a**) the shadow cast by one hand, projected on the table surface by a lateral light source from above the participant's head; (**b**) the polygonal shadow cast by a shaped glove; (**c**) a line drawing silhouette of a hand (right or left hand, depending on the presentation side). In experiments 1–3, participants completed 320 trials per experiment; 80 trials for each combination of presence and absence of shadow or silhouette, and side (left or right) of shadow or silhouette. In experiment 4, one hand (left or right) was near the visual distracters and the other hand (right or left) cast a shadow towards the visual distracters, while resting distant from them. Tactile targets were presented with equal probability on either hand (160 trials overall). All participants gave informed consent. The study design was approved by the Ethical Comittee at the Dipartimento di Scienze della Cognizione e della Formazione, Università di Trento.

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[1]Dipartimento di Scienze della Cognizione e della Formazione, Università degli Studi di Trento, Via Matteo del Ben 5 (third floor), 38068 Rovereto, Italy. [2]Department of Psychology, Royal Holloway University of London, TW20 0EX Egham, UK. Correspondence should be addressed to F.P. (pavani@form.unitn.it).

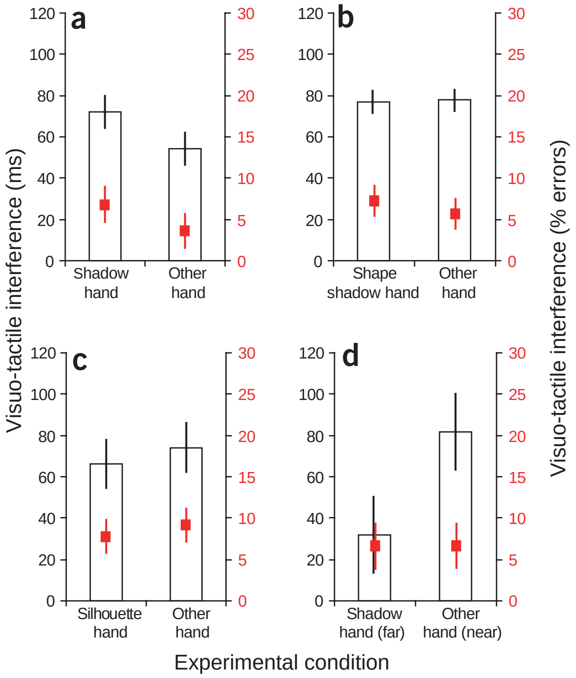

Figure 2 Modulation of visuo-tactile interference in the four experiments. (**a**) Experiment 1: both hands equidistant from the distracting lights, one hand casting a shadow near the visual distracters. (**b**) Experiment 2: both hands equidistant from the distracting lights, one hand casting a polygonal shadow near the visual distracters. (**c**) Experiment 3: both hands equidistant from the distracting lights, line drawing silhouette of a hand visible. (**d**) Experiment 4: one hand resting near the distracting lights (as if to grasp them), the other resting 30 cm away but casting its shadow near the visual distracters. Bar graphs, visuo-tactile interference with response time; squares, visuo-tactile interference with response accuracy; error bars, 95% confidence intervals.

interference was not significantly different between the hand corresponding to the silhouette (mean 66 ms) and the hand with no silhouette (mean 74 ms, on paired *t*-test $t_9 = 0.76$, nonsignificant; with no difference for errors, 8% versus 9%, respectively, $t_9 = 0.78$, nonsignificant; **Fig. 2c**). Both the shape shadow and the silhouette might have directed participant's visual attention to the distracters (as suggested by the large visuo-tactile interference effects observed in both experiments 2 and 3). Nevertheless, unlike in experiment 1, they did not differentially affect tactile performance at one hand as compared to the other. This suggests that only the hand shadow elicited a binding of the lights in extrapersonal space with the touches at the hands.

In a final experiment ($n = 8$, mean age 31 years, s.d. = 11; experiment 4), we compared directly the magnitude of the visuo-tactile interference effect when the hand shadow was cast near the visual distracters with the interference observed when either the left or right hand was physically near the distracting lights. The experimental setup was the same as in experiment 1 (**Fig. 1a**) except that the hand not casting a shadow rested on the table surface, immediately adjacent to the distracting lights as if to 'grasp' them. Here, visuo-tactile interference was larger at the hand physically near the visual distracters (mean 82 ms) than at the hand casting its shadow near the distracters, but actually resting 30 cm away from them (mean 32 ms, on paired *t*-test $t_7 = 3.18$, $P < 0.02$; with no difference for errors, 7% versus 7%, respectively, $t_7 = 0.01$, nonsignificant.; **Fig. 2d**). This result suggests that although the body schema can extend to incorporate body shadows (as we showed in experiment 1), the actual boundaries of the body (as defined by experience, vision and proprioception) remain understandably more relevant for estimating peripersonal space.

Binding of personal and extrapersonal space has been described in relation to artificial body parts (such as sham arms) that alter the perceived position of the body in space[1,2] or after repeated tool use[3–5]. This has been taken to show that the internal representation of the body's spatial extent (the so-called 'body schema'[3]) can extend beyond the physical limit of the skin. Our findings indicate that body schema can also extend to incorporate shadows cast by an individual's body parts. Thus, inaddition to their effects on visual perception[6–8], cast shadows could provide additional cues about body position in relation to objects in the world, enhancing the ability to interact with objects in real as well as virtual environments. Body shadows may thus represent a new means for investigating the relationship between dynamic coding of peripersonal space and the control of action[9,10].

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COMPETING INTERESTS STATEMENT
The authors declare that they have no competing financial interests.

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