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Reaching with a tool extends visual–tactile interactions into far space: evidence from cross-modal extinction

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Abstract

Several recent studies have shown cross-modal visual–tactile extinction in patients with right hemisphere lesions. In the present case, patient BV, a visual stimulus close to the right hand extinguished awareness of a touch on the left hand that would otherwise have been felt. Such extinction was reduced if the right visual stimulus was placed more distant from the patient's hand in the radial plane. However, when the patient held sticks in both hands, so that a far right visual stimulus was now at the end of the "tool" in his right hand, cross-modal extinction from this far stimulus increased. This effect depended on the patient holding a stick that reached to the position of the far visual stimulus; a similar large stick, but not connected with the patient's hand and laying passively on the right, had no effect. Wielding the stick induced a re-mapping of space, so that the far light became treated as near (and reachable by) the hand, thus modifying the spatial nature of cross-modal extinction. This may relate to the properties of multimodal neurons as found in the monkey intraparietal sulcus.

Keywords: Neglect; Brain lesion; Space coding; Visual; Tactile; Cross-modal; Extinction

1. Introduction

Extinction is a common sign after unilateral brain damage, especially following right-hemisphere lesions [5,22]. The patient can perceive a contralesional stimulus in isolation, yet fails to perceive the same stimulus when delivered together with an ipsilesional one. Such extinction can arise cross-modally. For example, in patients with right-hemisphere lesions, a visual stimulus near the right hand may prevent awareness of a touch on the left hand that would otherwise be felt (e.g. [4,15,16,18]). Recent studies show that such cross-modal extinction is reduced by moving the right visual stimulus away from the right hand [4,15,16], so that it no longer falls in the 'peripersonal' space [20] immediately around that hand. This may relate to multimodal neurons found in several areas of monkey cortex, responding to both vision and touch with spatially corresponding receptive fields in the two modalities [2,8–11]. For such cells, if the tactile receptive field is on one hand, the visual receptive field will fall in the peripersonal space around that hand, and indeed will shift along with postural changes of the hand [10,11]. If similar cell populations exist in humans, a visual stimulus near one hand might thereby boost the representation of that hand [6], to compete [5] with the activity produced by touch on the other hand, thus producing cross-modal extinction when the other hand has been disadvantaged by a unilateral lesion [4,15].

Here we tested whether cross-modal extinction of left touch in a right-hemisphere patient could be increased for a visual stimulus that is *far* from the right hand, when connected to that hand by a stick which the patient holds (see [19] for a related stick manipulation in normals). This situation tests whether the critical factor determining cross-modal extinction is the physical distance between a visual stimulus and the hand (as might be expected on simple 'spotlight' models; [6]), or instead whether the visual stimulus falls within the possible action-space of the hand, which is extended by

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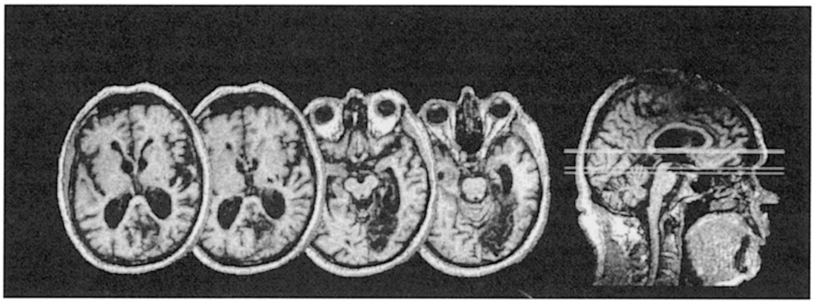

Fig. 1. MRI scan showing BV's lesion (right hemisphere is on the right). The lesion is located in the posterior aspect of the right hemisphere. It involves the calcarine area, the cuneus, fusiform, lingual, parahippocampal gyri and the pulvinar, as confirmed by coregistering the MRI data in Talairach stereotaxic space using the linear normalization functions of SPM99 (www.fil.ion.ucl.ac.uk/spm).

holding a stick [1,7]. Increased extinction when wielding the stick could be predicted on the basis of recent physiological results from multimodal neurons in the intraparietal sulcus [13].

2. Materials and methods

2.1. Patient

BV was a 67 yr-old right-handed male who suffered a right hemisphere ischaemic stroke in the territory of the posterior cerebral artery (Fig. 1).

On neurological assessment five weeks later, he showed a left homonymous hemianopia plus a mild distal motor and proprioceptive impairment for the left limbs. He also showed left neglect in daily life and formal testing (Behavioural Inattention Test [23] score was 31; cut-off is 129). On confrontation with light touch, tactile sensitivity appeared normal on both hands for unilateral stimuli, but dense left extinction was found for bilateral tactile stimulation (0/20 correctly reported left touches on bilateral trials, versus 10/10 detections on each side for unilateral trials).

Of most relevance to this paper, *cross-modal* extinction was present between vision and touch when the patient was tested by confrontation with light touch (direct manual palpation) on the dorsal aspect of the third finger of the left hand, together with brief visible movement of the examiner's finger (as if "pretending to touch") in a symmetrical position just above the right hand. Left tactile stimuli (never visually perceived by the patient, given his profound left hemianopia) were always perceived if delivered alone (10/10 correct), but missed if given together with right visual stimuli (0/20 correct responses on bilateral trials, with only the right visual stimulus being reported). Importantly, cross-modal extinction was strongly reduced (as in [4,15]) if the right visual stimulus was presented *far* from the right hand; that is, at about 40 cm above it (12/20 correct left detections on bilateral stimulation), or at the same elevation as the right hand, but 50 cm away from it in the radial plane (14/20 correct).

2.2. Experimental sessions

Two experiments were conducted, after BV's written informed consent. The first used confrontation stimuli, generated manually by the experimenter (as in the clinical testing above, plus [4,15,18]). The second used computer-generated stimuli, for more exact control of stimulus properties. Both experiments compared the amount of cross-modal extinction of left touch in the following basic conditions: (1) right visual stimulus delivered near to the right hand (expected to produce maximal extinction); (2) right visual stimulus far from the right hand in the radial plane (expected to give minimal extinction); (3) right visual stimulus equally far from the right hand, but now falling at the end of a stick actively held in that hand (expected to restore cross-modal extinction, if this depends on the 'action-space' of the hand, not just physical distance from it).

To control for the mere visible presence of a long stick on the right in the latter condition, some versions of condition (2) could also have sticks present, but with a gap to the patient's hand so that the stick no longer altered reachable space.

2.3. Experiment 1: confrontation stimuli

The patient sat with his hands on a table, 20 cm from the midsagittal plane on either side. A central fixation point was placed on the table at 65 cm distance. The examiner sat in front of the patient, monitoring central fixation and delivering the stimuli. BV was presented with tactile and visual stimuli like those in the clinical examination (see above). Tactile stimuli were always delivered to the dorsal aspect of the left third finger, while the position of right visual stimuli varied according to three blocked experimental conditions:

Near Hand condition: BV's hands rested 40 cm from his body. To avoid trivial sensory differences with the

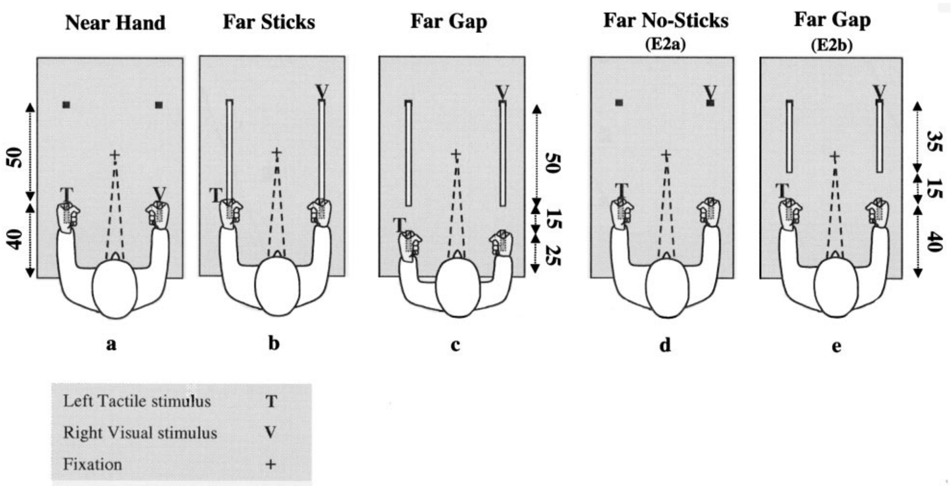

Fig. 2. Schematic drawing (bird's eye view) of the five possible blocked conditions, only some of which were used in each experiment (refer text). The patient's hands and any sticks always lay on the table top. The numbers given are distances, in centimetres, along the table top. Letters T and V represent the locus of the tactile and visual stimulation, respectively (manually delivered in the first experiment, computerised in the second). E2a = Experiment 2 session a; E2b = Experiment 2, session b.

other conditions (see below), BV was asked to hold a short stick in each hand (a section of plastic piping 7 cm in length, 3 cm in diameter, held so as to emerge by just a few millimetres from the hand). He was instructed to keep each short stick pointing towards a black 2 cm square of cardboard, placed directly in front of the hand on either side (Fig. 2a), at 50 cm distance. Right visual stimuli were delivered immediately above the right hand.

Far Sticks condition: BV kept his hands in the same positions as for the previous situation, but a 50-cm-long white plastic stick was now physically inserted into each of the short sticks, which the patient still gripped within each hand as in the previous condition. Together, the short-plus-long sticks thus formed a single extended object on each side. The patient was instructed to rest his hands on the table and orient the distal end of each composite-stick to touch the 50-cm-distant black mark already described. To reinforce the active component of this task, BV was reminded to check the position of the sticks at repeated points during the block, between trials. Right visual stimuli were now delivered just above the far end of the long right stick (i.e. at the same 50 cm distance from the right hand that substantially reduced cross-modal extinction in initial clinical screening; Fig. 2b).

Far Gap condition: BV now rested his hands closer to his body (25 cm away) and gripped the short sticks as before, again pointing each towards the far black mark on the same side. The two 50 cm long sticks now lay *passively* placed on the table, at the same absolute locations as in the previous condition (with their far ends again on the appropriate black marks), but with their near ends now separated by a 15 cm gap from each of BV's hands (Fig. 2c). The right visual stimulus was again presented at the far end of the long stick. Thus, the length of the sticks, plus the retinal eccentricity and distance of the right visual target, were kept constant, but BV's right hand was no longer physically connected to the far right visual target by the stick which he held.

Two blocks were performed for each condition, in an ABCCBA order (Near Hand, then Far Sticks, then Far Gap, then the reverse). Within each block, a total of 32 randomised stimuli were delivered; 8 unilateral left touch, 8 unilateral right vision, and 16 bilateral/bimodal. At the end of each trial, BV was asked to report which stimuli had been delivered, saying either "right vision", "left touch" or "both". Each block lasted ≈ 5 min, with a 5-min rest between blocks.

2.4. Experiment 2: computerised stimuli

Tactile stimuli were now short vibrations of 85 ms duration at 70 Hz, delivered to the left hand by a small electromagnetic vibrator. This vibrator was placed inside the near end of the 7 cm short stick, held by the patient for all conditions as in the previous experiment. Continuous white noise from a central loudspeaker masked completely the small noise produced by the vibrator. The right visual stimulus was now an 85 ms flash with a luminance of 40 cd/m^2, produced by a red turbo LED, 1 cm in diameter.

This experiment comprised the same three basic conditions as experiment 1 (E1) (i.e. Near Hand, Far Sticks, Far Gap), but with the following modifications in two successive sessions of experiment 2 (E2a vs. E2b).

E2a: This session had an additional *Far No-Sticks* condition (Fig. 2d), with the right visual stimulus at the

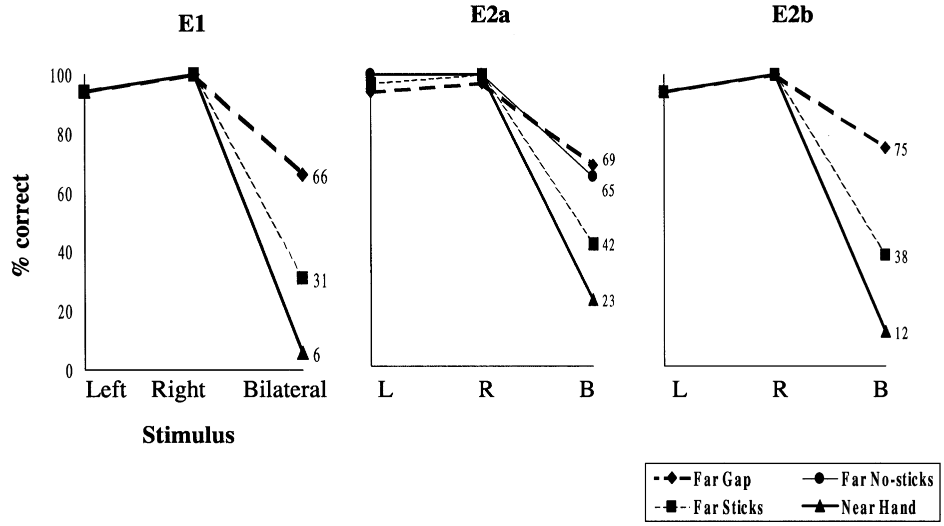

Fig. 3. Percentage of correct responses on unilateral left tactile, unilateral right visual, and bilateral–bimodal trials in Experiments 1, 2a, and 2b (E1 = Experiment 1; E2a = Experiment 2, session a; E2b = Experiment 2, session b). Errors on bilateral trials were always misses of left touches. The numbers at the right of each graph give the percent-correct score for bilateral trials in each condition.

same distance as for the Far-Stick condition, but with no long stick present. This aimed to replicate the basic effect of distance in empty space (as found in the initial clinical examination), but with computerised stimuli.

E2b: In the Far Gap condition for this session only, the patient's hands were kept at 40 cm from his body, just as in the Near Hand and Far Sticks conditions, with the gap now being introduced by replacing the 50 cm stick with a 35cm stick (Fig. 2e). This avoided any possible confound due to different distances of the patient's hands from his body, or from the visual stimulus, across conditions.

As in E1, the position of the right visual stimulus and the patient's pointing or reaching with the sticks varied according to the experimental condition. In the Near Hand condition, the right LED was fixed on the table, immediately in front of the patient's right hand, contacting the far end of the short stick held by the patient. In the other conditions, the right LED was placed 50 cm further forward on the table surface, just in front of the black mark on that side. In the Far Sticks and Far Gap conditions, the far end of the long right stick contacted this LED, either because the patient actively reached with the long stick to that position (Far Sticks) or by passive placement of the long stick on the table (Far Gap).

In E2a, eight blocks were performed, in ABCDDCBA sequence (Near Hands, then Far Sticks, Far No-Sticks, Far Gap conditions, then the reverse) with a total of 56 trials per block (16 unilateral right vision, 16 unilateral left touch and 24 bilateral/bimodal, all randomly intermingled). In E2b, the order of blocks and stimulus numbers were as for E1.

Statistical analysis of the critical extinction rates was conducted by χ^2 comparisons, on the number of correctly versus incorrectly reported left tactile stimuli for bilateral (bimodal) trials, in the different conditions.

3. Results

E1: The percentage of correct responses on unilateral and bilateral trials is shown in Fig. 3 (Leftmost graph, E1) for each condition. BV's performance for unilateral trials was virtually errorless. By contrast, performance on bilateral trials showed many errors, all taking the form of missing the left touch while reporting only the right visual stimulus. Extinction rate depended on condition. The most severe extinction was in the Near Hand condition (6% bilateral correct), followed by the Far Sticks (31%) and then the Far Gap (66%). Statistical comparison of bilateral performance in these conditions showed a highly significant difference among them ($\chi^2(2) = 48.8$; $P < 0.01$). Direct pairwise comparisons showed a significant difference between Near Hand versus Far Sticks ($\chi^2(1) = 6.5$; $P < 0.01$) and Far Gap ($\chi^2(1) = 24.5$; $P < 0.01$). Critically, Far Sticks and Far Gap also differed significantly ($\chi^2(1) = 6.8$; $P < 0.01$), with more extinction when the patient reached with a stick to the far right visual stimulus.

E2: As in E1, BV was virtually errorless for unilateral trials. Performance on bilateral trials followed the same general pattern as for E1 (Fig. 3, E2a and E2b). Moreover, in E2a, performance for the new Far-No-Stick condition was similar to Far Gap. Likewise, Far Gap yielded very similar performance across E2a and

E2b (confirming that the gap had a similar effect, whether caused by moving the hands back (Fig. 2c), or by shortening the additional stick (Fig. 2e)).

For brevity, results from common conditions in E2a and E2b were pooled in the analyses presented here, but separate analysis of these sessions shows the same pattern. The extinction rate varied by experimental condition overall ($\chi^2(3) = 33.4$; $P < 0.01$). Direct pairwise comparisons showed that all differed significantly, except for Far Gap versus Far No-Sticks ($\chi^2(1) = 0.8$; $P > 0.3$). The critical difference between Far Sticks and Far Gap was replicated ($\chi^2(1) = 15.9$; $P < 0.01$), with more extinction for Far Sticks (which likewise exceeded Far No-Sticks ($\chi^2(1) = 6.5$; $P < 0.01$). Finally, Near Hand produced more extinction than Far Sticks ($\chi^2(1) = 9.6$; $P < 0.01$).

4. Discussion

The results from both experiments show that cross-modal extinction was modulated not only by the physical distance of the right visual stimulus from the right hand (cf. [4,15,16]), but also by the patient wielding a stick in the right hand which reached to that far visual stimulus. The latter condition increased the cross-modal extinction produced by the far visual stimulus. Adding a long stick, which rested on the table without connecting the hand to the far visual stimulus (Gap conditions), produced no such increase in cross-modal extinction, as compared to the Far No Sticks condition. This suggests that the crucial determinant of cross-modal extinction was whether the right visual stimulus fell within the 'action space' of the right hand, which was extended when wielding the long stick.[1] The mere presence of a large visual object passively resting on the right side had no such effect.

The visual stimulus in E1 (finger movements by the experimenter, as in [4,15,18]) produced somewhat more cross-modal extinction than the computerised stimuli in E2, although the latter effects were still highly reliable. This may relate to the fact that moving visual stimuli approaching the body are most effective in driving cross-modal, tactile-visual neurons like those found in the monkey brain (e.g. [10,11,13]). Such neurons may play a role in tactile–visual extinction [4,15,16], as discussed earlier. Neurons in the intraparietal sulcus have a bimodal and bilateral representation of the hand, in both monkeys and humans (e.g. [14,17]), providing one possible substrate for the effects of a visual stimulus near one hand upon touch on the other hand. Our critical effect of wielding a long stick may also relate to properties of intraparietal neurons, as Iriki et al. [13] found that the visual receptive field of such multimodal neurons, with tactile receptive fields on the hand, could be extended into more distant visual space if the monkey was trained to wield a long tool.

Berti and Frassinetti [1] made a related observation in a previous neuropsychological study of visual neglect. Their right-hemisphere patient showed rightward errors in line-bisection with a laser pointer, within near but not far visual space. However, when bisecting far lines with a long stick, which brought the far lines into 'reachable' space, her neglect returned. The authors suggested that wielding the tool may have extended the patient's "body schema" [3,12], so that stimuli in extrapersonal space began to behave like those in peripersonal space. A similar account may apply to our extinction data, which further show that such remapping of space by tool-use can have *cross-modal* implications (see also [7]), which could relate directly to multimodal cell populations. Interestingly, in both our own study and that of Berti and Frassinetti [1], such remapping of space was apparent without any extensive training in use of the tool (c.f. [7]), unlike the monkey study ([13]). Indeed, humans may immediately perceive the affordance of a long stick. On the other hand, while wielding the long stick reliably increased cross-modal extinction relative to Far Gap conditions, the extinction rate was still higher in the Near Hand condition. Perhaps longer experience in tool-use is required before a tool (e.g. a prosthesis) can become exactly equivalent to a true body part, if this is possible at all.

In conclusion, the present study found that the effect of a distant visual stimulus on cross-modal extinction can be modified by its relation to a wielded stick, behaving more like a stimulus in peripersonal space (i.e. closer to the body) when connected to the body by such a tool. A far visual stimulus can thus sometimes behave like a near visual stimulus, with the critical factor apparently being its relation to potential 'action space' [1,19], rather than merely its physical distance per se. This may relate to the existence of multimodal neural circuits representing particular action-spaces [2,21].

[1] Note that wielding a tool not only extends reachable *visual* space, but also potentially *touchable* space. In the present experiments, we kept the tactile stimulation constant, focusing on the effects of particular *visual* stimuli on cross-modal extinction. We did so because visual stimuli can be directly presented in near vs. far space, in a highly controlled manner. It is less clear whether tactile stimuli could ever be truly delivered in 'far' space, given that touch is a uniquely proximal sense. Nevertheless, it would be extremely interesting to test whether a tactile stimulus delivered at the far end of a tool (e.g. as when mechanics perceive engine vibrations through a screwdriver) operates as if presented in far space (where its spatial source lies) or in near space (where it contacts tactile receptors). We are grateful to an anonymous referee for raising this.

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