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Shaping multisensory action–space with tools: evidence from patients with cross-modal extinction

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Abstract

Recent findings from neurophysiology, neuropsychology and psychology have shown that peri-personal space is represented through an integrated multisensory processing. In humans, the interaction between peri-personal space representation and action execution can be revealed through the use of tools that, by extending the reachable space, modify the strength of visual–tactile extinction. We have previously shown that the peri-hand space whereby vision and touch are integrated can be expanded, and contracted, depending upon tool-use. Here, we show that these dynamic changes critically depend upon active tool-use, as they are not found after an equally long, but passive exposure to an elongated (hand + tool) body configuration. We also show that the extent of the peri-hand space elongation, as assessed at fixed far location (60 cm from the hand), varies according to the tool length such that a 30 cm long tool produced less elongation than a 60 cm long tool. This reveals for the first time that the distal border of elongated area is not sharply limited to the tool length, but extends beyond its physical size to include a peri-tool space whereby the strength of visual–tactile integration seems to fade. Remarkably, a similar amount of peri-hand space elongation was found when the effects of using a 30 cm long tool were compared with those produced by using a tool that was physically 60 cm long, but operationally 30 cm long. By dissociating with this ‘hybrid’ tool, the amount of space that is globally added to the hand (60 cm) from the one that is actually reachable (30 cm), we provide here the first evidence that the extent of peri-hand space elongation after tool use is tightly related to the *functionally effective* length of the tool, and not merely to its absolute length.

Keywords: Multisensory; Cross-modal; Visual–tactile; Extinction; Tool use

1. Introduction

Tools enable us to modify our action–space for various purposes, facilitating our daily interactions with objects in the environment (Beck, 1980; Napier, 1956). Also, non-human primates can spontaneously use tools for diverse purposes (e.g., branch-hook-use during locomotion and leaf-pads-use during feeding) and acquire a more ‘sophisticated’ control of the environment (Bradshaw, 1997; Fox & bin’Muhamad, 2002; Johnson-Frey, 2003). Effective tool-actions require sensing polymodal properties of (a) the agent, e.g., the effector’s location and its motor properties; (b) the object, e.g. target object’s location and its material properties; (c) the mean, e.g., the shape, size and functional properties of the tool. Here, we address several questions mainly related with the latter component, by investigating the effects that distinct experiences with various types of tools can produce on the multisensory representation of peri-personal space. Indeed, the sector of space surrounding the body (Rizzolatti, Fadiga, Fogassi, & Gallese, 1997) seems to be represented in primates by multisensory systems that share several functional commonalities (Làdavas, 2002; Rizzolatti, Matelli, & Pavesi, 1983).

In monkeys, multisensory processing of peri-hand space is achieved at the single cell level, as in bimodal visuo-tactile neurons that are activated both by touches delivered within the hand somatotopic receptive field (RF) and visual stimuli presented near the same RF (Bremmer, Schlack, Duhamel, Graf, & Fink, 2001; Duhamel, Colby, & Goldberg, 1991, 1998; Graziano & Gross, 1995, 1998; Rizzolatti, Luppino, & Matelli, 1998; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981). Typically, neuronal visual responses vary as a function

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of the distance of the visual stimulus from the hand somatosensory RF, increasing when the stimulus comes closer, and decreasing at farther distances (Duhamel, Colby, & Goldberg, 1998; Fogassi et al., 1996, 1999).

In humans, multisensory activity has been identified in possibly homologous cerebral areas by functional imaging studies (Bremmer, Schlack, Shah et al., 2001; Culham & Kanwisher, 2001; Grefkes, Weiss, Zilles, & Fink, 2002; Lloyd, Shore, Spence, & Calvert, 2003; Macaluso & Driver, 2001; Macaluso, Frith, & Driver, 2000; Weiss et al., 2000; Weiss, Marshall, Zilles, & Fink, 2003).

However, compelling evidence for functional similarities in representing peri-personal space in human and non-human primates has been provided by neuropsychological studies (di Pellegrino, Làdavas, & Farnè, 1997; Làdavas, di Pellegrino, Farnè, & Zeloni, 1998; Làdavas, Zeloni, & Farnè, 1998). In some right brain-damaged (RBD) patients with cross-modal extinction on double simultaneous stimulation (Bender, 1952; Mattingley, Driver, Beschin, & Robertson, 1997; Rapp & Hendel, 2003) contralesional tactile perception can be modulated by the distance at which ipsilesional (auditory or visual) stimuli are presented from a body-part (Farnè & Làdavas, 2002; Farnè, Demattè, & Làdavas, 2003). In the case of the hand, nearby visual stimuli (∼5 cm) are more efficient than farther ones (∼35 cm) in extinguishing contralesional tactile stimuli, this spatial modulation representing a behavioural hallmark of multisensory coding for peri-hand space (see for review Làdavas, 2002).

Because of its limited extension, peri-hand space would go little beyond the hand-reachable space when the arm is fully stretched-out. However, tools can make out-of-reach objects reachable by the hands. Furthermore, kinematics of prehensile actions performed directly by the hand or through a hand-held tool are remarkably similar (Jeannerod, 1986; Jeannerod, Arbib, Rizzolatti, & Sakata, 1995; Gentilucci, Roy, & Stefanini, 2004). The merging of sensory information from different locations (somatosensory inputs from the hand and visual inputs from the tool tip) may be useful for optimal tool-manipulation of objects that are not at hand. Indeed, multidisciplinary evidence widely supports the notion that tool-use can extend the multisensory coding of near space into far space (Làdavas & Farnè, 2004a; Maravita, Spence, & Driver, 2003; Calvert, Spence, & Stein, 2004). In a seminal work, Iriki, Tanaka, and Iwamura (1996) revealed that visual RFs of monkey's parietal neurons enlarged along the axis of a rake immediately after its use for retrieving distant food pellets. After prolonged passive tool-wielding, they also documented a backward shrinking of the same visual RFs, thus showing an activity-dependent re-mapping of far visual objects as nearer ones. Functional imaging studies have shown that the cerebral areas involved in tool-use are almost coincident with those involved in multisensory integration both in monkeys (Obayashi et al., 2001, 2002, 2003) and humans (Choi et al., 2001; Inoue et al., 2001; Moll et al., 2000; Grafton, Fadiga, Arbib, & Rizzolatti, 1997; Johnson et al., 2002; Johnson & Grafton 2003; Macaluso, Driver, & Frith, 2003).

In humans, Farnè and Làdavas (2000) reported behavioural evidence of tool incorporation in the multisensory peri-hand space by investigating cross-modal extinction in a group of RBD patients. Visual stimuli, presented at the tip of a 38 cm long rake statically held in the patients' ipsilesional hand, induced more contralesional tactile extinction immediately after tool-use (retrieving distant objects with the rake for 5 min) than before tool-use. Stronger cross-modal extinction at the same far location after tool-use can be considered as evidence for the extension of peri-hand space along the tool axis. In the same study, backward contraction of the extended peri-hand space was also documented, as cross-modal extinction was reduced at pre-tool-use levels after a longer interval of tool inactivity. In a closely related single case study, Maravita, Husain, Clarke, and Driver (2001) similarly found that visuo-tactile extinction was stronger when the patient wielded the tip of a stick close to the visual stimulus than in absence of the stick, or when the stick was present but physically disconnected from the hand.

Several reports have now shown that tool-use can change space perception both in normal subjects (Riggio, Gawriszewski, & Umiltà, 1986; Maravita, Spence, Kennett, & Driver, 2002a; Yamamoto & Kitazawa, 2001), and neglect or extinction patients (Ackroyd, Riddoch, Humphreys, Nightingale, & Townsend, 2002; Berti & Frassinetti, 2000; Maravita, Clarke, Husain, & Driver, 2002; Pegna et al., 2001), thus raising several questions about the crucial determinants of peri-hand space extension. Is a passive change of the corporeal configuration (hand + tool) sufficient, or is some goal-directed activity needed? Is there a linear relationship between the length of a tool and the amount of peri-hand space extension? A crucial question concerns the specificity and the critical determinant of the extent to which peri-hand space increases. Does this depend upon the physical, absolute length of the tool, or the length of the tool that can be effectively used to act on objects? Here, we addressed such questions, within the same cross-modal paradigm, to shed further light onto the crucial determinants of tool dependent re-sizing of peri-hand space.

To answer the first question (passive/active experience), we investigated whether a relatively prolonged, passive exposure to a hand-held tool induces an elongation of the peri-hand space representation. In the light of the above cited neurophysiological and psychophysical findings (Iriki et al., 1996; Maravita, Spence et al., 2002; Maravita & Iriki, 2004), we expected that a passive increase in body size, physically extended by the hand-held tool, would not elongate peri-hand space representation along the tool axis.

Concerning the second question (tool-length/peri-hand space length relationships), we verified whether differently sized tools produce differential amounts of peri-hand space expansion. We predicted that, with respect to a fixed far location (60 cm from the hand), the use of a 30 cm long tool would extend peri-hand space to a much lesser degree, if any, than the use of a 60 cm long tool. Preliminary support to the first two hypotheses was also based on a single case study (Farnè, Bonifazi, & Làdavas, in press).

To answer the third question (absolute/operative length effects), we devised a hybrid tool that measured 60 cm of absolute length, but whose functionally effective part (the tines) was only 30 cm away from the hand (see Fig. 2c). We reasoned that, by dissociating within the same tool its physical aspect from its functional properties, it would be possible to demonstrate whether peri-hand space elongation is determined by the absolute length of a tool, or by its relative, functional length. In particular, if the key element is the operative length (i.e. 30 cm), then a comparable amount of peri-hand space extension should be found after use of the hybrid tool and a regular, 30 cm long tool (see Fig. 2b). Alternatively, if the absolute length (i.e. 60 cm) of the tool is crucial, then peri-hand space extension after hybrid tool-use should be similar to that obtained after the use of a regular 60 cm long tool (see Fig. 2a).

These hypotheses were tested in a group of RBD patients with left tactile extinction, who were examined in a series of conditions involving either passive exposure (1) or active use (2) of different types of tools.

2. Methods

2.1. Subjects

A group of eight neurological patients gave their informed consent to participate in the study, which was approved by the local ethical committee. All patients were right-handed and suffered a right unilateral lesion due to haemorrhagic or ischaemic cerebro-vascular accident, as confirmed by CT scan. Table 1 illustrates the anatomical areas involved by the lesion from seven patients, according to the method of Damasio and Damasio (1989). For one patient (P7), the scan film was not available, and the lesion site was documented on the basis of the CT scan report. He was affected by a lesion involving part of the temporal lobe, extending to the underneath white matter, as well as the basal ganglia. Demographic and clinical details are reported in Table 2.

Sensorimotor deficits were assessed through a neurological examination. Seven patients manifested hemiplegia on the left arm, while two patients (P4 and P5) presented with milder contralesional motor deficits. On clinical examination, patients were alert and well oriented in time and space. None had a history of previous head injury, left hemispheric stroke or other neurological disorder.

They were selected from a larger population of right brain-damaged patients according to the absence of obvious somatosensory loss, and the presence of tactile extinction. To verify whether both criteria were met by a patient prior to the experimental investigation, tactile stimuli were manually delivered to either hand, or to both hands simultaneously, by using a set of probe fibres (analogous to Semmes–Weinstein probes) attached to a plastic rod handled by the experimenter.

Table 1
Right hemisphere lesion details

Patient	F1	F2	F6	F8	F9	F10	T1	T3	T4	T5	T6	T7	T8	T9	T10–11	T12	P1	P2	P3	P4	P5	P6	O1	O2	O4	O5	O6	O7	BG1, 2	BG3, 4	IC	Th
P1				x	m		x	x		x	x	x	x	x	m	x	m						x	x	x	x	x	x				
P2	x	x		x		x		x	x		x	x	x	x	x	x	x	x	x		x	x	m	x	x	x	x	x				
P3																											x				x	
P4				x		x		x	x		x	x	x	x		x	x				x	x			x		x					
P5				x	x		m	x		x	x	x	x	x	m	x	x				x						x		x	x	x	x
P6			x	x		x		x	x		x	x	x	x		x	x	x			x						x			x		
P8						x			x						x			x									x					

The table reports for each patient the areas that were involved by the lesion (x) of the right hemisphere, according to Damasio and Damasio's (1989) coding system. F: frontal, T: temporal, P: parietal, O: occipital; BG: basal ganglia; IC: internal capsule; Th: thalamus. Areas that were only minimally involved are also indicated (m).

Table 2
Patients clinical and demographic details

Patient	Sex/age	Years of schooling	Months post-stroke	Visual neglect	Visual extinction	Tactile extinction
P1	M/73	5	5	–	+	+ (18 gr)
P2	F/78	5	3	+	–	+ (45 gr)
P3	M/60	2	4	–	–	+ (MS)
P4	M/56	7	3	–	+	+ (MS)
P5	M/68	13	17	–	+	+ (45 gr)
P6	F/77	5	4	+	+	+ (MS)
P7	M/41	8	4	–	+	+ (45 gr)
P8	F/80	12	1	–	+	+ (6 gr)

'Visual neglect', 'visual extinction' and 'tactile extinction' columns report whether patients were affected (+) or not (−) by these left-sided deficits, assessed as reported in the text. The type of stimulation used to assess tactile extinction is also reported in brackets, detailing either the strength of the fibre or the use of manual stimulation (MS).

To assess contralesional somatosensory perception, each patient underwent a series of stimulations aimed at establishing the probe fibre that led to a minimum of 70% correct detection of left single touches. This level of accuracy was met by all patients with different probes, providing a nearly constant indenting pressure that varied with the probe diameter (from 6 g to 45 g for the monofilament to buckle; see Table 2). Probes were not used in three patients (Table 2), for whom manual stimulation (MS) was applied.

The presence of left tactile extinction (left–right difference, ≥20%) under condition of double simultaneous stimulation of the hands was similarly assessed. To this aim, 20 unilateral left and right tactile stimuli and 20 bilateral simultaneous tactile stimuli were delivered, before experimental testing, to the dorsal surface of the second phalanx of the subject's index finger of either hand. For each patient, the same probes chosen on the basis of single contralesional performance were used to assess tactile extinction, and were also used in the experimental testing of the present investigation.

Patients also underwent a neuropsychological assessment aimed at evaluating the presence and severity of visual extinction and visual neglect. The confrontation method was used to assess visual extinction (left–right difference, ≥20%), by delivering 20 unilateral left and right and 20 bilateral visual stimuli. As can be seen in Table 2, six patients turned out to be affected by visual extinction.

Several tests were used to asses visual neglect, among which are the line (Albert, 1973), letter (Diller & Weinberg, 1977) and bell (Gauthier, Dehaut, & Joanette, 1989) cancellation tasks, and a line bisection task taken from the Behavioural Inattention Test (BIT) battery (Wilson, Cockburn, & Halligan, 1987). At the time of testing, only two patients showed signs of visual neglect in at least one of these tasks (see Table 2).

2.2. Apparatus and procedure

Patients sat in quiet room, the hands resting on a table surface, separated by approximately 40 cm. At the beginning of each trial, the experimenter checked that the subject was gazing at a red dot, aligned with the subject's body midline and marked on the table surface (∼80 cm from the patient trunk), thus preventing the patient from seeing the experimenter's gaze. For the assessment of unimodal tactile extinction, two green plastic shields (width, 18 cm; height, 18 cm; depth, 40 cm) prevented subjects from viewing tactile stimuli delivered to their hands. In all the cross-modal visual–tactile conditions, only the shield concealing the patients' right hand was removed. For each patient, tactile stimulation was silently applied by means of the previously chosen pair of synthetic monofilaments. The probes were used to deliver brief touches (<1 s) on the dorsal aspect of the second phalanx of the subject's index fingers, thus providing symmetrical stimulation to either hand.

Visual stimuli consisted of a rapid flexion–extension of the examiner's left index finger (∼5 cm of excursion) and were presented either close to the patient's right hand (∼5 cm above it) or far from the patient's right hand (60 cm away in the radial plane).

Depending on the experimental session (see below), cross-modal extinction was additionally assessed while the patient passively held one of three possible tools in the ipsilesional hand. The tools were constituted by either a long (60 cm) or a short (30 cm) wooden rake, each attached to a wooden ergonomic handle (14 cm long), which was gently grasped by the patient, with the right hand laying on the table surface. A third tool was obtained by sliding backwards the distal tines, that is the operational part of the 60 cm long rake, which were firmly attached halfway the length of the tool axis. Thus, the latter rake was a hybrid, since it was functionally equivalent to the short tool (30 cm) although, in terms of absolute length, it was similar to the long (60 cm) tool (see Fig. 2).

Four types of stimulation were delivered in each experimental condition: unilateral left or right stimulation, bilateral simultaneous stimulation or no stimulation (catch trials). For each type of stimulation, two blocks of 10 trials were presented according to a fixed pseudo-random sequence, for a total of 80 trials per condition. Patients were informed that in some occasion they would not receive any stimulus (CT), and were required to report verbally the side(s) of the stimulation by saying 'left', 'right', 'both' or 'none', irrespective of stimulus modality.

All patients were submitted to two separate sessions containing different cross-modal conditions. The first set of conditions was aimed at evaluating the effect produced by passive exposure to the tool on the amount of cross-modal extinction. The conditions of the second session aimed at evaluating the amount of cross-modal extinction induced by the use of different types of tools. In both sessions, all conditions lasted about 5 min. An interval of 5–10 min was introduced between conditions, during which the tool (when appropriate) was removed and the patient was allowed to rest and verbally interact with the experimenter. In all cross-modal conditions, tactile stimuli were delivered to the patient's left screened hand.

2.3. Passive tool exposure

To avoid possible carry-over of cross-modal effects of tool-use on passive tool exposure, this session was always run first. It was constituted by four experimental conditions, whose order was randomly determined for the first block of trials, and reversed for the second block.

A unimodal tactile condition (T–T), whereby somatosensory stimuli were delivered to either the right, left or both screened hands, served to assess the amount of left tactile extinction.

In cross-modal condition 1 (V–T near), only the left hand was screened and cross-modal extinction was evaluated by delivering ipsilesional visual stimuli near the patient's right hand (see Fig. 1a).

Cross-modal condition 2 (V–T far) was similar to the previous one, except that the visual stimulus was presented 60 cm away, on the radial plane, from the patient's right hand (Fig. 1b). This condition assessed the amount of cross-modal extinction obtained by visually stimulating the far peri-hand space without any tool involvement.

Cross-modal condition 3 (V–T far tool exposure) was similar to the previous one, except that the empty space between the patient's hand and the far visual stimulus was now "filled" by a long rake (60 cm), which was passively held in the patient's right hand, as above described. Compared to condition 2, the visual stimulus was equally far from the patient's hand (60 cm), but was now presented at the distal edge of the rake, without touching it (Fig. 1c). Noteworthy, visual–tactile extinction in this condition was assessed immediately after a 5 min period during which the patient was exposed to the passive visual/somatosensory experience of having a long tool in her/his own hand. During the period of tool exposure, the patient was asked to look at the tool without moving it, and the experimenter verified the absence of hand movements.

2.4. Using tools with different functional length

In this session, which was run second, the visual stimulus was always presented in the far location, i.e. 60 cm away in the radial plane from the patients' right hand (see Fig. 2). It was constituted by three experimental conditions that were presented in a random order for the first block of trials, and in the reversed order for the second block.

Cross-modal condition 4 (V–T long tool use) was similar to condition 3, with the exception that cross-modal extinction was assessed after a 5 min period during which the patient was engaged in an active task involving the use of the hand-held rake to retrieve distant objects, located out of the hand-reaching space (Fig. 2a). Objects were constituted by plastic disks (3 cm diameter, 1 cm thick) presented one at a time in a working area (see the grey shaded area in Fig. 2) that was located out of the hand-reaching space. Patients were asked to reach and retrieve each object with the rake. The disks were randomly presented in correspondence with patients' midsagittal axis, or 10° and 20° to the left and to the right of the central position. After 50 retrieval movements, lasting about 5 min, cross-modal extinction was reassessed as in condition 3 (compare Fig. 1c and Fig. 2a), while the patient was passively holding the rake.

Cross-modal condition 5 (V–T short tool use) was similar to condition 4, but the patient passively held the short (30 cm) rake in his right hand (see Fig. 2b). The visual stimulus was located at the same far position (60 cm away from the patient's hand), and visuo-tactile extinction was evaluated after 50 movements, lasting about 5 min, aimed at retrieving less distant objects with the short rake from the working area.

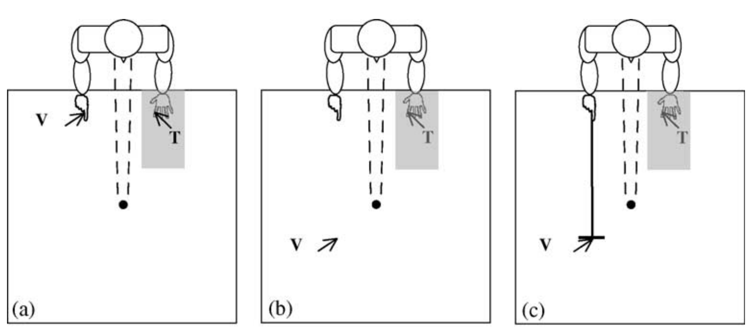

Fig. 1. Schematic illustration of the experimental setting for assessing visual–tactile extinction as a function of the cross-modal conditions, viewed from above. The visual stimulus (V) could be located near (a) or far (b and c) from the patient's right hand. Tactile (T) stimuli were delivered to the patients' left hand screened from view (grey rectangle). Note that the visual stimulus was presented at the same distant position (60 cm from the hand) in both the far condition (b) without any tool and (c) after passive visual/proprioceptive exposure to the 60 cm long tool.

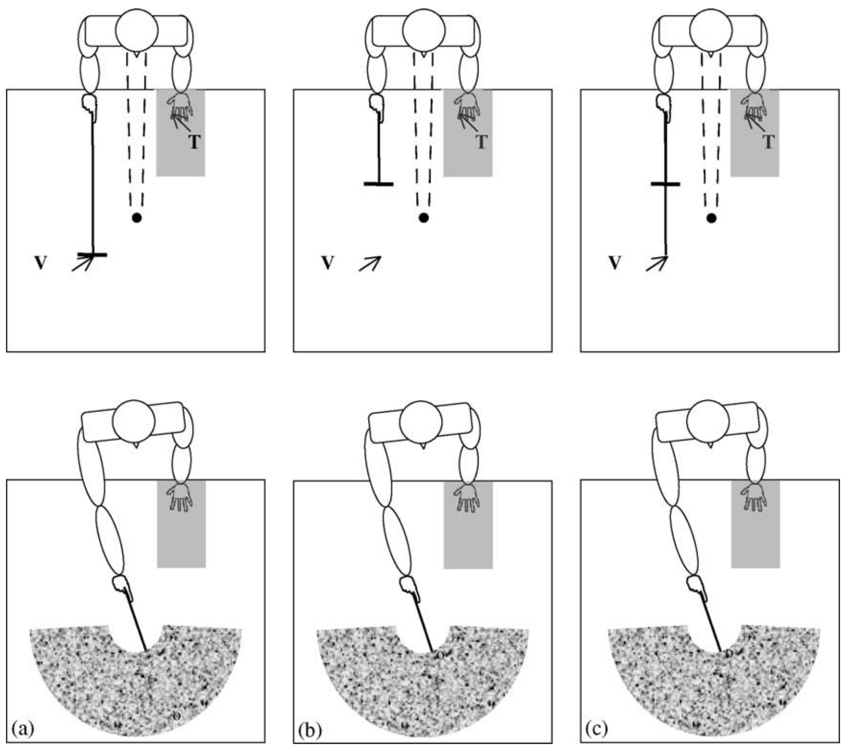

Fig. 2. Schematic illustration of the experimental setting for assessing visual–tactile extinction (upper row) after different types of tool-use (lower row), as a function of the cross-modal conditions (viewed from above). *Upper row*: The visual stimulus (V) was presented far from the patient's right hand. Tactile (T) stimuli were delivered to the patients' left hand screened from view (grey rectangle). Note that the visual stimulus was presented at the same distant position (60 cm from the hand) in all conditions: (a) after long tool use (60 cm), (b) after short tool use (30 cm) and (c) after hybrid tool use. *Lower row*: Retrieving movements were executed by the subjects to retrieve objects (black open circle), located one at a time in a work area (grey shaded sector), by using (a) the 60 cm long tool, (b) the 30 cm long tool and (c) the hybrid tool (absolute length, 60 cm; operative length, 30 cm).

Cross-modal condition 6 (V–T hybrid tool use) was similar to condition 5, but the patient passively held the hybrid tool, that is the operationally short (30 cm) rake that was visually long (see Fig. 2c). The visual stimulus was always located at the same far position (60 cm away from the patient's hand), and visual–tactile extinction was similarly evaluated after 50 movements, lasting about 5 min, aimed at retrieving similarly distant objects from the work-area by actively using the hybrid rake.

3. Results

All the patients performed very well on catch trials, almost never producing false alarms (none exceeded two false alarms per session). They performed the task flawlessly when considering single tactile or visual stimuli presented in the right hemispace. To verify the presence and the severity of unimodal tactile extinction, the mean accuracy in detecting touches on the left hand, as a function of unilateral and bilateral tactile stimulation, was computed in percentage for all patients. A one-way ANOVA with stimulation (unilateral, bilateral) as within-subject factor [$F(1, 7) = 163.53$, $P < 0.0001$] showed that patients were very accurate in reporting touches singly delivered to the left hand (97% detection), thus confirming a quite preserved somatosensory sensitivity; however, they reported only a minority (24% detection) of left touches under double simultaneous stimulation, showing to be severely affected by left tactile extinction.

To assess patients' performance in visuo-tactile conditions, the mean percentage of accuracy in reporting touches of the left hand as a function of single and double stimulation was computed. To ascertain patients' consistency in detecting touches singly delivered to the left hand across the different cross-modal conditions, two one-way ANOVAs were performed with the mean accuracy obtained in left unilateral trials as within-subject factor (single left accuracy in the three cross-modal conditions of each session). Since the analyses revealed no significant difference in patients' tactile sensitivity across conditions, a mean accuracy score (AS) was calculated for each patient, expressing the proportion of correct responses in bilateral compared to left unilateral trials per condition. This AS was then submitted to further ANOVAs according to the experimental session, which will be reported separately below.

3.1. Passive tool exposure

As can be seen in Fig. 3, besides showing unimodal tactile extinction, all the patients also showed cross-modal

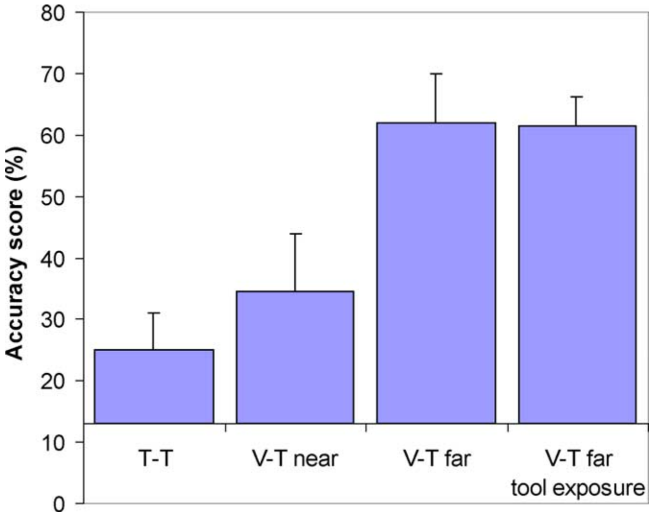

Fig. 3. Mean accuracy score of left contralesional tactile detection (in percentage) for the bilateral tactile condition (T–T) and the bilateral visual–tactile conditions (V–T). From left to right, subjects' performance is reported for conditions whereby visual stimuli were presented close (V–T near) or far (V–T far) from the patient's right hand, and at the same far position after passive exposure to the long tool (V–T far tool exposure). Bars represent standard error of mean.

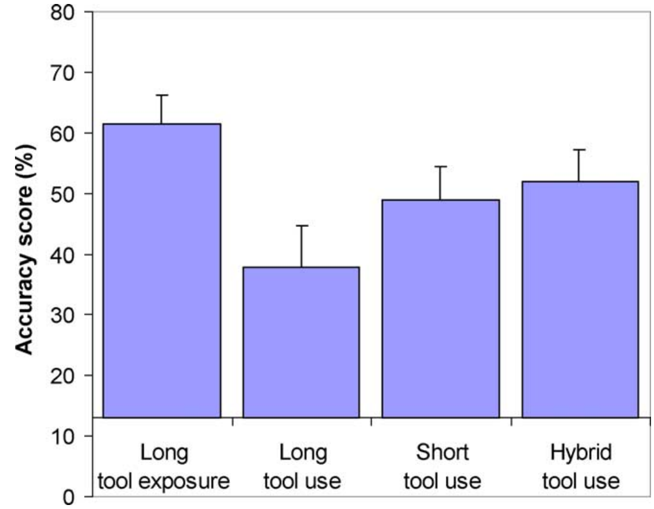

Fig. 4. Mean accuracy score of left contralesional tactile detection (as a percentage) for the bilateral visual–tactile conditions (V–T). From left to right, subjects' performance is reported for conditions whereby visual stimuli were presented at the same far location from the patient's right hand after different tool-related experiences: Long tool (passive) exposure, long tool use, short tool use and hybrid tool use. Bars represent standard error of mean.

visual–tactile extinction. A one-way ANOVA with stimulation (T–T, V–T near, V–T far, V–T far tool exposure) as within-subject factor was highly significant [$F(3, 21) = 13.24$, $P < 0.0001$], Newman–Keuls post-hoc test revealing that patients' unimodal (T–T) and cross-modal (V–T near) extinction were comparably severe (25% and 35% AS, respectively, n.s.).

Left tactile detection under bilateral cross-modal stimulation was significantly modulated by the distance at which visual stimuli were presented from the patient's right hand. Patients were less accurate when presented with visual stimuli close to the ipsilesional hand (∼5 cm above the patient's right hand, 35% AS) than far (60 cm) from the same hand (62% AS, $P < 0.003$).

Crucially, to test whether passively holding a tool modified patients' accuracy, cross-modal extinction obtained in the latter condition (V–T far) was compared to that obtained after 5 min of long tool-exposure (V–T far tool-exposure). As shown in Fig. 3, no significant change was observed between these conditions, patients' accuracy showing a comparable amount of extinction when the tool was absent (62% AS), or present after passive exposure (62% AS, n.s.).

3.2. *Using tools with different functional length*

To verify whether and to what extent the use of the different types of tools influenced patients' performance, the accuracy score was submitted to a one-way ANOVA with V–T far stimulation (long tool exposure, long tool use, short tool use, hybrid tool use) as within-subject factor. As illustrated in Fig. 4, the highly significant ANOVA [$F(3, 21) = 8.15$, $P < 0.001$], further explored with Newman–Keuls post-hoc test, showed that cross-modal extinction obtained after active use of the long tool (38% AS) was significantly more severe than that obtained after the passive exposure to the same tool (62% AS, $P < 0.001$).

Similarly, cross-modal extinction obtained after active use of the short tool (49% AS) was more severe than that obtained after passive tool exposure (62% AS, $P < 0.04$). Compared to the patients' performance after passive tool exposure (62% AS), a similar, marginally significant worsening of the accuracy was also present after active use of the hybrid tool (52% AS, $P = 0.059$). Interestingly, Fig. 4 clearly shows that the amount of cross-modal extinction induced after the use of the short tool and after use of the operationally short/physically long tool was absolutely comparable (49% and 52% AS, respectively, n.s.). Remarkably, the worst cross-modal performance at the far location was obtained after active use of the long tool (38% AS), as compared both to the use of the short tool (49% AS, $P < 0.03$), and the hybrid tool (52% AS, $P < 0.02$).

An additional comparison interestingly showed that the severity of visuo-tactile extinction observed after active long tool use (38% correct) was comparable to that shown by patients when the visual stimulus was presented close to their right hand (35% AS, n.s.).

4. Discussion

Three main findings were obtained by the present study. First, cross-modal extinction, as assessed 60 cm far from the patient's ipsilesional hand, did not increase after a 5 min period of passive exposure to a 60 cm long tool. Instead, cross-modal extinction assessed at an equally far distance increased after an equally long period of use of an equally long tool. Second, a differential amount of cross-modal extinction was induced, at the same 60 cm far location, by using tools that differed in length, shorter tools (30 cm) producing weaker effects than a longer one (60 cm). Although of reduced strength, a significant increase of cross-modal extinction was obtained at the same 60 cm far location even after use of a 30 cm long tool. Third, the amount of cross-modal extinction obtained after the hybrid tool-use was not compatible with that induced by a 60 cm long tool, but with that induced by a 30 cm long tool, i.e. the distance at which the operative part of the hybrid tool was located with respect to the hand. These findings and their implications will be discussed below.

When considering the first issue addressed by the present study, i.e. the role played by passive or active experience, the results were clear in showing that a relatively prolonged, but passive exposure to a visual/proprioceptive change in the spatial characteristics of the patients' body, failed to elongate the peri-hand space. Indeed, the amount of visual–tactile extinction obtained in the far location, after a short period while the patients passively experienced the wielding of a rake, did not change compared to that observed when there was no rake at all (Fig. 3). This finding implies that the phenomenon of tool incorporation into the multisensory peri-hand space cannot be solely based on passive perceptual assimilation of a new corporeal configuration (i.e. the bigger hand + tool 'arm'). On the contrary, an artificial extension of the reachable space, made possible by a hand-held tool, would not necessarily modify the 'body schema' (Head & Holmes, 1911–1912) in an effective way. Here, we refer to the original definition of body-schema, as a non-conscious aspect of the body that actively experiences and integrates its environment, and can be distinguished by the body-image by several operational criteria (Gallagher, 1986; Bermudez, Marcel, & Eilan, 1995).

In sharp contrast, a change in body-schema was found after tool-*use*. Immediately after the use of the same 60 cm long tool to retrieve distant objects, cross-modal extinction significantly increased compared to the situation of passive exposure reported above. In agreement with previous findings (Farnè & Làdavas, 2000), this result confirms that the peri-hand area, whereby visual–tactile information is processed by multisensory mechanisms, can expand along the tool axis towards the distal edge of the rake. This finding is also consistent with the activity of 'distal type' neurons previously reported (Iriki et al., 1996), whose visual receptive fields specifically extended along the axis of the tool used by the monkey. Whether the rate of cross-modal extinction would linearly vary with the distance from the body remains to be clarified by future studies.

Noteworthy, the present study compared cross-modal effects after an equally long period of active and passive tool experience, thus being particularly well suited to assess the relative role played by each experience in determining peri-hand space elongation. The fact that active tool use is necessary for modifying peri-hand space is prima facie at variance with a previous single case study (Maravita et al., 2001, 2003) whereby 'passive' experience with a stick increased cross-modal extinction. In fact, since the task required to actively wield and orient the stick to keep its distal end in contact within a restricted region of the far space, the inconsistency is only apparent (see also Maravita, Clarke et al., 2002). Therefore, the results of the present study converge with those reported in normal subjects (Maravita, Spence et al., 2002) and show that the key element leading to tool embodiment in the peri-hand space depends upon active processes, which may play a role also in the embodiment of other objects that are closely related to the corporeal experience, such as rings. Aglioti, Smania, Manfredi, and Berlucchi (1996) have previously shown that the body schema can be profoundly modified to include such paraphernalia, most likely because rings would participate to the multisensory experience of hand-related daily activities, physically interacting with objects during grasping and manipulative movements, and not just by modifying the visual/proprioceptive information concerning the bodily aspect.

Concerning our second question, i.e. the relationships between tool-length and amount of peri-hand space extension, we found that peri-hand space extension varied with tool length, without being strictly coincident with it. As expected, cross-modal extinction was stronger immediately after the use of a 60 cm long tool than the use of a 30 cm long tool (Fig. 4). It is important to remind that the less robust effect produced by the shorter (30 cm) tool was observed at the (60 cm) far location in space, that is well beyond its distal edge. However, the amount of cross-modal extinction obtained at this far location after the use of the *shorter* (30 cm) tool was still significantly larger compared to that obtained after the passive tool exposure (see Fig. 4). Therefore, although weaker, a significant amount of peri-hand space extension towards the (60 cm) far location was also obtained after short tool use. In addition, although marginally significant, a similar worsening of the patients' performance was observed after the 'hybrid' tool-use, which was operationally 30 cm long.

These results have two major implications. First, they show that the multisensory peri-hand area can be extended differentially by using tools of different length. Second, and most important, the present findings show for the first time that the peri-hand space extension produced by tool-use is not coincident with the length of the tool, but includes space located *beyond* the distal edge of the tool, although with a reduced integrative strength. In the light of these findings, we suggest that the external border of elongated area is not sharply limited to the tool tip, but extends (fading) beyond it. In this respect, it should actually be expected that, just as for the hand, the peri-personal space of a tool, once embodied, would go (a little) beyond its physical length.

As a third question, we asked whether the absolute or the operative length of the tool would be crucial in extending peri-hand space. In this respect, we found that the differential amount of cross-modal extinction obtained with different tools was not determined by the absolute length of the tool, but by its operative length. Indeed, the degree of cross-modal extinction observed at the same far location after the use of the hybrid tool was significantly less severe than that found after the use of the 60 cm long tool (see Fig. 4). Conversely, comparable cross-modal effects were induced after use of a regular 30 cm long tool and the hybrid tool, whose absolute length was the same of the 60 cm long tool, but whose functional length was the same of the 30 cm long tool. Since a comparable directional motor activity was performed with the rakes, the crucial difference between the 60 cm long tool and the hybrid tool was the location of the functional part of the rake (the tines). Therefore, these results constitute the first evidence that peri-hand space elongation is directly related to the *functionally effective* length of the tool, i.e. by the distance at which the operative part of the tool was located with respect to the hand.

As we reasoned elsewhere (Farnè & Làdavas, 2000; Làdavas & Farnè, 2004b), the main advantage provided by the expansion of the peri-hand area, whereby vision and touch are integrated, could be that of bringing multisensory processing where the goal of the action is. This might have some beneficial effects by allowing to manipulate far objects as nearer ones. However, the location of the action goal can markedly vary, such that tools of different shape and size are necessary to achieve it. The fact that a variable degree of peri-hand space expansion can be temporary 'locked' onto the functionally relevant segment of a tool, as we demonstrated here, might help achieving a tool-mediated goal-oriented action. In this context, classical psychological studies have shown how the cognitive label of the function of man-made tools may determine the way in which they tend to be used, a phenomenon called functional fixedness (Duncker, 1945; Glucksberg & Weisberg, 1966). While this type of mental set may prevent us from using objects for novel functions, here we show that a much lower level phenomenon, such as the elongation of peri-hand space, is critically dependent upon the operational aspect of a tool and can be dissociated from its global physical appearance.

Overall, these findings considerably extend our knowledge about the way in which tool-use can contribute to the construction of a cross-modal space representation and to its plastic modification. Most notably, the present findings are consistent with neurophysiological studies showing that the effects on visual RFs of monkeys' parietal neurons can be found immediately after tool use, but not passive tool wielding. In the cases reported in animals, tool-use usually involved rake-shaped tools and the associated retrieving actions (Iriki et al., 1996; Obayashi, Tanaka, & Iriki, 2000; Obayashi et al., 2001; Hihara, Obayashi, Tanaka, & Iriki, 2003). In humans, several effects of tool-use have been reported in normal subjects, and neglect patients (Ackroyd et al., 2002; Berti & Frassinetti, 2000; Pegna et al., 2001). In the latter case, neglect behaviour was altered while patients actively used sticks or rulers for bisecting lines or locating objects in space.

The fact that different actions like stick-pointing, stick-bisecting and rake-retrieving are all able to widen the peripersonal space is most probably related to the common aspect of 'acting in far space' allowed by the functional properties of these tools. A rake allows us to reach and grasp out-of-reach objects, whereas a stick enables us to accurately indicate far positions in space, in a much more efficient way than the deictic pointing of a finger (Bates & Dick, 2002; Kita, 2003). This raises the interesting question, to be investigated in future studies, of whether the appropriate action for a given tool is necessary to achieve such a widening. This might be potentially related to the present finding that peri-hand space expansion is not limited to the tool-tip. Indeed, the act of retrieving objects with a rake requires that the distal tines are brought beyond the target object, whereas this is not necessary in stick-pointing actions. It is also possible that the elongation of the multisensory area surrounding the hand is influenced by the complexity of the action required by a tool, and the incorporation of different types of tools or paraphernalia might require differential amount of practice. In support to this view is the fact that some tool-related actions affect space processing in an immediate, on-line fashion (Berti & Frassinetti, 2000; Pegna et al., 2001; Ackroyd et al., 2002; Maravita et al., 2001; Riggio et al., 1986; Yamamoto & Kitazawa, 2001), whereas others can be seen as off-line after-effects of tool-use (Farnè & Làdavas, 2000; Maravita, Clarke et al., 2002; present study) that can require relatively intense tool-training to become manifest (see Maravita, Spence et al., 2002).

From an evolutionary perspective, the ability to tune the multisensory processing of action–space according to the physical structure, the affordances and the relative size of tools might represent a clear advantage, which can potentially be linked to the emergency of some of the higher level cognitive abilities that are 'distinctively' human, such as language (Hihara, Yamada, Iriki, & Okanoya, 2003; Johnson-Frey, 2003; Johnson & Grafton 2003; Bradshaw, 1997). In this respect, the effort of grounding aspects of the linguistic encoding of space in properties of the visual system is of particular interest. As pointed out by Kemmerer (1999), although several languages have two basic types of demonstrative terms (proximal and distal), language allows to specify a virtually unlimited range of spatial distances. By bridging proximal and distal space, tool-use might represent the sensorimotor counterpart of those communicative features that allow us to modulate near and far space along a continuum in language, which probably rely on different neural circuits (Tranel & Kemmerer, in press).

To conclude, here we showed new critical features of tool-use that modify action–space representation through multisensori-motor transformations, underlying that is the '. . . brain who questions and shape the environment, lives in it, and little by little, controls it' (Jeannerod, 1983).

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