INTRODUCTION

In the last decade, the physiological and behavioural study of multisensory integration processes and their neural bases has seen an exponential growth (Spence and Driver, 2004; Calvert et al., 2004). Since Iriki et al.’s (1996) seminal paper, this growth also propelled several investigations of the physiological and behavioural effects exerted by the use of tools upon the multisensory coding of near personal space (Làdavas, 2002; Maravita and Iriki, 2004). Iriki et al. (1996) reported that visual receptive fields (RF) of monkey’s parietal visual-tactile neurons enlarged along the axis of a rake soon after its use for retrieving distant food pellets. The same visual RFs shrunk backwards following passive tool-wielding, recorded immediately after tool-use, thus showing a tool-use-dependent extension of the visual-tactile peri-hand space (Farnè and Làdavas, 2000). The re-sizing of peri-hand space seems to be selective for tool-use, as directional motor activity alone (i.e., pointing without the tool) and visual/proprrioceptive experience alone (protracted passive exposure to the tool) does not vary the extent of the visual-tactile peri-hand space (Farnè et al., 2005a). Moreover, the amount of dynamic re-sizing varies with the length of the used tool, and is specifically centred on the functionally relevant part of the tool (Farnè et al., 2005b). Here, besides reviewing and discussing these results, we report new evidence, based on a single-case study, supporting the idea that dynamic re-sizing of peri-hand space consists of a real spatial extension of the visual-tactile integrative area along the tool axis.

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DYNAMIC SIZE-CHANGE OF PERI-HAND SPACE FOLLOWING TOOL-USE: DETERMINANTS AND SPATIAL CHARACTERISTICS REVEALED THROUGH CROSS-MODAL EXTINCTION

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ABSTRACT

In human and non human primates, evidence has been reported supporting the idea that near peripersonal space is represented through integrated multisensory processing. In humans, the interaction between near peripersonal space representation and action execution can be revealed in brain damaged patients through the use of tools that, by extending the reachable space, modify the strength of visual-tactile extinction, thus showing that tool-mediated actions modify the multisensory coding of near personal space. For example, following the use of a rake to retrieve distant, otherwise non reachable objects, the peri-hand multisensory area has been documented to extend to include the distal part of a rake (Farnè and Làdavas, 2000). The re-sizing of peri-hand space seems to be selective for tool-use, as directional motor activity alone (i.e., pointing without the tool) and visual/proprrioceptive experience alone (protracted passive exposure to the tool) does not vary the extent of the visual-tactile peri-hand space (Farnè et al., 2005a). Moreover, the amount of dynamic re-sizing varies with the length of the used tool, and is specifically centred on the functionally relevant part of the tool (Farnè et al., 2005b). Here, besides reviewing and discussing these results, we report new evidence, based on a single-case study, supporting the idea that dynamic re-sizing of peri-hand space consists of a real spatial extension of the visual-tactile integrative area along the tool axis.

Key words: multisensory, space, tool-use, extinction, body schema
peri-hand area within which visual-tactile integration occurs. For example, adapting to humans the task originally introduced for monkeys (Iriki et al., 1996), we showed that the weak visual-tactile integration usually observed far from the subject’s hand can be significantly increased, at the same far location, following tool-use (Farnè and Lädavas, 2000). By investigating left cross-modal extinction in right brain-damaged (RBD) patients, we found that ipsilesional visual stimuli presented at the distal edge of a 38 cm long rake induced more left tactile extinction immediately after tool-use (retrieving far objects with the rake for 5 minutes) than before tool-use. Moreover, when tool-use was impeded, the severity of cross-modal extinction decreased to pre-tool-use levels. Thus, stronger cross-modal extinction after tool-use, as measured at the same location far from the hand, has been taken as evidence for an extension of peri-hand space along the tool axis, whereas its reduction following tool-inactivity has been considered as the behavioural counterpart of backward contraction of the formerly extended peri-hand space (Farnè and Lädavas, 2000). In a similar vein, Maravita et al. (2001) also found stronger visual-tactile extinction at the tip of a stick wielded by a patient, as compared to when the stick was absent, or present but not connected to the patient’s hand. Further evidence of tool-related far/near space re-mapping has been documented in neglect patients (Ackroyd et al., 2002; Berti and Frassinetti, 2000; Maravita et al., 2002b; but see, Pegna et al., 2001; Humphreys et al., 2004). Convergent evidence comes from healthy participants investigated in tasks involving the displacement and/or crossing of hand-held “tools” (Riggio et al., 1986; Yamamoto and Kitazawa, 2001). Maravita et al. (2002a), for example, have shown that significant changes in the spatial distribution of cross-modal effects may emerge when subjects repeatedly cross-over two hand-held tools, and that the phenomenon develops with increased practice in crossing the tools.

By assessing visual-tactile extinction in RBD patients, we also investigated the crucial determinants of peri-hand space extension. In a single-case study (Farnè et al., 2005a) we verified the role played by passive versus active experience with tools in re-sizing peri-hand space. In particular, we investigated whether a prolonged passive experience with a rake (60 cm long) was sufficient to elongate the peri-hand space, or whether active tool-use was necessary. The results showed that the severity of visual-tactile extinction, as assessed at the distal edge of the tool (60 cm away from the patient’s hand) after a prolonged passive exposure to the proprioceptive and visual experience of wielding a rake, did not differ from that obtained when the tool was absent. In contrast, cross-modal extinction was significantly increased when assessed equally far in space, but following an equally long period of active use of the same tool. Therefore, in agreement with both neurophysiological and neuropsychological findings (Iriki et al., 1996; Maravita et al., 2002a, 2002b) these results suggested that plastic modifications of the body schema (Head and Holmes, 1911) require the tool to be actively involved in a task.

In a recent group study (Farnè et al., 2005b) we investigated the relationships between the physical and functional properties of an active tool-use and the spatial extent of the subsequent peri-hand space elongation. In particular, by assessing visual-tactile extinction far from the patients’ hand (60 cm) after use of a 60, or 30 cm long rake, we found that peri-hand space elongation varied according to the tool length. When assessed at the same 60 cm far location, cross-modal extinction was stronger after use of a long tool (60 cm) as compared to the use of a short tool (30 cm). Remarkably, even the use of the short tool (30 cm) produced a significant increase of cross-modal extinction at the same far location (60 cm), although weaker than that induced by the use of the long tool (60 cm). This indicates that the elongated area is not sharply limited to the tool tip, but extends beyond it including a peri-tool space whereby visual-tactile integration fades. In the same study we also showed that the extent of tool embodiment tightly depends upon the functional, not the physical, length of the used tool, when these were dissociated through a hybrid rake that was physically long (60 cm), but operationally short (30 cm). Indeed, the severity of cross-modal extinction observed at the same far location (60 cm) after the use of the hybrid tool was significantly less severe than that found after the use of the 60 cm long tool. In contrast, comparable cross-modal extinction was observed after use of the short tool (30 cm) and the hybrid tool, whose absolute length was the same as the 60 cm long tool, but whose functional length was the same of the 30 cm long tool. As the two rakes were identical, except for the spatial location of the tines, and required similar motor activity, the findings showed that the functionally effective length of the tool is the crucial determinant of the spatial extension of peri-hand space (Farnè et al., 2005b).

But is this a real elongation of the visual-tactile integrative area along the tool axis? The question concerning the shape of the peri-hand space representation and its tool-related plastic changes (Lädavas et al., 1998b; Farnè et al., 2005a) has been recently addressed by Holmes et al. (2004) in normal subjects by investigating visual-tactile congruency effects in three positions along a tool (handle, middle, tip). In this context, though, the nature of the cross-modal task was quite different from the typical confrontation method used to assess extinction in brain damaged patients, as it was the task to be performed with the tools. In particular, cross-modal congruency refers to a behavioural paradigm of visual-tactile interference
(Spence et al., 1998, 2004) that measures the subjects' ability in discriminating the spatial location of a tactile stimulus on his/her body (e.g., thumb vs. index finger) in the presence of visual distractors that can be spatially congruent or incongruent with the tactile target location on the skin. Despite the fact that visual distractors are totally irrelevant for the tactile discrimination task, the incongruent visual-tactile mapping (e.g., a light aligned with the index with simultaneous tactile stimulation of the thumb) produces an interference, as compared to the congruent mapping, worsening the subjects' performance. Holmes et al. (2004) asked subjects to perform this cross-modal congruency task interleaved between series of “tool use” trials (p. 64). Tool-use consisted in having the subjects to use the tip, the shaft, or the handle of one of the two hand-held tools to push a button located at different distances form the subject’s body. They found that, when the task involved the use of the shaft (or the tip) of the tool, visual-tactile interaction were stronger at the tips of the tools than in the middle of the shaft. They suggested their findings were more compatible with selective incorporation of the tool-tip, rather than with peri-hand space elongation encompassing the whole tool. Besides the obvious differences, which may surely be responsible for the different results, Holmes et al.’s (2004) findings may appear at variance with neurophysiological evidence showing that, after tool-use, visual RFs of bimodal parietal neurons actually enlarge along the tool axis, or extend to the whole space that can be reached by the tool (Iriki et al., 1996).

To shed light on this issue, we assessed cross-modal visual-tactile extinction in a RBD patient while she was wielding a 60 cm long rake, before and immediately after its use to retrieve distant objects. At variance with previous patients studies, visual-tactile extinction was assessed near the ipsilesional hand (holding the rake handle), near the distal edge of the rake, as well as in a middle position between the hand and the distal end of the rake. In the light of the previously reported neurophysiological findings, we expected that tool-use would increase cross-modal extinction both at the distal and middle positions, whereas no change was expected near the patient’s hand.

**METHODS**

**Case Report**

The patient (T.R.) is a 72-year-old right-handed woman (5 years of education) who suffered a haemorrhagic stroke in the right hemisphere 3 months before the test. She gave her informed consent to participate in the study, whose experimental procedures were approved by the local ethics committee. The investigation was carried out according to the Declaration of Helsinki. At the time of the investigation she did not present left hemiparesis, on neurological examination. A computed tomography (CT) scan revealed that the lesion involved the inferior and superior parietal lobules (BA 39, 40, 5, 7), the paraventricular parieto-occipital area, the posterior part of the middle temporal gyrus (BA 37) and the auditory area (BA 22; see Figure 1). She was alert, well oriented in time and space and very collaborative. Signs of moderate left visuospatial neglect were present when she was submitted to the Behavioural Inattention Test (BIT) battery (Wilson et al., 1987), whereas personal neglect was absent (Cocchini et al., 2001).

She was enrolled in the present study because of her severe tactile extinction. When light touches (20 trials for left and right single stimulation and 20 trials for double simultaneous stimulations) were manually delivered (through Semmes-Weinstein-like monofilaments) to the dorsal surface of the second phalanx of her index fingers she reported correctly all left unilateral stimuli (100% of accuracy), as well as all the ipsilesional single visual stimuli (100% correct), but reported only a minority of left touches presented concurrently with proximal visual stimulation (30% of accuracy).
Cross-modal extinction was also assessed by presenting ipsilesional visual stimuli further away (~35 cm) from the visible right hand, in two locations (see Figure 2), one on the vertical and the other in the para-sagittal plane. The same number of trials as before was used to assess cross-modal extinction in both far positions (20 trials for left and right single stimulation and 20 trials for double simultaneous stimulations). Again, her performance in reporting single touches of the left hand was errorless (100% accuracy). In addition, under simultaneous visual-tactile stimulation, cross-modal extinction was much weaker as compared to stimulation near the hand, as she was able to report 75% of left touches, both in the vertical and para-sagittal plane (~35 cm). Therefore, the distance-dependent modulation of left tactile detection under cross-modal stimulation induced a change in performance corresponding to 45% of accuracy.

**Apparatus and Procedure**

For the experimental investigation, the patient had to fixate a red dot, aligned with her sagittal axis and located on the table surface (45 cm from the proximal border of the table) while passively keeping her hands on the table surface (separated by 45 cm).

At the beginning of each trial, the experimenter checked that the subject was keeping fixation. A green plastic shield (width 18 cm, height 18 cm, depth 40 cm) was used to prevent vision of tactile stimulation delivered to the left hand. Tactile stimulation was silently applied by means of a pair of synthetic monofilaments, analogous to Semmes-Weinstein probes, which provide near identical indenting stimulation across trials and conditions (see, for details, Farnè et al., 2003). Visual stimuli consisted of a rapid flexion-extension of the examiner’s left index finger (~5 cm of excursion). The efficacy of this clinical approach to visual-tactile stimulation paradigms has been confirmed by studies from other laboratories that, by employing computer-controlled stimuli, found very similar results in both patients and neurologically intact subjects (Maravita et al., 2001; Kitagawa and Spence, 2005).

Both before and after tool-use (see below), cross-modal extinction was assessed as follows (see Figure 3). The patient wielded the wooden ergonomic handle (14 cm long) of a wooden rake (60 cm long) that was oriented along the para-sagittal plane and whose distal tines were laying on the table surface (total tool length = 74 cm). The handle was gently grasped by the patient, with the right hand passively laying on the table surface. While passively grasping the tool, the most distal part of the patient’s right hand was located near the distal border of the handle (~2 cm). Three different locations along the tool axis, called hereinafter near (N), middle (M) and far (F) were probed for assessing visual-tactile extinction. In separate blocks of trials, presented in a prefixed pseudo-random order, visual stimuli could be presented immediately above (~5 cm) the patient’s right hand holding the tool (N), or immediately above (~5 cm) the middle location (M) along the tool shaft (i.e., ~32 cm from the patient’s hand), or immediately above (~5 cm) the distal edge (F) of the tool (i.e., ~62 cm from the patient’s hand). In each block, four types of stimulation were delivered: unilateral left or right stimulation, bilateral simultaneous stimulation, or no stimulation at all (catch trials – CT). The patient was instructed to verbally indicate the side of the stimulation by saying “left”, “right”, “both”, or “none”, independent of stimulus modality. She was informed that in some occasion she would not receive any stimulus (catch trials). For each type of stimulation, 10 trials were presented according to a fixed pseudo-random sequence. Each block was run four times in separate sessions, whereby cross-modal extinction was assessed both before and after tool use. Across four sessions, the pre-tool use blocks of trials for each location of the visual stimulus along the tool (arranged in the following order: NMF-FMN-MFN-NMF) always preceded the post tool-use blocks (order: FMN-MNF-NFM-NMF), which were run immediately afterwards.

Tool-use consisted of 50 tool-mediated retrieval movements, lasting about 5 minutes. The patient was asked to use the rake to reach and retrieve an object located on the table, out of the hand-reaching space. Objects were constituted by plastic disks (3 cm of diameter, 0.5 cm thick) and were presented one at a time. They were randomly presented in correspondence with patients’ midsagittal axis, or 10 and 20 degrees to the left and to the right of the central position.
RESULTS

T.R. made no false alarm on catch trials throughout the experiment. Across all the blocks of trials, she performed errorless when responding to single touches delivered to her left hand (100% of accuracy). However, her performance was poor under bilateral stimulation conditions. In the next sections, her performance before tool-use will be reported first, followed by the performance obtained after tool-use.

Before using the tool, as expected, the amount of visual-tactile extinction was significantly modulated by the distance at which the visual stimulus was presented from the patient’s hand (see Figure 3), as statistically assessed by using the Fisher Exact Test, after alpha-correction for multiple comparisons. Cross-modal extinction was more severe near the patient’s right hand holding the rake (35% of accuracy), as compared to both the middle (73% of accuracy; p < .001) and the distal location (78% of accuracy; p < .001) along the tool. Cross-modal extinction did not differ between the two latter positions (p = .4).

After tool-use, the amount of visual-tactile extinction was no longer significantly modulated by the distance of the visual stimulus from the patient’s hand; actually, the same amount of visual-tactile extinction was observed before and after tool-use (35% of accuracy). As expected on the basis of previous studies, cross-modal extinction was more severe after tool-use when measured at the distal edge of the rake (28% of accuracy), as compared to before tool-use (78% of accuracy; p < .001 by Fisher Exact test). Critically, cross-modal extinction following tool-use was more severe also when measured at the middle location (45% of accuracy), as compared to before tool-use (73% of accuracy; p < .01 by Fisher Exact test). Therefore, the reason why visual-tactile extinction was no longer modulated by the distance of the visual stimulus from the patient’s hand was due to the fact that its severity increased, after tool-use, both at the middle and distal location along the tool axis, but not at the proximal position.
DISCUSSION

The present study was aimed at investigating the spatial characteristics of the increase in cross-modal effects, documented in cross-modal extinction patients after training in using tools. In particular, we verified whether this increase is due to an actual elongation of the visual-tactile peri-hand area along the tool axis, or to the shift or the creation of a new integrative area at the distal edge of the used tool. These alternative possibilities were verified by probing different tool locations for visual-tactile extinction in a RBD patient, T.R., before and after the active use of the same tool. Three main findings were obtained and will be summarised and discussed below.

First, before tool-use, cross-modal extinction was more severe when assessed close to the patient’s hand (holding the rake) than at farther distances. This finding is consistent with previous reports and further confirms the well-known near-far modulation (di Pellegrino et al., 1997; Lадавас, 2002; Maravita et al., 2001). The new result here consisted in showing that outside the area of maximal visual-tactile integration (near the hand) cross-modal effects dropped off without showing any further significant decrement. Cross-modal extinction, which was quite strong at the hand location (only 35% of accuracy), was comparably weak both at the middle (30 cm) and distal (60 cm) location (73% and 78% of accuracy, respectively). This shows that, once the borders of the peri-hand integrative area are exceeded, the relationships between the distance of the visual stimulus and the severity of cross-modal effects are no longer present. This finding is in agreement with neurophysiological data showing a limited extension in depth of the visual RFs of monkey’s visual-tactile neurons (Duhamel et al., 1998; Graziano and Gross, 1998; Rizzolatti et al., 1981). Although one needs to be cautious in generalizing single-case based evidence, this finding may suggest that the distance of about 30 cm, which has been repeatedly documented to show a significant near-far modulation of cross-modal extinction in group-based studies, may represent a reliable estimate of the extent of the near peripersonal space in humans.

Second, after tool-use, there was no change in the severity of cross-modal extinction measured at the level of the hand (35% before and after tool-use). This result is consistent with the view that the visual-tactile peri-hand area did not shift, but rather extended from the hand to a farther location. Indeed, if the peri-hand space had shifted, we should have expected to find a better performance at the level of the hand after tool-use. Instead, the lack of any change following tool-use suggests that the integrative strength at the level of the hand was kept constant, which is compatible with an expansion of the peri-hand area to a farther location. This conclusion was supported by further results, as described below.

Third, and most relevant for the purpose of the present study, a significant worsening of cross-modal extinction was present after tool-use as compared to before tool-use. The worsening was present both at the distal edge (28% vs. 78% of accuracy), as well as midway (45% vs. 73% of accuracy) between the hand and the tool-tip. The worsening of the patient’s performance at the middle location sharply contrasts with what should be expected if the peri-hand space had shifted from the hand towards the tool-tip following tool-use. It also contrasts with the possibility that tool-use would generate a new visual-tactile integrative area in correspondence with the distal edge of the tool. Both these hypotheses, in fact, predict that no change should be observed at the middle location. In contrast, the significant worsening of cross-modal extinction observed after tool-use at the middle location clearly supports the notion that tool-use induces a real extension of the peri-hand space (Farnè and Lадавас, 2000; Farnè et al., 2005a, 2005b).

In this respect, it should be noted that in absolute terms, but not statistically, cross-modal extinction after tool-use was somewhat more severe at the distal location (28% of accuracy) compared to the middle one (45% of accuracy). Bearing in mind the caveat for overgeneralization from single-case evidence, this seems to suggest that the way in which tool-use extends the peri-hand space along the tool-axis might be non homogeneous, certain portions of the tool (e.g., the handle and the tines) being allocated with more integrative strength than others (e.g., the shaft). Although preliminary findings from two additional patients, examined with a similar procedure, seem to support this result, more complete investigations are needed to address this issue (Bonifazi et al., in press), as it may be relevant to solve the apparent discrepancy between the results of the present study and those recently reported in normal subjects (Holmes et al., 2004). By assessing visual-tactile interference effects at different locations along hand-held tools, Holmes et al. (2004) did not find significant effects at a middle location, but only at the proximal (handle) and distal (tool-tip) position. The null effect at the middle location was observed despite the fact that subjects had to use each part of the tool to perform an active task (pushing a button). On the basis of their results, these authors suggested that tool-use may highlight only certain portions of a tool, as the handle and the tip. However, taking into consideration previous tool-use studies on humans, as well as the neurophysiological findings, they also acknowledged that some forms of tool-use may result in a genuine extension of peri-hand space (Holmes et al., 2004), as we report here for the first time in a single case. Other accounts have been proposed and deserve further investigations in the
future (see Holmes et al., 2004; Humphreys et al., 2004).

The present study, by showing that tool-use literally extends the visual-tactile integrative area surrounding the hand along the tool axis, thus encompassing both the distal and the middle location along the shaft of the rake, may both solve the apparent discrepancy between normal and pathological evidence in humans, and reconcile the behavioural evidence in humans with the neurophysiological findings in monkeys.

Indeed, the present results are fully consistent with the work reported by Iriki and colleagues (Iriki et al., 1996, 2001; Obayashi et al., 2001), documenting a real enlargement of visual RFs of bimodal neurons following tool-use, rather than a shift, or a split of visual integrative areas.

Furthermore, these findings add to the previous results from our laboratory in showing that plastic modifications of peri-hand space representation may be highly flexible. For example, we previously showed that the multisensory peri-hand area can be extended differentially by using tools of different length, and that the external border of the area elongated through the use of tools is not sharply limited to the tool tip, but extends (fading) beyond it (Farnè et al., 2005a). The present results further support this view, in that the integrative strength, as measured at the level of the hand and the tool-tip through cross-modal extinction, was absolutely comparable. Indeed, this pattern of results is what should be expected in the case of a real elongation of the hand-centred peripersonal space to include the distal edge of the rake, as if it were the hand. Finally, the strong increase in cross-modal extinction obtained after tool-use at the distal edge of the rake is also consistent with previously reported evidence showing that the distal border of the elongated peri-hand space is tightly linked to the functionally effective part of the tool (Farnè et al., 2005b).

Overall, the reviewed findings together with the new evidence reported here favour the notion that cross-modal effects documented in extinction patients reflect a genuine extension of the peri-hand space that is specifically dependent upon the functionally effective use of a tool. While it remains entirely possible in humans, as it has been demonstrated in the monkey, that a new visual-tactile integrative area can originate in a remote location physically disconnected with the body (Iriki et al., 2001), the active use of a tool to physically and effectively interact with objects in the distant space appears to produce a spatial extension of the multisensory peri-hand space that encompasses the whole length of the tool.

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Tool-use shapes multisensory space


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