
Agency and control for the integration of a virtual tool into the peripersonal space

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Abstract. Our representation of the peripersonal space is tied to our representation of our bodies. This representation appears to be flexible and it can be updated to include the space in which tools work, particularly when the tool is actively used. One indicator of this update is the increased efficiency with which sensory events near the tool are processed. In the present study we examined the role of visuomotor control in extending peripersonal space to a common virtual tool—a computer mouse cursor. In particular, after participants were exposed to different spatial mappings between movements of the mouse cursor and movements of their hand, participants' performance in a motion-onset detection task was measured, with the mouse cursor as the stimulus. When participants, during exposure, had the ability to move the cursor efficiently and accurately (familiar hand-cursor mapping), they detected motion-onset targets more quickly than when they could not move the cursor at all during exposure (no hand-cursor mapping). Importantly, reversing the spatial correspondence between the movements of the hand and the cursor (unfamiliar hand-cursor mapping) during exposure, which was thought to preserve the ability to move the cursor (ie agency) while weakening the ability to make the movements efficiently and accurately (ie control), eliminated the detection-facilitation effect. These results provide evidence for the possible extension of peripersonal space to frequently used objects in the virtual domain. Importantly, these extensions seem to depend on the participant's knowledge of the dynamic spatial mapping between the acting limb and the visible virtual tool.

1 Introduction

Successful interaction with the environment requires that we process relevant external information while maintaining a dynamic representation of the body and, in particular, of the effectors (eg Ehrsson et al 2004; Graziano 1999; Graziano and Gross 1998; Iriki et al 1996). The idea of a neurologically distinct representation of the space surrounding the limbs and hands, known as peripersonal space, is supported by single-cell studies of the primate brain that have found neurons in the premotor and the parietal regions that are responsive to stimuli presented in the space near the hands (Graziano and Gross 1998) and whose activity is sensitive to the position of the hands (Ehrsson et al 2004; Graziano 1999). Importantly, Iriki and colleagues (1996) reported that the receptive fields of some of the neurons whose responses are normally confined to the space near the hand extend to incorporate the space near a hand-held tool after the tool is used actively. In humans, recent behavioural studies of healthy participants have found that perceptual processing is enhanced for stimuli appearing on or near a hand (Brown et al 2009; Dufour and Touzalin 2008; Hari and Jousmäki 1996), a hand-held tool (Kao and Goodale 2009; Reed et al 2010), or even a virtual limb (Short and Ward 2009). These findings suggest that the representation of peripersonal space is flexible and can be extended to include tools (Maravita and Iriki 2004).

Interestingly, facilitated visual processing can occur near the hands even when the hand is viewed at a distance from the observer's body. For instance, simple facilitatory effects have been obtained when participants observe a live video image of their hand

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appearing on a distant screen (Longo and Haggard 2009; Whiteley et al 2004, 2008). In a study by Whiteley et al (2004), participants' direct view of their hands was occluded while they viewed a live video image of their hand projected on a distant screen. Participants were faster to process visual targets appearing on their hands compared to targets appearing on a control object. Follow-up experiments found that this effect was present only when targets appeared on the participants' own hand, demonstrating that this performance enhancement is not due to the perceptual salience of the human hand and that it can be at least partially attributed to the recognition of one's own hand (Whiteley et al 2008).

Whiteley et al's (2004, 2008) findings of facilitated processing near one's distantly viewed hand could be attributed to the participants' recognition of their own hand as a unique visual object. Alternatively, the effect could be driven by the participants' perceived ability to move the distantly viewed hand. The latter possibility does not rely on the unique visual characteristics of the hand as much as it relies on agency, which refers to the knowledge that one can cause the seen effector to move. More generally, agency is thought to extend to a tool (real or virtual) when the observer knows that the tool's movements are immediate effects of the movements she/he makes (eg with own hand; see Nahab et al 2011; Shimada et al 2005; Short and Ward 2009).

To distinguish between these alternatives (visual recognition of one's own hand versus recognition of agency), Short and Ward (2009) used a virtual-reality setting in which participants' real hands were associated with two observable virtual limbs. Whereas the virtual limbs were visually dissimilar from the real hands and not connected to a virtual body, the movements of the virtual limbs corresponded, spatially and temporally, to the movements made by the participant with his real hands. The authors hypothesised that the link between the movements of the real and virtual hands would establish the participant's agency over the virtual hands, and thus extend the visual facilitation effect associated with peripersonal space into the virtual setting, allowing for faster responses to targets appearing near the virtual hand compared to targets appearing far from the virtual hand. Their results confirmed this prediction and further demonstrated that the visual properties of the virtual limb and the perceived distance between the virtual limb and the participants' body are not factors determining the facilitatory effect on target detection. Importantly, however, when the virtual limbs remained stationary as the participant moved or moved only occasionally, effectively weakening agency, facilitation for targets appearing near the virtual-hand detection disappeared.

The reviewed research suggests that extensions of peripersonal space to virtual entities depend on the participants' understanding that their movements cause the viewed limb or tool to move: the viewed limb must be their own (Whiteley et al 2008) or its movements must be linked consistently to the movements of their own (unseen) limbs (Short and Ward 2009). These findings suggest that the participant must experience agency for the viewed limb (Longo and Haggard 2009; Short and Ward 2009). It is not clear, however, whether merely the possibility of causing movement (ie agency) is sufficient, or if participants also need to be able to control the viewed virtual limb. Having sensorimotor control over a tool requires both agency and an accurate representation of the relationship between one's motor commands and the tool. This representation, also known as an internal model (Ito 1984; Kawato et al 1987; Wolpert 1997), is acquired with practice and enables the user to predict the temporal and spatial properties of the tool's movements based on his/her own motor command. Notably, changing the properties of a tool (eg length, weight, etc) or the context of tool use (eg force field) can reduce control and necessitate construction of a new internal model, without eliminating agency. In the studies reviewed so far, the two concepts of agency and control have been confounded. Although the acquisition of control might also affect one's sense of agency, it is possible to have agency with little or no control.

We propose that sensorimotor control, ie an accurate and stable internal model relating the participants' movements to that of the tool, plays an important role in the incorporation of a virtual tool into peripersonal space. This proposal is in line with neuropsychological studies showing the importance of active tool use (versus passive holding) for the extension of effects associated with peripersonal space to a tool (Farnè et al 2005a). Of particular importance, Farnè et al (2005b) found that the degree of cross-modal extinction at the tool tip depended on whether the tool length during the extinction test matched the tool length during tool-use training. This result suggests that active training with the tool provides the user with visual, proprioceptive, and tactile information about the length of the tool. The proposal is also in line with neurophysiological evidence suggesting that the visual receptive fields of visual–tactile bimodal neurons grow to include hand-held tools only after active use, and not after passive holding (Iriki et al 1996).

In the present study, we used a visual motion-onset detection test to examine visual facilitation near a virtual effector, here represented by the computer mouse cursor, and to replicate and extend the findings of Short and Ward (2009). Although the computer mouse is a commonly used interface, and is thought to extend the peripersonal space to the computer screen (Bassolino et al 2010), it differs from other visual stimuli, such as virtual hands. Namely, the standard mapping of the hand to a mouse cursor translates movements of the hand on a two-dimensional horizontal plane into movements of the cursor on a two-dimensional vertical plane, such that hand movements in the forward, backward, leftward, and rightward directions are mapped onto movements of the cursor in the upward, downward, leftward, and rightward directions, respectively. Furthermore, the distance travelled by the hand is often magnified when translated to the movements of the cursor (the cursor travels farther than the hand). Despite the complexity of the relationship between the movements of the hand and the movements of the cursor on screen, computer users quickly build a reliable internal model of this mapping.

To distinguish between the contributions of agency and control, we designed an experiment with three conditions. Specifically, the experiment began with an exposure phase in which participants were exposed to either a familiar, unfamiliar, or no mapping between the position and movements of the hand and the mouse cursor. In the exposure phase, participants performed a targeted-movement task in which movements of the hand were mapped onto movements of the cursor in the familiar (standard) way, in a spatially reversed unfamiliar way, or not associated at all. We reasoned that, when exposed to the familiar mapping condition, participants would experience both agency and control over the mouse cursor. By contrast, when exposed to the unfamiliar mapping condition, participants would experience agency but no or little control over the mouse cursor, because there was still a clear causal temporal link between movements of the hand and movement of the cursor, but no established model for the reversed mapping. Finally, in the no-mapping condition, participants observed movements of the cursor controlled only by an experimenter. Therefore, when exposed to the no-mapping condition, participants should have experienced neither agency nor control over the mouse cursor. The exposure phase was followed by the visual facilitation test phase, in which the participants' task was to detect the onset of cursor motion as quickly as possible. We chose this task because our previous research suggests that visual motion processing is sensitive to the current state of the motor system (Brown et al 2007). To our knowledge, the present study is the first to investigate the possible visual facilitation for a hand-associated mouse cursor (but see Bassolino et al 2010), for an examination of auditory–tactile sensory integration involving the space near the mouse cursor).

We predicted that, if visuomotor control over the cursor plays a role in the extension of peripersonal space to the space occupied by a virtual tool (mouse cursor), then participants would respond faster to motion-onset detection targets after being exposed to the familiar-mapping condition than after being exposed to the unfamiliar- or no-mapping conditions. Alternatively, if agency is sufficient to drive this extension, the strong prediction is that we would find no differences between the familiar- and unfamiliar-mapping conditions, and significantly poorer detection performance in the no-mapping condition.

2 Method

2.1 Participants

Twelve undergraduate students from Trent University participated in a single session in exchange for money or course credit. All participants reported being right-handed and having normal, or corrected-to-normal, vision. All were naive to the purpose of the study. All the experimental protocols were approved by the Research Ethics Board at Trent University.

2.2 Apparatus and stimuli

The experiment was run in Matlab (MathWorks, Natick, MA) using the psychophysics toolbox (Brainard 1997; Pelli 1997; version 3.0.8). A cortical optical computer mouse (Logitech, Mississauga, ON) was used as the connection between the mouse cursor and the participants' hand. Visual stimuli were displayed on a 38 cm × 30 cm LCD monitor (Dell, P190st) with a resolution of 1280 × 1024 pixels, and a refresh rate of 60 Hz. The viewing distance from the monitor was about 65 cm. This distance was not fixed, therefore the visual properties of the stimulus are reported both in centimetres and in estimated visual angle.

Stimuli were presented on a black background, and consisted of an arrow-shaped mouse cursor [0.4 cm (0.35 deg) × 7 cm (0.62 deg)], and a series of rectangles [width: 0.65 cm (0.53 deg); height: 1.0 cm (0.9 deg)] that acted as target locations in the movement task, described below. The rectangles were presented one at a time, and were brighter (~ 60 cd m⁻²) during the movement task relative to the detection task (~ 3 cd m⁻²), as described below.

2.3 Design

The experiment consisted of three blocks, each presenting a different spatial mapping between the movements of the participants' hand and the computer mouse (familiar mapping, unfamiliar mapping, and no mapping). This factor was manipulated within subjects and the sequence of the three blocks was counterbalanced across the twelve participants, resulting in the assignment of two participants to each possible sequence.

The primary difference between the three conditions was in the movement task. In the familiar-mapping condition, movements of the mouse cursor corresponded to the built-in standard mapping that normally characterises the relationship between hand movement and mouse cursor movement. For example, hand movements to the left moved the mouse cursor to the left, and hand movements toward the body moved the cursor downward on the screen. In the unfamiliar reversed-mapping condition, movements of the mouse cursor were temporally linked to the hand movements of the participant, but cursor movements were spatially opposite to those of the hand. For example, hand movements to the left moved the mouse cursor to the right, and hand movements toward the body moved the cursor upward on the screen. Finally, in the control no-mapping condition, no association was made between the participants' hand and the mouse cursor, and an experimenter performed the movement task.

Each of the three experimental blocks consisted of a movement task (10 trials), a practice detection task (10 trials), a second movement task (10 trials: as an additional reminder of the type of association between the hand the cursor), and an experimental

motion-detection task (60 trials; lasting less than 5 min). The detection task began right away after exposure to each mapping (ie movement task). There was, however, a short break (10 to 15 min) after finishing each detection task and before moving to the next mapping condition. The movement task was presented only for the purpose of exposing the participant to the specific hand-cursor association, and performance was not recorded or analysed. Certainly, many research studies show that learning a new one-dimensional visuomotor mapping takes at least 50 trials of practise (eg Held 1968; Martin et al 1996; Wang and Sainburg 2004), and the unfamiliar mapping we used here manipulated the spatial mapping between hand and cursor, both along the azimuth and in depth. We are confident that these brief exposures were not sufficient to induce sustained learning of the unfamiliar mapping.

2.4 Procedure

The movement task involved moving the mouse cursor with the goal of placing it inside the small rectangle, whereas the detection task involved making speeded keypress responses to the motions (generated by the experimental program) of the mouse cursor. There were clear and distinct breaks between the two tasks, and participants were both verbally and visually (the rectangle's reduced brightness) informed whenever the detection task began.

On each trial of the movement task, a rectangle appeared at a random location on the screen. During the familiar- and unfamiliar-mapping conditions, participants were instructed to move the mouse cursor as quickly as possible to the target. During the no-mapping condition, an experimenter performed this speeded movement task using the familiar-mapping condition. After a fixed time interval (1500 ms for familiar- and no-mapping conditions and 3000 ms for the unfamiliar mapping) the rectangle disappeared and re-appeared in another randomly chosen location on the screen. These fixed intervals were used to encourage speeded performance, and a longer interval was allocated for the unfamiliar-mapping condition because of the relative difficulty of the movements. Participants were instructed to initiate movements to the new target location as soon as the target appeared in its new location.

The movement task ended when the cursor was placed inside the last rectangle, which was less bright and located at the centre of the screen. The participants in the familiar- and unfamiliar-mapping conditions were instructed to keep their hands on the mouse and to refrain from moving the mouse. Participants were then instructed to press the space bar with their left hand to initiate the detection task. To ensure that movements of the cursor were never induced by the participant, the mouse was disconnected from the cursor at initiation of the detection task. To maintain participants' subjective experience of agency and/or control, they were not informed of this disconnection. During the no-mapping condition, participants' hands were not on the mouse (although their hand was still positioned on the table to maintain a similar posture across conditions).

At the beginning of the detection task, the mouse cursor was visible at a central start location. After a delay that varied randomly between 1000 and 3000 ms, the mouse cursor was set into motion. The velocity of the computer-generated motion was set at 3 cm s^{-1} (2.6 deg s^{-1}) to the left or right (direction was chosen randomly). Participants were instructed to press the space bar (with their left hand) as soon as they detected motion onset. Response time was measured in milliseconds. Immediately upon response, the cursor was automatically relocated to the central starting position and the next trial began.

3 Results

Response times (RTs) three standard deviations below or above the overall mean (2.2% of the trials) were excluded from the following analyses. Mean RTs from the remainder of the data were submitted to a two-way repeated-measures ANOVA ($\alpha = 0.05$) with hand-cursor mapping (familiar mapping, unfamiliar mapping, no mapping) and direction of the stimulus motion (left versus right) as independent variables. This analysis revealed a significant main effect of mapping ($F_{2,22} = 6.01$, $MSE = 119$, $p = 0.008$, $\eta_p^2 = 0.353$ —see figure 1). No main effect of motion direction or interaction between mapping and motion direction was found ($F_s < 1$). Paired-samples t -tests (two-tailed) showed that responses in the familiar-mapping condition ($M \pm SE = 339 \pm 11$ ms) were faster than responses in the no-mapping (346 ± 11 ms— $t_{11} = 4.1$, $SE = 1.76$, $p = 0.002$) and the unfamiliar-mapping condition (348 ± 10 ms— $t_{11} = 2.8$, $SE = 3.39$, $p = 0.016$). The estimated effect sizes (Cohen's d , using standard deviation of contrast differences for each participant) for these two contrasts were 1.96 and 0.82, respectively. The difference between the no-mapping and the unfamiliar-mapping conditions was not significant ($t_{11} = 0.59$, $SE = 3.88$, $p = 0.565$).

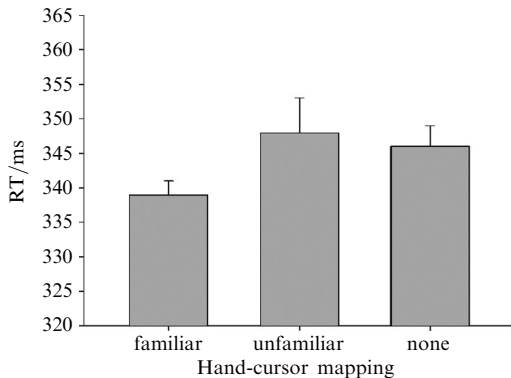


Figure 1. Speed of performance on the detection task as a function of hand-cursor mapping. The error bars indicate within-subjects 95% confidence intervals (Cousineau 2007; Loftus and Masson 1994).

The size of the effects in this experiment (Cohen's d for pair t -tests) should be compared with other studies in which the visual stimulus is under the participants' control but does not share the visual properties of the hand or any biological body part. Of note, the experiment by Short and Ward (2009; experiment 5) where the virtual limbs were shaped like cones, also obtained the effect size of approximately 1 SD (Short and Ward 2009, pages 1097–1098).

We examined how the effect of exposure to different mappings may change over time. First, we examined the possibility that a change in alertness or fatigue may be responsible for the differences across the mapping conditions. If the hand-cursor mapping manipulation influences performance only late in the experimental session, it is possible that placing the hand on the mouse in the familiar condition simply helped subjects to maintain alertness throughout the experimental block, instead of inducing control and agency over the cursor. Second, we considered the possibility that, as participants viewed the mouse cursor move independently of the hand during the detection task, the effect of exposure to different hand-cursor mappings might be reduced. To test how the effects of mapping change with time, we made planned comparisons (two-tailed, dependent t -tests) between the first (trials 1–30) and the second (trials 31–60) halves of each experimental session separately for each mapping condition. As figure 2 shows, the only condition that seemed to change over time was the unfamiliar condition. It would be expected that the effect of this novel and briefly exposed mapping (ie too brief to induce motor learning) would fade with time, although the difference in RT between first half (353 ± 12 ms) and second half (343 ± 10 ms) of the unfamiliar

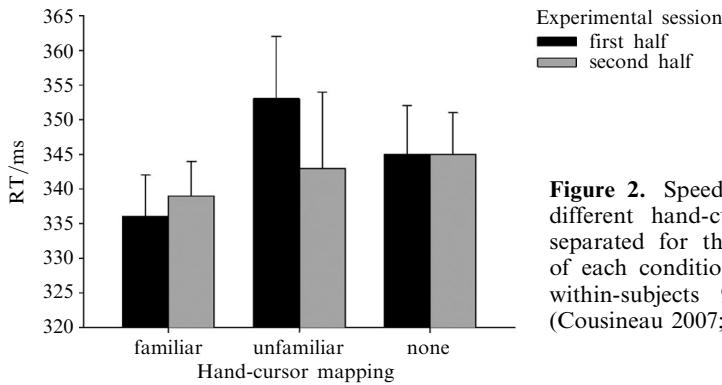


Figure 2. Speed of performance on the different hand-cursor mapping conditions separated for the first and second halves of each condition. The error bars indicate within-subjects 95% confidence intervals (Cousineau 2007; Loftus and Masson 1994).

condition did not reach statistical significance ($t_{11} = 1.08$, $SE = 9.14$, $p = 0.3$). Likewise, no significant differences in RT were found between the first half and the second half of the experimental sessions for the familiar- and the no-mapping conditions ($ts < 1$). This absence of change in performance (and, in particular, no increase in RTs in the second halves of the unfamiliar- and no-mapping conditions) over the course of the experiment is inconsistent with the idea that the difference across the mapping conditions was due to maintained alertness or fatigue.

4 Discussion

Our representation of peripersonal space is tied to our representation of our body (Cardinali et al 2009a). Both appear to be flexible in that they can be updated to incorporate objects, particularly when an object is used to perform actions (Maravita and Iriki 2004). One indicator that a real or virtual tool has been incorporated into the representation of peripersonal space is the increased efficiency with which targets presented near the tool are processed (Berti and Frassinetti 2000; Di Pellegrino and Frassinetti 2000; Farnè et al 2005a, 2005b, 2007; Holmes et al 2007a; Kao and Goodale 2009; Maravita et al 2001, 2002; Reed et al 2010; Short and Ward 2009; but see Holmes et al 2007b). On the basis of previous research it may appear as though agency—the understanding that one can cause the seen effector move—is sufficient to drive changes to the representation of peripersonal space (eg Longo and Haggard 2009; Short and Ward 2009). Here, we proposed that the incorporation of a tool into the representation of peripersonal space depends on participants' ability to control the movements of the tool, where control is defined as the ability to accurately predict the spatiotemporal properties of the tool's movements in response to user's movements.

To test this proposal, we exposed participants to three different spatial mappings between the movements of the hand and the movements of an on-screen mouse cursor (our virtual tool), and then we tested participants' ability to quickly detect the onset of mouse-cursor motion. We found faster responses when, during exposure, participants had both agency and control over the movements of the mouse cursor (familiar hand-cursor mapping) relative to when they had no agency and no control (no hand-cursor mapping). Importantly, we found that by reversing the spatial correspondence between the movements of the hand and the cursor during exposure, which we reasoned preserved agency and weakened control (unfamiliar hand-cursor mapping), this facilitation was eliminated. This second finding suggests that the extension of peripersonal space to the space in which virtual tools operate depends on the participants' ability to control the movements of the virtual tool.

4.1 *Near-tool facilitation depends on motor control*

As predicted, the familiar mapping between the hand and the cursor leads to faster responses in the motion-detection task compared to the no-mapping condition. This finding converges with others showing speeded visual processing for stimuli appearing near real and virtual tools to which participants have been actively, not passively, exposed [Berti and Frassinetti 2000; Farnè et al 2005a, 2005b; Kao and Goodale 2009; Reed et al 2010; Short and Ward 2009; although see Costantini et al (2011) for a study in which passive observation of tool use was sufficient to induce the extension of peripersonal space]. More importantly, however, reversing the spatial association between the hand and the cursor movements eliminated this facilitation effect. In fact, performance in the detection task in the unfamiliar-mapping conditions did not differ from the no-mapping condition.

We reason that in the no-mapping condition, participants had no agency or control associated with the cursor. The sense of agency alone has previously been shown to be important for obtaining the sensorimotor advantages of the extended body representation (Longo and Haggard 2009; Short and Ward 2009). To manipulate agency, a temporal delay can be introduced between the motor command and its associated visual feedback (Longo and Haggard 2009; Shimada et al 2005) or the synchronous visual feedback can be provided only on some trials (Nahab et al 2011; Short and Ward 2009). Both of these manipulations have been used to argue that, when one interferes with the sense of agency for the observed limb, the sensorimotor advantages associated with the body representation and peripersonal space diminish (Longo and Haggard 2009; Nahab et al 2011; Shimada et al 2005; Short and Ward 2009). Here we note that conditions used to manipulate agency in past studies may have reduced control as well, as participants no longer experienced a consistent one-to-one correspondence between their movements and the visual feedback provided by the virtual tool. In other words, conditions used to manipulate agency in previous studies did not necessarily disambiguate agency from motor control. Although agency and control could be conceived of two points on a single continuum, to the extent that our research question was directed at the comparison between the two extremes of the continuum (and our experimental conditions also aimed to achieve that), we treated agency and control as distinct categories. But it should be noted that a qualitative distinction between agency and control is made only in the specific state of unskilled/ineffective tool-use, achieved by exposing people to the reversed-mapping condition.

In the present study, we reasoned that agency was preserved in both the familiar- and unfamiliar-mapping conditions by providing constant, systematic, and reliable visual feedback associated with the participants' hand movements, and by preserving the temporal synchrony between the movements of the hand and the cursor. Within these conditions, we manipulated participants' ability to control the movements of the cursor by varying the veridicality of the internal model relating movements of their hand to the movements of the cursor. The internal forward model enables participants to predict movements of the cursor based on its current state (eg its position and velocity) and the current motor command, and is thus necessary for the control of the cursor (Ito 1984; Kawato et al 1987; Wolpert 1997). This model should have been veridical during the familiar-mapping conditions and non-veridical during the unfamiliar-mapping conditions. Whereas, on some level, our instructions may have allowed our participants to 'predict' the outcomes of their actions in the unfamiliar-mapping condition, without an established internal model the motor command generated would not (and did not) move the cursor in the correct direction without reverting to the very slow, deliberate, and variable movements characteristic of unskilled behaviour. Importantly, the facilitation of motion-onset detection observed in the familiar-mapping condition was not observed during the unfamiliar-mapping condition, suggesting that control over the

movements of the cursor (in addition to the sense of agency) may be necessary for peripersonal space to be extended to the virtual tool (mouse cursor).

Although the advantage of the familiar mapping may be attributed to the relative spatial congruency of this mapping (eg left/right hand movement causing a left/right movement in the cursor), an internal forward model predicts both the direction of cursor motion (in a two-dimensional space that may be different from the space in which the hand moves) and other cursor-motion properties, such as acceleration and velocity. An explanation based on the internal model also fits well with previous neurophysiological evidence from monkeys, suggesting the necessity of practice (ie acquisition of an internal forward model) for the extension of peripersonal space onto tools (Iriki et al 1996). Humans may need less practice than other primates to become skilled tool users, however, and this may explain the rapid assimilation of tools/objects into the body representation in everyday situations (eg Cardinali et al 2009b; Carlson et al 2010). This ease means that exploring the role of control in this process requires employing conditions that depart drastically from the familiar.

4.2 *Other considerations*

The facilitation effect in the speeded motion detection task may be attributed to an enhancement in visual-perceptual processing (Whiteley et al 2004) or to an enhanced motor processing (Longo and Haggard 2009). Visual discrimination of targets (eg location discrimination) can be enhanced when the stimulus is associated with the hand (Whiteley et al 2004). On the other hand, Longo and Haggard (2009) argued that the sense of agency extended to the display does not facilitate perception of visual stimuli, but instead primes the motor system for manual responses. They supported this claim by showing that the hand-association effect was present only when participants were asked to make manual (keypress) responses but not when they were asked to make vocal responses. Since we used manual keypress responses in the present study, our findings do not discriminate between the perceptual and the motor account of facilitation and, therefore, emphasise the common aspect of both explanations. The observed facilitatory effect seems to arise from the ability to perform actions with the cursor that have predictable visual consequences. The recognition of this ability forms an association between the virtual tool and the observer's body, facilitating the responses to motion onsets.

In our analyses, we examined two alternatives to our proposed explanation. First, the positioning of the hand on the mouse may have overcome a possible selective stimulus-response compatibility present in the control condition. Specifically, detection of the rightward computer-generated motions of the cursor may have benefited from positioning the right hand on the mouse (see Ivanoff and Klein 2001), and this source of compatibility may have driven the facilitation observed in the familiar-mapping condition. This possibility seems highly unlikely due to the absence of an interaction between motion direction and our primary manipulation (hand-cursor mapping). Furthermore, no main effect of motion direction was found.

Second, the positioning of the hand on the mouse during the familiar-mapping condition may have somehow aided sustained alertness, preventing effects of fatigue. This account also seems unlikely, since experimental fatigue is more likely to occur during the second half of each block. The planned comparisons between the first and the second halves of the detection tasks revealed no significant change in performance. The only noticeable but non-significant difference appeared as a reduction in RTs during the second half of the unfamiliar-mapping condition. We argue that, even if this early disadvantage approached statistical significance, it would provide additional evidence for our proposal, due to the specific nature of the present task. Namely, it seems plausible that the computer-generated movements of the cursor would eventually

diminish the effect of the novel and briefly exposed (ie too brief to induce any motor learning) unfamiliar mapping. Therefore, accounts based on posture or sustained attention do not seem to be strong explanations in comparison to the account based on differences in control.

It should also be noted that the kind of facilitation that this study reports has also been commonly discussed in the context of body schema rather than peripersonal space, particularly because the body schema is more commonly thought to be maintained using somatosensory, proprioceptive, kinesthetic, and tactile information (Cardinali et al 2009a), and thus its extension is often thought in relation to tools/objects that are in physical continuity with the body (eg Carlson et al 2010). Although it seems appropriate to assume that kinesthetic and tactile informations are used in skillful use of the computer, and although peripersonal space and body schema are both defined as representations that inform action in the near-body space, distinguishing between them requires other measures beyond the scope of the present study (Cardinali et al 2009a).

4.3 Conclusion

Successful interaction with the environment depends on learning the rules that relate motor commands to sensory experiences. The results presented here highlight how the relationships that we rely on to control real body–environment interactions (the synchronicity of the felt and observed movements, supporting the sense of agency, and the learned spatial correspondence between the movements, supporting the sense of control) may be essential for us to treat virtual tools as extensions of our bodies.

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