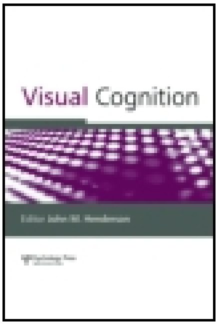

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A behavioural experiment in virtual reality to verify the role of action function in space coding

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Neurophysiological data indicate that the reachable peripersonal space and the unreachable extrapersonal space are represented in segregated parietofrontal circuits and that when the unreachable space becomes reachable because of tool use, it is automatically coded by the network selective for peripersonal space. Here we directly tested the role of action's consequences in space coding. Thirty-eight participants bisected lines at either a reachable distance (60 cm) or unreachable distance (120 cm) using either a laser pointer or laser cutter. The laser cutter but not the laser pointer had an action consequence; the line broke into two pieces. The results showed that distance moderated the effect of action. At an unreachable distance, the mean bisection point was closer to the centre when participants used the laser cutter compared to when they used the laser pointer. There were no differences at a reachable distance (60 cm). This result suggests that the space in which the individual may determine a physical consequence is categorized as peripersonal space, independently from its actual distance from the individual's body.

***Keywords**:* Spatial perception; Motor processes; Line bisection; Tool use; Virtual reality.

In the present article, we considered the nature of an action's consequences and their role in modulating action execution. In particular, we compared the

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influence that to act causing quantifiable effects in the outside world, and to execute the same action without causing any effect, have on space coding. The only space that can be acted upon directly by the unaided use of the arm and the hand, and where the actions can lead to some consequence, is by definition the peripersonal space, which surrounds our bodies (Rizzolatti, Fadiga, Fogassi, & Gallese, 1997). Objects within peripersonal space can be grasped and manipulated; objects located beyond this space, termed extrapersonal space, cannot normally be reached but only smelled, heard or seen. The division of the space on the basis of the potential actions that can be performed in it is reflected also by the relative neural representation localized in separated parietofrontal circuits. Two are the main circuits involved in this type of coding: the LIP-FEF, devoted to the movement programming of the eyes (Barash, Bracewell, Fogassi, Gnadt, & Andersen, 1991); and the VIP-F4 dedicated to the encoding of movements of head, arm and hand (Fogassi et al., 1996). In these circuits neurons with both visual- and movement-related activity are present. In LIP-FEF they fire when a stimulus is presented in the visual receptive field and when a saccade is executed towards it. Visual responses are coded in retinotopic coordinates: When the eyes move, the receptive field also moves (Andersen & Gnadt, 1989; Goldberg & Segraves, 1989). In VIP-F4 they fire when a stimulus is applied in the tactile receptive field or in the visual receptive field anchored to the tactile one, and when a movement of the related body part is executed. Visual responses are coded in body-centred coordinates: Visual receptive fields remain anchored to the tactile receptive field, which moves together with its relative body part.

Therefore, the reachable peripersonal space and the unreachable extrapersonal space are anatomically and functionally represented in segregated circuits. Yet, what happens when the unreachable space becomes reachable because of the use of a tool? Iriki, Tanaka, and Iwamura (1996) trained macaques to retrieve distant objects using a rake and they recorded neurons in the intraparietal cortex responding to both somatosensory and visual stimulation. Results showed that after the training these neurons showed a visual receptive field including the entire length of the rake or covering the expanded accessible space. Therefore, it seems that the peripersonal space is not defined by metrical parameters (i.e., the length of our effectors) but by functional ones: If I am able "to do" something in a space, then that becomes my peripersonal space. Inspired by these experiments, several researchers have investigated the behavioural effects of tool use in humans. These studies aimed to identify whether tool-assisted reaching for far stimuli would produce similar behavioural effects as direct reaching for nearby stimuli with the hands alone. Berti and Frassinetti (2000) examined the effect of tool use in a brain-damaged patient, whose neglect selectively affected the peripersonal space. When requested to show the midpoint of a drawn line, she put her mark further towards the right from the objective midpoint. However, when lines were presented in the extrapersonal space and she was requested to use a laser pointer, her performance was almost flawless. By contrast, when a long stick was used for the same far-line bisection, she showed a rightward bias again. One difference between a laser pointer and a long stick is their different capacity to be used in actions in the far space. The laser pointer simulates the eyes' behaviour: It is possible to focus it on a precise position of the far space but only to indicate it. On the contrary, the stick simulates a finger behaviour, which is able to modify the state of the selected space region (e.g., to turn on the light switch on the far wall). The results of the Berti and Frassinetti experiment support the idea that when the stick made far space reachable, this became automatically coded by a neural network selective for peripersonal space whereby neglect was selectively present in the patient. Studies of line bisection in right brain damaged patients (Neppi-Mòdona et al., 2007), of crossmodal extinction in patients (Farnè & Làdavas, 2000; Maravita, Husain, Clarke, & Driver, 2001), of crossmodal congruency in normal participants (Maravita, Spence, Kennett, & Driver, 2002), of modulation of auditory peripersonal space during mouse use (Bassolino, Serino, Ubaldi, & Làdavas, 2010), and of pseudoneglect in real (Longo & Lourenco, 2006) and virtual environments (Gamberini, Seraglia, & Priftis, 2008), also support the view that tool use can modulate peripersonal space.

However, these studies did not directly test the effects of tool functionality, since they either compared different types of tools (i.e., stick and laser pointer) or the effects of the same tool used by the right or the left hand. As evident, many confounding variables, such as the difference in proprioceptive feedback or the involvement of the dominant hand, may have affected the results. The aim of the present article was to manipulate the capacity to act of one single tool and to test if the mere presence of a different use is able to produce in the far space similar behavioural results as those obtained in the near space. We selected the experimental paradigm introduced by Longo and Lourenco (2006) showing that a line bisection task in healthy adults presents a difference in performance when executed in near and far space. In a virtual environment, we asked participants to bisect lines at different distances by using a tool projecting a red dot on the line. After response, in one session nothing happened and the red dot simply indicated the selected midpoint (laser pointer), in the other session the red dot determined the line break into two pieces that fell down (laser cutter). Therefore, the experimental situation in terms of visual and proprioceptive perception was exactly the same until the response was given. If the possibility of physically modifying the objects has a role in space coding, the results should show a difference according to tool function when line bisection is executed in the far space. In particular, when the laser cutter is used results should not be different from those recorded during line bisection in the near space.

METHODS

Participants

Thirty-eight participants (19 male; mean age: 25.32 ± 3.85 years, range 22–39) took part in the experiment after providing their informed consent. All participants had normal or corrected-to-normal vision.

Apparatus and stimuli

Participants saw a virtual environment through a head-mounted display (HMD, Virtual V8 Research, Tracker Intersense). 3DStudio Max 8 was used for the development of three-dimensional objects and Virtools 5 for the interaction with them. A virtual room was created with a "wooden" table in the centre. Above and aligned with the table's centre, there was a white panel (50 × 50 cm) for displaying horizontal lines.

Virtual lines were presented at two distances: 60 cm and 120 cm. In order to keep constant the visual angle, lines were 8 cm (7.54°) and 16 cm (15.27°) long at the distance of 60 cm, and 16 cm (7.54°) and 32 cm (15.27°) long at the distance of 120 cm. Line thickness visual angle was kept constant at 0.19° (2 mm at the distance of 60 cm and 4 mm at the distance of 120 cm). Each millimetre of each line was subdivided in four segments. To simulate the laser pointer, a Nintendo Wiimote® was used. The Wiimote® operates as a normal mouse through the software GlovePIE™ (http://glovepie.org/glovepie.php/). In the virtual environment the Wiimote® moved a 2.5 mm red dot as a simulation of the same one represented by a real laser pointer. The virtual red dot was represented by a three-dimensional cone whose tip could collide with the lines, giving the point of contact over them. The A button on the Wiimote® served to memorize the response and to switch to another trial. The virtual environment was perceived stereoscopically thanks to two cameras placed at a distance of 6.5 cm from each other (Seraglia et al., 2011). The task was divided into two blocks: the CUT block and the NOT-CUT block. Each block comprised 64 trials in which the participant had to bisect the lines. In the CUT block only, after button switching the line was broken into two pieces according to the participant's response (Figure 1).

Procedure

Participants were invited to sit on a comfortable chair in front of a table and dress the virtual reality helmet. They placed their right hand holding the Wiimote® centrally over a soft substrate on the table. Participants firstly performed a training task (16 trials) and then the experimental task began. Instructions were to first place the red dot inside a circle appearing randomly to

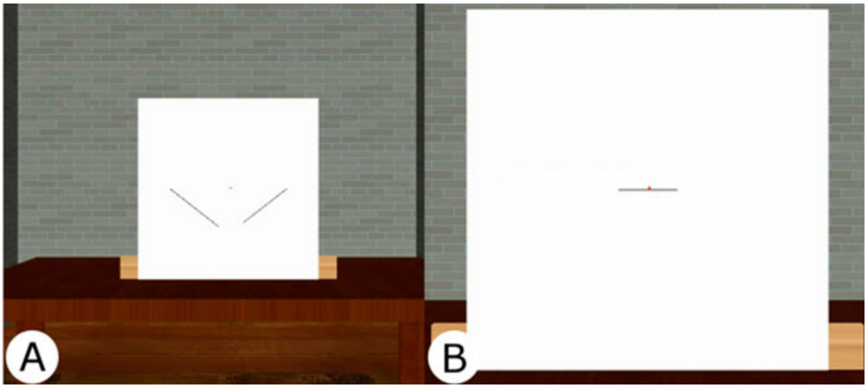

Figure 1. The virtual environment used for the experiment was a room inside which a wooden table was placed. A white vertical panel was used for the presentation of the lines. (A) An example trial of the CUT condition at 120 cm distance. (B) An example trial of the NOT-CUT condition at 60 cm distance. To view this figure in colour, please see the online issue of the Journal.

the left or to the right of the white panel in order to calibrate the starting position of the Wiimote® and, after the appearing of the line, to place the red dot at the centre of it and subsequently to press the A button of the Wiimote® to confirm the position. A 10 ms masking panel appeared before the presentation of the line (Figure 2). At the beginning of each block participants were informed about the type of block (CUT or NOT-CUT). The presentation of lines and distances were randomized. The order of blocks was counterbalanced across participants. There was no time limit to perform the task. Two dependent variables were considered: the time (Time) to complete each bisection; the difference in percentage with respect to line length (Error %) between the indicated midpoint and the objective midpoint. Positive values indicated shifts to the right of the objective midpoint, whereas negative values indicated shifts to the left.

At the end of the experiment, participants were asked to give a subjective estimate of the two distances perceived within the virtual environment. The experimenter placed a retractile meter on the participants' chest, and started to stretch it until the participant stopped him, according to the subjective virtual distance perceived. Participants indicated a mean value of 47.2 cm for the 60 cm virtual distance, and of 112.4 cm for the 120 cm virtual distance.

The overall duration of the experiment was 30 minutes.

RESULTS

A multivariate analysis of variance (MANOVA) for repeated measures was performed on Error % and on Time, considering as factors action (CUT, NOT-CUT) and distance of the line (60 and 120 cm). The analysis indicated a

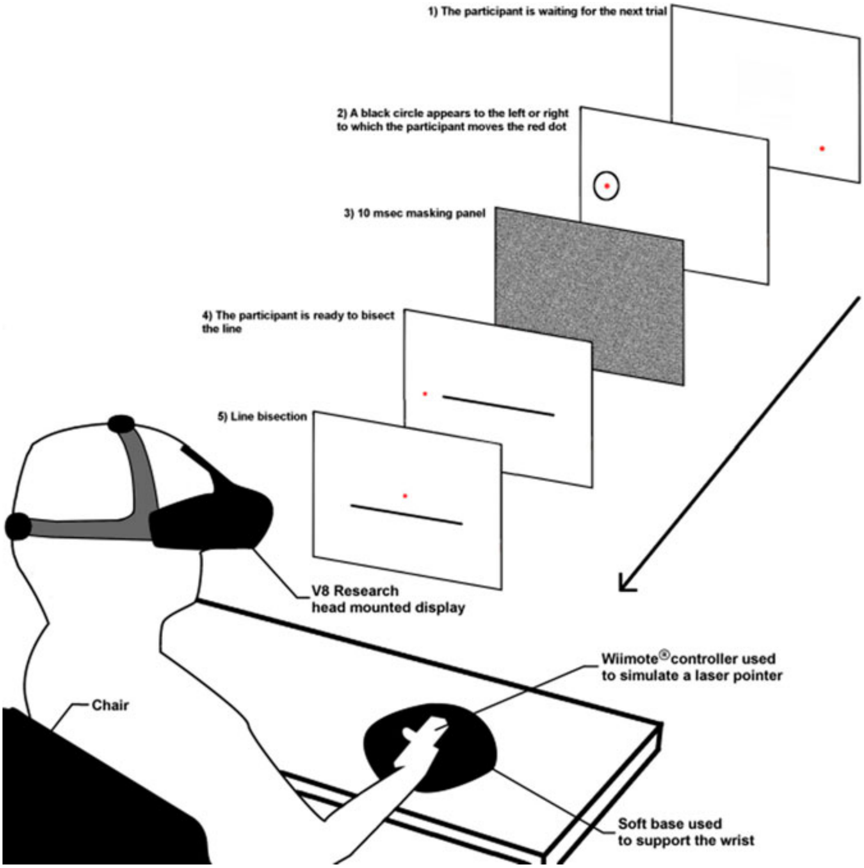

Figure 2. The lower part of the figure shows the participant wearing a V8 Research head mounted display and placing the wrist over a soft base to manipulate the Wiimote® controller. The upper part of the figure represents the experimental trial sequence from the waiting of the line to the bisection of it.

significant multivariate effect of distance, $F(2, 36) = 12.49$, $p = .001$, $\eta_p^2 = .410$, and a significant multivariate interaction effect between action and distance, $F(2, 36) = 4.16$, $p = .024$, $\eta_p^2 = .188$.

The analysis revealed a significant main effect of distance for Error %, showing that participants bisected to the left of the true midpoint when the line was presented at 60 cm (Mean = −0.219%, *SD* = 1.02) and to the right of the true midpoint when it was presented at 120 cm (*M* = 0.186%, *SD* = 1.09), $F(1, 37) = 11.56$, $p = .002$. The interaction between action and distance was significant, $F(1, 37) = 8.55$, $p = .007$. Bonferroni post hoc analysis revealed a significant difference between CUT (*M* = 0.00%, *SD* = 0.16) and NOT-CUT (*M* = 0.44%, *SD* = 0.2) at the distance of 120 cm ($p = .028$), showing a greater error to the right for

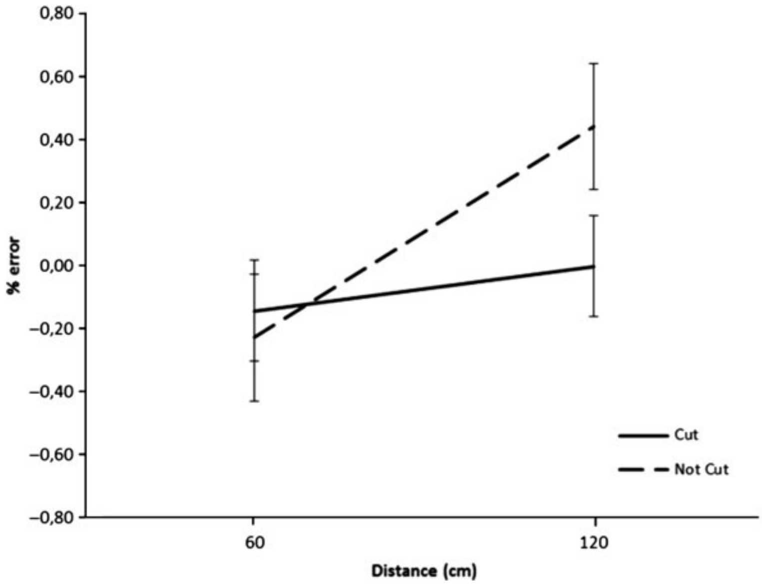

Figure 3. The graph shows the percentage error (Y axis) along the distances of line presentation, 60 and 120 cm (X axis) in the interaction between the factors distance and action. Negative values indicate an error on the left of the true centre of the line; positive values indicate an error on the right of the true centre of the line. Error bars represent the standard error ± SE.

the latter, whereas at the distance of 60 cm the difference was not significant (CUT: $M = -0.14\%$, $SD = 0.16$; NOT-CUT: $M = -0.23\%$, $SD = 0.2$) and the error was always to the left. As can be seen in Figure 3, the pattern of differences is similar to that recorded in research into pseudoneglect used to check space categorization into peripersonal and extrapersonal in healthy subjects (see Jewell & McCourt, 2000).

The analysis revealed a significant main effect of distance for time, showing that participants took more time to bisect the line at 60 cm (4.03 s; SD = 1.21) than at 120 cm (3.87 s; SD = 1.39), $F(1, 37) = 6.52$, $p = .015$, $\eta_p^2 = .150$. However, neither the main effect of action nor the interaction between action and distance were significant, indicating the absence of any effect of action on the time required to bisect the lines.

DISCUSSION

The aim of the present article was to directly test the effects of the function of the tool in the coding of space by manipulating, in a virtual environment, the distance of the line to be bisected and the effects of the tool used to indicate the midline. The mean reported distance of the line was 47.2 cm for the close line and 112.4 cm for the far line. The tool was a Wiimote® that in half of the trials behaved as a laser pointer and in the other half as a laser cutter. In both cases it directed a red dot on the screen following participants' hand movements. At the time of the buttonpress, the position of the red dot on the line was recorded as the response. Only after the response, the different effects of the tool were evident: In the case of the laser cutter, the line was broken into two pieces, whereas, in the case of the laser pointer, it was not. According to the definition, discussed in the introduction to this article, of peripersonal space as the only space in which the actions of an individual can lead to some consequences, the experimental question was: If I use a tool whose effects physically modify the space in which I act, is that space always encoded as peripersonal space? The results of the present experiment seem to support this possibility. When bisecting the close line, there was no difference in the response given by the two tools (CUT: −0.14%; NOT-CUT: −0.23%; the error was always to the left of the objective midpoint), replicating the findings of Berti and Frassinetti (2000) on the neglect patient: The space close to the body was always coded as peripersonal (as indicated by the presence of the syndrome) independently from the tool used. When bisecting the far line, instead, the response differed according to tool's effects: In the neglect patient, the use of a laser pointer cancelled the bias towards right that was still present when using a stick. In the present experiment, when using the laser cutter (0.00%), the response was the same as when the task was performed on the close line; when using the laser pointer (0.44%; the error was to the right of the objective midpoint) the response was different. Therefore, the data indicate that the space in which a far line is placed is coded as peripersonal space when the effects of the tool used to perform the response are able to physically modify the line by breaking it into two pieces.

These results may be attributed exclusively to the knowledge that the participant has about the effects determined by the tool used in that block of trials, since, from the proprioceptive, visual, motor, and tactile points of view, the relationship between the agent and the tool until response was exactly the same in both blocks. Furthermore, the absence of a statistical difference between the two experimental conditions when bisecting the close line ensures that midpoint error feedback provided only during CUT condition by breaking the line into two pieces that separate cannot be the reason of the presence of a statistical difference between the two conditions when bisecting the far line.

Finally, the absence of a bias in the far space for the CUT condition suggests the possibility of a different strategy in task performance according to space coding: higher accuracy when the participant acts in a space coded as peripersonal, both when this space is defined by metric parameters (CUT and NOT-CUT at 60 cm) and when it is defined by functional ones (CUT at 120 cm). This possibility proposes that, as mentioned in the introduction to this article, the nature of an action's consequence may have a role in modulating action execution.

In conclusion, the present article attributes a crucial role in the coding of space to tool function and, in particular, suggests that the space in which the individual is able to determine a physical consequence is categorized as peripersonal space, independently from the actual distance of that space from the individual's body.

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