

Crossing the Pillars of Hercules: The role of spatial frames of reference in error making

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This paper introduces a perspective accounting for errors that may occur as a result of the human interaction with the three-dimensional (3D) space. Particularly, we are interested in errors that are caused by cognitively crossing the boundary between peripersonal and extrapersonal space. Several behavioural, neurophysiological, and neuropsychological perspectives are reviewed in order to develop the theoretical framework on which our ideas are founded. We argue that cognitively crossing the boundary implies switching from one frame of reference to another, which, as a consequence, implies specific costs. The results of five experiments (overall involving 76 participants) support our hypothesis, suggesting the existence of different action-oriented spatial frames of reference.

When we interact with objects in space, we have the feeling that our brain makes use of a unitary map of the three-dimensional (3D) space, possibly a topographical one, which is common to all our senses and is used to programme our actions. Actually, it is well known that senses and effectors define multiple spaces (retinal, auditory, oculomotor, limb spaces, and so forth), which are very different from each other. A consequence of the multiplicity of modality-specific spaces is that all of them make use of different coordinate systems, or frames of reference (Berti & Frassinetti, 2000; Bjoertomt, Cowey, & Walsh, 2002; Cowey, Small, & Ellis, 1999; Kerkhoff, 2000; Lacquaniti, 1995; Marshall & Fink, 2001; Pegna et al., 2001; Pitzalis, Di Russo, Spinelli, & Zoccolotti, 2001; Pizzamiglio et al., 1989; Pouget & Driver, 2000; Weiss, Marshall, Zilles, & Fink, 2003). How the brain, or the

cognitive system, makes order of the multiple, incomplete, and partially distorted sensory information is a long-lasting problem in psychology and neurophysiology. It is widely recognized, for example, that action within 3D space not only is a matter of perceptual cues, but also depends on the type of actions that we are supposed to perform on the basis of the perceptual information (Ishimura, 1995; Ishimura & Shimojo, 1994; Wohlschlager, 2000, 2001; Wohlschlager & Wohlschlager, 1998). Finally, the discovery of visuomotor neurons in the ventral premotor cortex reported by Murata et al. (1997), Fadiga, Fogassi, Gallese, and Rizzolatti (2000), Rizzolatti, Fogassi, and Gallese (1997, 2002) in monkeys, and in humans (Rossetti, 1998), might be viewed as a further neurophysiological evidence of the mutual connection between motor and sensory systems (see Rizzolatti, Fadiga, Fogassi, &

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Gallese, 2002, for a recent account on mirror neurons).

Frames of reference

Several authors have proposed that our brain codes different representations of space, and different neural systems have been identified that subserve the interaction of individuals with different regions of the 3D space around them. For instance, Previc (1998) has suggested a model that distinguishes among four main spatial systems: (a) peripersonal, (b) focal extrapersonal, (c) action extrapersonal, and (d) ambient extrapersonal. According to this author, the peripersonal system (PrP) is involved in reaching movements and objects manipulation, and is mainly based on the dorsolateral visual cortical pathways, as defined by Ungerleider and Mishkin (1982). The focal extrapersonal system (FcE) is mainly related to visual search and object recognition, and is mainly based on ventrolateral visual cortical pathways. The action extrapersonal system (AcE), instead, is mainly involved in navigation and orienting, and is mainly based on ventromedial visual cortical pathways. This account is also in line with the suggestion that the dorsal system is involved in the visuo-motor transformations needed to perform actions on objects in the external space (Bridgeman, Peery, & Anand, 1997; Milner & Goodale, 1995). Rizzolatti and coworkers (Rizzolatti & Camarda, 1987; Rizzolatti, Gentilucci, & Matelli, 1985) proposed a different model that also posits the existence of multiple representations of the 3D space. On the basis of their findings in brain-damaged subhuman primates, they identified a personal space, mainly characterized by oral and tactile interactions between the individual and the world, a peripersonal space, where reaching movements occur, and a far space, where only oculomotor actions may occur. In addition, Grusser (1983) distinguished between a grasping space, which is similar to the one proposed by other authors (Jeannerod, 1988; Paillard, 1982; Rizzolatti & Camarda, 1987), a near-distant space, a far-distant space, and a visual background. Finally, Cutting and Vishton

(1995) proposed that the interactions between individuals and the world occur within three main portions of the 3D space: a personal space, which is delimited to be within 2 metres around the observer; an action space, which extends for 30 metres; and a vista space beyond the latter. Although there is still disagreement about the number of representations and the location of the boundaries between them, it seems quite clear that a distinction between peripersonal (near) space and extrapersonal (far) space is widely accepted.

A fallible representational system

All the perspectives reported above offer a set of detailed hypotheses about the cognitive representation of 3D space. The behavioural data from studies with normal subjects has relied solely on the reaction time needed to switch from one space to another. The issue of whether switching space also leads to higher probability of committing errors has never been investigated so far.

In the following studies, we investigated the effects of switching between peripersonal and extrapersonal spaces (i.e., crossing the border separating them) on error making.

The agreement between models regarding the location of the boundary between PrP and FcE offers a great advantage from a methodological point of view, allowing the researcher to make precise predictions about the use of such representations. Crossing that border may, in fact, lead to the engagement and disengagement of two spatial representations that are very different. According to Previc (1998), the PrP system, in fact, concerns arm and hand control programming as well as smooth oculomotor activity programming needed to acquire relevant spatial information, while the principal motor systems related to FcE representation concern the control of head in space and secondarily the control of the position of the eyes (especially for saccadic activity) and the torso.

If the representations described above really exist in the brain, and if the hypothesis that a mismatch between these representations can be

responsible for shortcomings in human performance is plausible, then it will be possible to include into the current models of space representation the notion that crossing the border between PrP and FcE involves specific costs in terms of reduced speed and accuracy. Particularly, such a perspective would predict that switching attention from one portion of space to another would lead to the occurrence of errors.

EXPERIMENT 1

Switching from one 3D representation to another could affect performance in terms of accuracy and/or speed. In order to verify this prediction, a paradigm to investigate attentional shifts in depth was devised. The apparatus used in this first experiment involved stimuli displaced at different depth planes: some belonging to the peripersonal space and others to the extrapersonal space. The apparatus was basically the same as that used by Couyoumdjian, Di Nocera, and Ferlazzo (2003). However, the procedure was radically different, as no cueing was used: Participants were only requested to respond as quickly as possible to the presence of a stimulus by responding on an eight-button box.

We hypothesized that performance is worse when sequentially performing a cognitive operation related to stimuli that are presented in different functional portions of space than when stimuli are presented in the same space, distances between stimuli being equal.

Method

Participants

A total of 16 students (8 males and 8 females) volunteered for the experiment. Their mean age was 26.18 years, ranging from 20 to 30 years. All had normal or corrected-to-normal vision. They were right-handed, and they were naive to the purpose of the experiment.

Apparatus

The experimental apparatus was an empty wooden box (200 × 50 × 50 cm, see Figure 1). One end

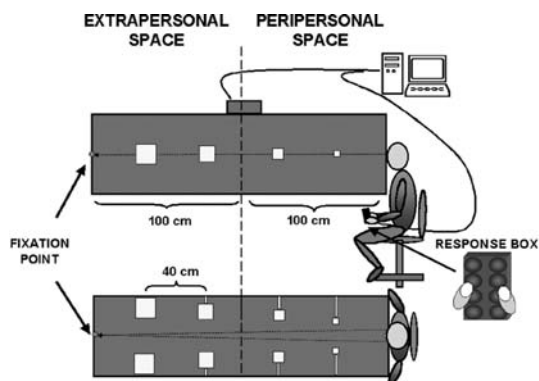


Figure 1. Lateral and top view of the apparatus used in Experiments 1 and 2.

was open to allow the observer to look inside. The inner walls were painted black in order to reduce any visual information about depth, apart from that due to the stimuli presentation.

Stimuli

The stimuli were eight translucent cubes (2.8° in size), each one containing a yellow light-emitting diode (LED). They were placed at eye-level along the inner vertical walls of the apparatus, four on the right side and four on the left side. The four pairs of cubes, one cube on the left and one on the right, were at 40, 80, 120, and 160 cm from the observer, so that the distance between all adjacent cubes was equal. The luminance of the stimuli was also adjusted across distances. The eccentricity of the cubes was about 8°, but it was not exactly matched across stimuli in order to avoid the complete occlusion of the distal cubes. In this set-up, ocular cues such as binocular disparity were the more effective cues to distance. The border between the peripersonal space and the extrapersonal space was located at the midpoint between the second and the third pair of cubes, at 1 m from the observer. Four cubes (two on the right side and two on the left side) were within the peripersonal space, and four cubes laid within the extrapersonal space.

The fixation point was a red LED placed in the centre of a plaque located at 2 m from the observer.

Response box. A set of eight microswitch buttons, reproducing the stimuli mapping, was developed in order to collect the participants' responses (Figure 1). The buttons were round, had a diameter of 2.5 cm, and rose 2 mm above the surface of the response box. Participants held the 9×12 -cm response box with the two hands in such a way that all the buttons were reachable by their left and right thumbs. Furthermore, they were invited to put their thumbs in the middle of the box at each trial. Both stimuli presentation and response collection were controlled by software developed using LabVIEW by National Instruments. The time resolution for both stimuli presentation and response collection was 1 ms.

Procedure

Participants sat in a dark and silent room, looking inside the apparatus through the open end. Their head movements were constrained by an adjustable head-and-chin rest, in such a way that the stimuli were at eye-level, and the first row of cubes was at a distance of 40 cm. Participants were told to maintain their gaze on the fixation point at all times during each experimental session.

On each trial, a pair of stimuli was turned on one after the other, with a mean interstimulus interval of 800 ms. The mean intertrial interval was 1,200 ms. On each trial, the two stimuli were presented for 200 ms and could appear at different locations or the same location. This yielded four experimental conditions: (a) both stimuli within a pair were located in the peripersonal space, but at different locations ("peripersonal" condition); (b) both stimuli within a pair were located in the extrapersonal space, but at different locations ("extrapersonal" condition); (c) the stimuli within a pair were located in two different spaces, either extra-peri or peri-extra ("crossing" condition); (d) the two stimulus locations were actually the same location ("same" condition). Participants' task was to press the button corresponding to each stimulus immediately after its presentation. They were asked to be as fast and accurate as possible, and they were not allowed to look at the response box.

Participants performed the task in four sessions consisting of 182 trials presented in a random order. Participants were allowed to rest for a few minutes after each session. A training session was administered before the experimental blocks.

Design

All the analyses were run on errors to the second stimulus of each pair. Only errors generated after a correct response to the first stimulus of the pair were considered. Angular transformed proportions of errors [$2\sqrt{\arcsin(x)}$, where x is the proportion] were analysed using a Hand (2) \times Location (4) repeated measures analysis of variance (ANOVA). Angular transformed data were used, as proportions cannot be analysed through ANOVA (e.g., Hinkelmann & Kempthorne, 1994). The factor hand produced two conditions (left and right), and the factor location produced four conditions (same, peripersonal, crossing, and extrapersonal). Errors were both incorrect and missing responses. An identical analysis was carried out on the reaction times to the second stimulus of each trial in order to test for any speed/accuracy trade-off effect. Two further analyses were carried out in order to rule out any bias due to the stimuli positions inside the apparatus, or to the positions of the buttons on the response box. They were performed on the reaction times and angular transformed proportion of errors to the second stimulus of the "same" trials, as a function of its side (left and right) and distance (40, 80, 120, and 160 cm) from the observer. Reaction times (RTs) faster than 100 ms and slower than 1,000 ms were excluded from the analyses. Omission and commission errors were considered alike because the mechanism that we hypothesized to be involved in error making would be responsible for both.

Results

The analysis showed no statistically significant main effect of the hand, $F(1, 15) = 1.17$, $p = .296$. Differences between the error rates in the four experimental conditions were instead significant, $F(3, 45) = 19.29$, $p < .0001$. As expected,

Duncan test showed that participants made more errors in the crossing condition than in the two no-crossing conditions (peripersonal and extrapersonal) and fewer errors in the same condition (Table 1). The location by hand interaction was also significant, $F(3, 45) = 10.39$, $p < .001$, but it was only due to the larger difference between the proportions of errors made by the two hands on the extrapersonal trials than in the other conditions.

Analysis on RTs showed significant main effects of both hand and location, $F(1, 15) = 20.16$, $p < .001$, and $F(3, 45) = 83.84$, $p < .0001$, respectively. Duncan testing showed that responses on trials belonging to the same condition were faster than those belonging to the other conditions ($p < .01$), whereas responses on trials belonging to the crossing condition were slower than those belonging to the peripersonal

($p < .01$) and extrapersonal conditions ($p < .01$). The interaction between hand and location was also significant, $F(3, 45) = 3.35$, $p < .05$. Duncan testing showed that individuals were faster to respond with their right hand than with their left hand on trials belonging to the peripersonal and extrapersonal conditions ($p < .05$ in both cases), but not on trials belonging to the same and crossing conditions.

In order to test for stimulus or button location biases, one further analysis was carried out on error proportions (angular transformed) and RTs on trials belonging to the same condition, as a function of both distance from the observer and side. No main effects of stimulus/button distance and side emerged for errors, $F(3, 45) = 1.78$, $p = .16$, and $F(1, 15) = 0.22$, $p = .64$, respectively, nor distance by side interaction, $F(3, 45) = 1.14$, $p = .34$ (Table 2). However, results on RTs

Table 1. Mean reaction times^a and mean percentages of errors on the same, peripersonal, crossing, and extrapersonal trials with right and left hands in Experiment 1

		Trial							
		Same		Peri		Cross		Extra	
	Hand	M	SD	M	SD	M	SD	M	SD
Reaction times	Right	386.45	52.03	519.16	53.71	575.53	45.45	519.41	52.08
	Left	392.88	52.60	540.30	57.32	584.91	46.07	550.96	55.29
% Errors	Right	15.18	7.89	27.18	14.9	35.70	15.7	21.50	11.8
	Left	16.12	11.2	22.18	13.1	37.20	15.3	31.82	16.0

^aIn ms.

Table 2. Mean reaction times^a and mean percentages of errors on the same trials as a function of side of stimulus and distance from observer in Experiment 1

		Distance ^b							
		40		80		120		160	
	Side	M	SD	M	SD	M	SD	M	SD
Reaction times	Right	358.65	66.90	420.55	72.58	410.74	65.89	411.24	72.68
	Left	366.34	64.59	396.87	59.08	397.58	74.66	387.09	75.63
% Errors	Right	11.72	11.09	24.06	17.72	17.81	14.72	17.18	17.22
	Left	15.31	16.78	18.43	10.75	16.25	11.03	16.87	14.82

^aIn ms. ^bIn cm.

showed a difference in terms of speed, $F(3, 45) = 4.02$, $p = .012$, due to the faster responses made with the buttons located nearest to the observers.

Discussion

In Experiment 1, observers were presented with stimuli appearing in sequence at the same or different depths, within peripersonal and extrapersonal space. The observers were required to press as fast as possible the button that corresponded to the location of the stimulus. In the critical crossing condition, two successive stimuli appeared in different spaces. It was expected that a larger proportion of errors would be made in that condition, as a consequence of the fast switching between two different representations of space.

The results showed that participants made significantly more errors on the crossing trials than when they were presented with stimuli appearing at different locations in the same space, distances being equal.

Several other potential explanations for the boundary-crossing effect need to be considered and ruled out, though. First, one might propose that the crossing effect is merely due to perceptual factors, due to using a real 3D scene. If this were correct, then a linear effect of distance would be expected upon the proportion of errors, and the crossing effect would be reduced to a random variation around it. This does not seem to be the case. The proportions of errors that participants made on the peripersonal and extrapersonal trials do not differ from each other. That is, the probability of making an error does not increase linearly with the distance from the observer. Second, a two-dimensional account for the boundary-crossing effect is also unlikely. The eccentricities of the stimuli were not exactly matched, in order to prevent occlusion. Thus, one might speculate that participants oriented their attention on a frontal plane, rather than in depth. However, this suggestion would also predict linear effects of distance, and this was not observed.

Third, an explanation for the boundary-crossing effect based upon vergence or accommodation programming or execution is also unlikely. Only

two patterns of results would be expected if the boundary-crossing effect were due to vergence or accommodation. If the direction of the vergence determined the effect, then no difference would be expected among the proportions of errors that participants made on the three experimental conditions (peripersonal space, crossing, extrapersonal space), because the direction of vergence movement was identical in all those cases. On the other hand, if the amplitude of the vergence determined the boundary-crossing effect, the proportion of errors would be expected to decrease linearly with the distance from the observer. This is because the vergence movements would have been expected to be larger on trials occurring in the peripersonal space, intermediate on crossing trials, and smaller on trials occurring in the extrapersonal space. Thus eye movements cannot account for the observed pattern of results.

The analysis of same trials did not reveal any effect of stimuli side (left and right) and distance (40, 80, 120, and 160 cm) from the observer. This suggests that the stimuli that appeared at the spatial locations involved in the crossing trials were as easy to detect as those that appeared at the other spatial locations. This finding confirms that the boundary-crossing effect on errors cannot be accounted for by a bias affecting a particular side or spatial location.

The results of this experiment also showed a boundary-crossing effect on the reaction times. Participants were slower to respond to a stimulus after they had responded to a stimulus presented in a different space. As both errors and reaction times increased on crossing trials, the effect cannot be explained by a speed/accuracy trade-off.

In sum, the larger proportion of errors made on crossing trials than on no-crossing trials is accounted for by the hypothesis that on crossing trials the participants had to shift from one representation of the 3D space to another.

EXPERIMENT 2

The procedure of Experiment 1 was aimed at reducing the role of visual distance cues as much

as possible. Indeed, both the relative size and the luminance of the stimuli were matched across distances. Stimulus eccentricity was also manipulated, even though it was not perfectly equated across locations in order to avoid a complete occlusion of the distal stimuli. Moreover, no cue was available from inside the apparatus, except when a stimulus was turned on and briefly lightened the interior of the apparatus. With this arrangement, distance cues from the apparatus were available only on the instant a stimulus appeared, but it is unlikely that such an intermittent lightening was enough to use them efficiently. Although such a condition was important in order to rule out the influence of confounding factors, it was also rather unfamiliar to participants and not ecologically valid.

In order to replicate the results of Experiment 1 and to investigate the effect of visual depth cues on the genesis of action slips, we carried out a second experiment that was almost identical to the first one. The only exception was that participants could see all the stimuli within the apparatus at all times and thus use all the visual cues to organize the space within. The failure to replicate the boundary-crossing effect, in this new condition, would suggest a negligible role of visual and perceptual cues of distance in yielding the distinction between “far” and “near” space. On the contrary, larger amplitude of the boundary-crossing effect would suggest that visual and perceptual cues have a primary role.

Method

A total of 16 students (8 males and 8 females) volunteered in the experiment. Their mean age was 25.92 years, ranging from 21 to 30 years. All of them had normal or corrected-to-normal vision. All participants reported to be right-handed, and they were naive as to the purposes of the experiment. None of them had also participated in the previous experiment. The same stimuli and procedure as those used in Experiment 1 were also used in the present experiment. The only exception was that the posterior base of the apparatus was removed, and the room was dimly illuminated, allowing the observer to see all the stimuli inside the box, even while they were switched off.

Results

The analysis carried out on error proportions (angular transformed) as a function of location (same, peripersonal, crossing, and extrapersonal) and hand (right and left) did not show any statistically significant main effect of the hand, $F(1, 15) = 0.5$, $p = .82$. A significant main effect of location was found instead, $F(3, 45) = 26.41$, $p < .0001$. Duncan testing showed that in this experiment the error rate on trials in the crossing condition was significantly higher ($p < .01$) than that in all the other conditions (Table 3). Also, participants made fewer errors in the same condition than in the others ($p < .01$), whilst no difference

Table 3. Mean reaction times^a and mean percentages of errors on the same, peripersonal, crossing, and extrapersonal trials with right and left hands in Experiment 2

		Trial							
		Same		Peri		Cross		Extra	
		Hand	M	SD	M	SD	M	SD	M
Reaction times	Right	369.50	66.47	476.94	55.85	489.26	67.55	469.17	63.18
	Left	385.62	68.72	492.57	74.61	512.80	67.26	509.68	58.15
% Errors	Right	8.13	3.76	15.0	6.07	19.1	9.08	12.8	5.03
	Left	6.18	0.73	13.0	6.80	18.6	7.43	16.5	7.67

^aIn ms.

between error rates on trials belonging to the peripersonal and extrapersonal conditions was found. A condition by hand interaction was also significant, $F(3, 45) = 3.12, p < .03$, but again this was due to the larger difference between the proportions of errors made by the two hands on the extrapersonal trials than in the other conditions.

An identical analysis performed on RTs showed significant main effects for both hand and location, $F(1, 15) = 30.92, p < .0001$, and $F(3, 45) = 44.33, p < .0001$, respectively. Duncan testing of the location main effect showed that RTs on trials belonging to the same condition were significantly faster than RTs on all the other conditions ($p < .01$), but there were no differences among RTs on trials belonging to the peripersonal, crossing, and extrapersonal conditions. Furthermore, reaction times were faster for the responses given with the right hand than for those given with the left hand ($p < .05$). Interaction between hand and location was also significant, $F(3, 45) = 3.06, p < .05$, due to a larger left/right difference in the extrapersonal condition.

Results of the analysis carried out on error proportions (angular transformed) on trials belonging to the same condition as a function of distance from the observer and side did not reveal any significant main effect or distance by side interaction, $F(3, 45) = 1.67, p = .19$, $F(1, 15) = 0.76, p = .40$, $F(3, 45) = 0.99, p = .41$, respectively (Table 4).

Additional analyses carried out on RTs showed significant main effects of both stimulus/button distance and side, as well as a distance by side

interaction, $F(3, 45) = 12.32, p < .01$, $F(1, 15) = 10.42, p < .01$, $F(3, 45) = 6.92, p < .01$, respectively. Duncan testing showed that participants were slower to respond to stimuli appearing at a distance of 160 cm than to stimuli appearing at the other distances ($p < .05$) and slower to give a response with their right hand than with their left hand for stimuli appearing at a distance of 160 cm ($p < .05$).

Discussion

Results from this experiment replicated almost perfectly those of Experiment 1. The lowest error rate was again found in the same condition, and the highest on trials in the crossing condition. The only difference between the results of the two experiments was that in the second study participants made fewer errors overall. This is not surprising and can be easily attributed to the more favourable light conditions. The proportions of errors that participants made on the peripersonal and extrapersonal trials did not differ from each other. This finding supports the hypothesis that the boundary-crossing effect cannot be accounted for by the distance from the observer. In contrast to Experiment 1, participants did not show an effect of crossing on RTs. However, this finding also suggests that a speed/accuracy trade-off accounting for the crossing effect on errors is not indicated.

The responding hand had similar effects on RTs in both the experiments. Indeed, participants

Table 4. Mean reaction times^a and mean percentages of errors on the same trials as a function of side of stimulus and distance from observer in Experiment 2

		Distance ^b							
		40		80		120		160	
	Side	M	SD	M	SD	M	SD	M	SD
Reaction times	Right	387.14	83.46	362.43	61.83	347.80	72.10	444.13	97.61
	Left	399.85	83.73	344.89	60.55	341.22	61.54	393.58	90.85
% Errors	Right	5.75	6.99	8.15	7.76	9.11	9.08	6.59	7.34
	Left	6.90	6.85	11.94	8.45	7.21	6.63	8.78	6.23

^aIn ms. ^bIn cm.

were faster when they responded with the right hand than when they responded with the left hand. Such an effect was of course expected, as all the participants were right-handed. Finally, side and distance from the observer again did not affect the proportion of errors that the participants made, suggesting that locations were comparable in terms of difficulty. As the effects of side and distance on RTs were only present at the farthest right location, and absent in the previous experiment, they were probably due to chance.

Results of Experiment 2 support the hypothesis that specific spatial representations for the peripersonal and the extrapersonal space exist. Furthermore, results suggest that visual and perceptual cues of distance are not likely to be the only determinants of the distinction between the peripersonal and extrapersonal spaces on its own, because in that case a larger crossing effect was to be found in the present experiment. Nevertheless, the availability of clear visual distance cues does not cause the crossing effect to fade away, and this suggests a role of visual and perceptual cues of distance (e.g., Coello, Magne, & Plenacoste, 2000), though limited.

EXPERIMENT 3

Results from Experiments 1 and 2 were interpreted as switching costs between the representations of peripersonal and extrapersonal space. In both experiments a shift of attention was obtained by presenting stimuli in different regions of the 3D space, while participants used a response box to indicate the position of the stimuli. The use of this response box might be a confounding factor. The central buttons of the response box could be the most difficult to discriminate in a “near and far” logic, and the occurrence of slips when pressing those buttons may simply have been due to a higher probability of their occurrence. The present experiment was planned to eliminate doubts related to such a confounding variable, by using the same task and the same response box as those in the previous experiments, but a two- instead of a three-dimensional

layout of stimuli. In this way, any border-crossing effect should be attributed to the response box rather than to the cognitive representations of the 3D space.

Method

Participants

A total of 12 students (5 males and 7 females) volunteered in the experiment. Their mean age was 26.4 years, ranging from 20 to 30 years. All had normal or corrected-to-normal vision. They were all right-handed, and they were naive to the purposes of the experiment.

Stimuli

The stimulus array, consisting of a 4×2 matrix composed of eight squares, reproducing the same mapping of the response box, was displayed on a computer screen. However, no depth information was provided by such stimuli as they were on the same depth plane. Each square subtended the same visual angle as did the cubes used in Experiments 1 and 2 (2.8°). The squares acted like the cubes used in the previous experiments, lightening up for 200 ms when turned on, and the shapes of the squares were always visible. The fixation point was a red spot in the middle of the matrix (see Figure 2).

Procedure

Participants sat in a dark and silent room and were told to maintain their gaze on the fixation point at all times during each experimental session. The sequence was composed of the same 182 trials as those used in the other experiments. A training session was administered before the experimental

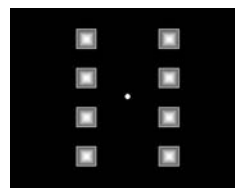


Figure 2. 2D layout used in Experiment 3. The stimuli were administered on a computer screen.

blocks, and participants were allowed to rest for a while after each session.

Design

Angular transformed proportions of errors to the second stimulus of each pair were analysed using a Hand (2) \times Location (4) repeated measures ANOVA. However, in the present experiment the peripersonal, crossing, and extrapersonal conditions were fictitious, as all the stimuli were on the same depth plane.

Results

The analysis carried out on angular transformed error proportions as a function of location (same, peripersonal, crossing, and extrapersonal) and hand (right and left) did not show any significant main effect of hand, $F(1, 11) = 0.19$, $p = .67$, but a significant main effect of location was found, $F(3, 33) = 6.57$, $p = .001$. Location by hand interaction, $F(3, 33) = 1.21$, $p = .32$, was not significant. Duncan testing of the location main effect showed that participants made fewer errors in same conditions than in all the other conditions ($p < .01$). As expected, no crossing effect and no difference between the peripersonal and extrapersonal conditions were found in this experiment (Table 5).

Discussion

Results of the present experiment showed that participants made fewer errors in the same condition than in any other conditions. However, they did not make more errors on the crossing trials than on the peripersonal or extrapersonal

trials. As the experimental set-up in this experiment was identical to that of the previous experiments, except for the use of a two-dimensional array of stimuli in place of the three-dimensional layout previously used, these results confirm that the boundary-crossing effect was not due to factors related to the response box used. The relevance of this result is two-fold. First, they rule out an important confounding variable, related to the response box, confirming that the boundary-crossing effect is not an artefact but a genuine effect. Second, they support the hypothesis that the boundary-crossing effect depends on the processing of 3D spatial information.

EXPERIMENT 4

Results of the previous experiments confirm that individuals make more errors when required to respond to two successive stimuli that are processed in different spatial representations than when required to respond to two successive stimuli within the same space, even though the distance between stimuli is always the same. Such a boundary-crossing effect was not due to vergence or accommodation programming or execution, as has been discussed above, nor to artifacts due to the response box. However, a potentially confounding factor was present in those experiments because the peripersonal and the extrapersonal space trials involved the closest and the farthest locations from the observer. Those locations might act as reference points for the observers, possibly leading to an anchor effect (e.g., Sadalla, Burroughs, & Staplin, 1980) favouring the

Table 5. Mean percentages of errors made on the (pretending) same, peripersonal, cross, and extrapersonal trials with right and left hands in Experiment 3

Hand	Trial							
	Same		Peri		Cross		Extra	
	M	SD	M	SD	M	SD	M	SD
Right	10.05	17.63	12.61	14.48	12.43	14.86	14.16	17.60
Left	4.87	2.44	13.53	12.50	14.67	13.11	12.85	14.57

attention shifts from or to those points. Such an anchor effect would not be present on cross-space trials because they only involved the two central rows of stimuli inside the apparatus. Furthermore, as the spatial locations involved in the cross-space trials are the central locations of the apparatus, they could lead to a centre of mass effect (Shuren, Jacobs, & Heilman, 1997) that could also account for the larger number of errors on those trials. Consequently, we ran two more experiments in which the effect of the boundary between the two spaces and the effect of symmetry plane were dissociated by shifting all of the stimuli 40 cm farther from the observer. With this arrangement, the boundary between the peripersonal and the extrapersonal spaces was located between the first and the second row of targets, whereas the symmetry plane was located between the second and the third row of targets.

Method

Participants

A total of 18 students (5 males and 13 females) volunteered in the experiment. Their mean age was 24.39 years, ranging from 20 to 36 years. All had normal or corrected-to-normal vision, were right-handed, and were naive to the purposes of the experiment.

Apparatus

The apparatus was the same empty box as that described for Experiments 1 and 2, but stimuli were rearranged, as described below.

Stimuli

The stimuli were identical to those used in Experiments 1 and 2, with the only exception being that their locations inside the box were shifted 40 cm away from the observer. Thus, the four pairs of cubes, one cube on the left and one on the right, were at 80, 120, 160, and 200 cm from the observer. With this new arrangement, the border between the peripersonal space and the extrapersonal space was located between the first and the second row of cubes, at 1 m from the observer, and the symmetry plane was located between

the second and the third row (see Figure 3). Two cubes (one on the right side and one on the left side) lay within the peripersonal space, and six cubes lay within the extrapersonal space.

The fixation point was always a red LED placed in the centre of a plaque located at 2 m from the observer.

Response box. The same response box containing eight press buttons as that used in Experiments 1 and 2 was used in the present experiment.

Procedure

The same procedure used in Experiment 1 was also used in the present experiment. Participants sat in a dark and silent room, looking inside the apparatus through the open end.

There were 182 trials. On each trial, two stimuli were turned on one after the other, with a mean interstimulus interval of 800 ms. Mean intertrial interval was 1,200 ms. The stimuli within each trial were presented for 200 ms and could appear in the same or different spaces, or could be presented at exactly the same location. This yielded four experimental conditions: (a) The two stimuli locations were the same ("same" condition); (b) the two stimuli were located in two different spaces, one in peripersonal and the other in extrapersonal space ("crossing" condition);

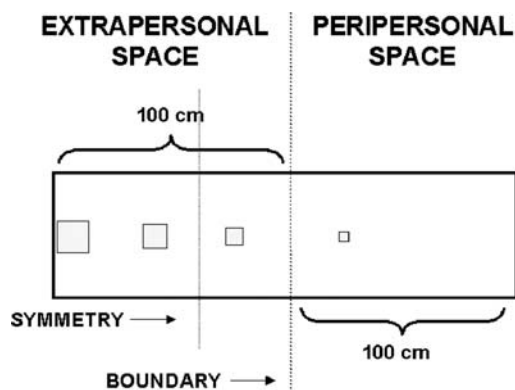


Figure 3. Lateral view of the apparatus used in Experiments 4 and 5.

(c) the two stimuli were located at two different sides relative to the symmetry plane (“symmetry” condition); (d) both stimuli within the pair were located in the extrapersonal space, but at different locations (“extrapersonal” condition). Participants’ task was to press the button corresponding to each stimulus immediately after its presentation. Participants were asked to be as fast and accurate as possible, and they were not allowed to look at the response box.

Design

Angular transformed proportions of errors to the second stimulus of each pair were analysed using a Hand (2) × Location (4) repeated measures ANOVA. The factor hand produced two conditions (left and right), and the factor location produced four conditions (same, crossing, symmetry, and extrapersonal). Errors were both incorrect and missing responses. An identical analysis was carried out on the reaction times to the second stimulus of each trial in order to test for any speed/accuracy trade-off effect. RTs faster than 100 ms and slower than 1,000 ms were excluded from the analyses.

Results

The analysis of errors showed significant main effects of hand and location, $F(1, 17) = 24.19$, $p < .0001$, and $F(3, 51) = 9.14$, $p < .0001$, respectively, as well as a hand by location interaction, $F(3, 51) = 3.12$, $p < .05$. As a main

effect, participants made more errors using their right hand (Table 6). Moreover, Duncan testing showed that participants made more errors in the crossing condition than in the same, symmetry, and extrapersonal conditions ($p < .01$; Table 6) and fewer errors in the same condition than in the crossing and symmetry conditions ($p < .01$). Duncan testing of the hand by location interaction showed that participants made more errors with their right hand in all but the crossing condition ($p < .05$).

The analysis on the RTs showed significant main effects of hand and location, $F(1, 17) = 21.56$, $p < .001$, and $F(3, 51) = 54.05$, $p < .0001$, respectively. The effect of the hand was due to the participants being slower when they responded with their left hand than with their right hand (Table 6). Duncan testing of the location main effect showed that RTs to the stimuli in the same condition were significantly faster than those in all the other conditions ($p < .01$), and RTs to stimuli belonging to the extrapersonal condition were significantly faster than those belonging to the crossing and symmetry conditions ($p < .01$). No interaction was found between factors hand and location.

Two additional analyses were carried out on error proportions (angular transformed) and RTs on trials belonging to the same condition in order to rule out confounding effects due to the distance of the stimuli from the observer. Results did not show any effect of the position of the stimuli from the observer on errors,

Table 6. Mean reaction times^a and mean percentages of errors on the same, crossing, symmetry, and extrapersonal trials with right and left hands in Experiment 4

		Trial							
		Same		Cross		Symm		Extra	
		M	SD	M	SD	M	SD	M	SD
Reaction times	Right	433.12	73.40	547.19	67.90	552.86	77.30	508.55	59.24
	Left	451.09	72.58	576.04	52.19	593.31	50.93	552.67	64.44
% Errors	Right	21.18	16.67	27.36	18.13	26.16	15.23	19.93	11.84
	Left	15.67	13.76	25.97	20.40	19.63	12.51	12.64	11.36

^aIn ms.

Table 7. Mean reaction times^a and mean percentages of errors on the same trials as a function of distance from observer in Experiment 4

	Distance ^b							
	80		120		160		200	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Reaction times	442.13	81.84	440.81	76.73	448.51	80.54	445.91	83.37
% Errors	16.03	17.23	18.75	21.48	16.11	17.54	13.75	18.36

^aIn ms. ^bIn cm.

$F(3, 51) = 1.82, p = .16$, or RTs, $F(3, 51) = 0.11, p = .95$ (Table 7).

EXPERIMENT 5

In order to replicate the results of Experiment 4, we ran a further experiment in which visual cues were available to the participants, as we did for Experiment 2. Of course, the failure to replicate the findings of Experiment 4 in this new condition would cast doubts over the interpretation of the results in terms of conflict between different representations of the external space.

Method

A total of 14 students (8 males and 6 females) volunteered for the experiment. Their mean age was 23.92 years, ranging from 20 to 30 years. All of them had normal or corrected-to-normal vision, were right-handed, and were naive to the purposes of the experiment. The same stimuli and procedure as those used in Experiment 4 were also used in the present experiment. The only exception was that the posterior end of the apparatus was removed, and the room was dimly illuminated, allowing the observer to see all the stimuli inside the box, even while they were off.

Results

The analysis performed on the participants' proportions of errors to the second stimulus of the

pair (angular transformed) showed a significant main effect of location, $F(3, 39) = 7.92, p < .001$, but no effect of hand, $F(1, 13) = 1.85, p = .20$, and no significant hand by location interaction, $F(3, 39) = 0.61, p = .61$. Duncan testing showed that participants made more errors in the crossing condition than in any of the other conditions ($p < .05$) and made fewer errors on trials belonging to the same condition than on trials belonging to the crossing and symmetry conditions ($p < .01$; Table 8).

Analyses on RTs showed an effect of both hand, $F(1, 13) = 14.04, p < .01$, and location, $F(3, 39) = 38.04, p < .0001$, but no hand by location interaction, $F(3, 39) = 1.67, p = .19$. Not surprisingly, Duncan testing showed that participants were faster when they responded to stimuli on trials belonging to the Same condition ($p < .01$), but no significant differences were found between the crossing and symmetry conditions, ruling out any speed/accuracy trade-off accounting for the crossing effect observed on errors. Participants were also faster when they responded with their right hand than when responding with their left hand.

The analyses carried out on proportions of errors (angular transformed) and RTs on same trials did not show any effect of stimuli distance from the observer on errors, $F(3, 39) = 0.40, p = .75$ (Table 9), but a significant effect on RTs, $F(3, 39) = 8.23, p < .001$. Duncan testing showed that participants' responses to stimuli presented at 160 cm from the observer were faster than those to stimuli presented at the other distances ($p < .01$).

Table 8. Mean reaction times^a and mean percentages of errors on the same, crossing, symmetry, and extrapersonal trials with right and left hands in Experiment 5

		Trial							
		Same		Cross		Symm		Extra	
		<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
	<i>Hand</i>								
Reaction times	Right	402.63	70.30	502.48	61.31	497.49	75.93	464.37	73.04
	Left	426.70	74.25	534.49	62.41	542.22	73.35	514.08	90.00
% Errors	Right	9.23	9.62	16.8	16.9	13.4	11.6	9.36	7.36
	Left	7.37	7.02	15.4	11.7	11.1	7.07	5.19	3.88

^aIn ms.**Table 9.** Mean reaction times^a and mean percentages of errors on the same trials as a function of distance from observer in Experiment 5

		Distance ^b							
		80		120		160		200	
		<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Reaction times		450.34	75.35	417.19	62.39	377.25	81.85	427.37	81.52
% Errors		8.77	9.88	10.40	11.00	6.96	6.69	8.93	9.08

^aIn ms. ^bIn cm.

Discussion

Experiments 4 and 5 provided additional evidence supporting the hypothesis that a border between peripersonal and extrapersonal space exists, excluding the possibility that the observed crossing effect was merely associated with the symmetry of the original layout. The separation of the boundary from the symmetry plane was also very useful to show the reliability of the crossing effect and to rule out any possible consequence of the response modality.

GENERAL DISCUSSION AND CONCLUSIONS

Results showed that participants made more errors responding to the second stimulus on those trials in which the two stimuli appeared in different spaces (peripersonal and extrapersonal) than when they appeared at two different locations in

the same space (peripersonal or extrapersonal), distances being equal. Also, participants made fewer errors on trials in which the stimulus appeared twice at a given location than in any other condition. This pattern of results cannot be accounted for by any biases affecting specific stimuli locations or press buttons, since errors did not vary according to which button was pressed, or according to the absolute location of the stimuli. Furthermore, speed/accuracy trade-off cannot account for the boundary-crossing effect, as RTs on crossing trials were slower than RTs on the other conditions.

The boundary-crossing effect found supports the hypothesis that interaction with objects located in a 3D space depends on spatial representations that link the perceptual information and the set of possible actions to be performed on those objects. According to such a hypothesis, it was indeed predicted that switching from one representation to another might lead to performance costs in terms of accuracy. Namely, a larger

proportion of errors was expected when a fast switching from one representation to another was required in order to comply with the task at hand. Of course, collapsing errors prevents us from ascertaining whether the crossing effect was due to the longer time it took to shift between representations or to the higher probability that such shifting does not occur at all. Nevertheless, in both cases errors seem to stem from participants being hindered in using different representations of the 3D space.

Results of the first experiment raised the question of whether the representations of the peripersonal and extrapersonal spaces only derive from processing of visual information (i.e., purely perceptual), or should be considered as action based. It should be noted here that we refer to the nature of the representations of space, rather than action programming and execution. Such a specification is relevant as our participants obviously gave their responses within the reaching space. The hypothesis that the representations of the external space are action based seems to make more sense, as the distinction between peripersonal and extrapersonal spaces is founded upon the difference between the actions that can be performed in each space. Nevertheless, the purely perceptual hypothesis cannot be ruled out just on the basis of results of Experiment 1, because at least Cutting and Vishton (1995) proposed a model in which the distinction between peripersonal and extrapersonal spaces was only founded upon visual depth cues. Also, Coello and coworkers (Coello et al., 2000; Magne & Coello, 2002) found that pointing to locations in the external space is more precise in a structured environment, suggesting that retinal information plays the greater role in pointing to objects within the reaching space.

However, the design of this study was effective in ruling out several alternative hypotheses: vergence and accommodation effects (Experiment 1), biases induced by the use of the response box (Experiment 3), and centre of mass effects (Experiment 4), as well as effects induced by the use of perceptual cues of depth only (Experiments 2 and 5).

Overall, the results of these experiments are in fair agreement with the hypothesis that multiple representations of space are involved in dealing with objects located in the three-dimensional space around us. However, it is worth noting that the previously claimed notion (e.g., Cutting & Vishton, 1995; Grusser, 1983; Previc, 1998; Rizzolatti, Gentilucci, & Matelli, 1985) that multiple representations of space are actually coded in the human brain does not necessarily imply that they also represent a likely mechanism underlying the genesis of action slips. Instead, in order to account for the higher percentage of errors on crossing trials that we found in Experiments 1 and 2 it is also necessary to assume that such multiple representations may be simultaneously active and competing for the control of the behaviour, at least in some circumstances. Such a condition is not met by the simple notion that a given representation of the space layout is only used in order to localize an object at a given spatial location. If that were the case, in fact, no conflict should arise when two objects have to be spatially localized at different points in time, and hence no error should be made. Simultaneous activation of different frames of reference should be possible. However, only one frame should be selected to act (whatever the reason). Indeed, in the two-dimensional domain, Carlson-Radvansky and Irwin (1993) showed how in conflicting situations, such as a placement task, in which two possible frames of reference were possible because of the ambiguity of an orientation description (i.e., the word "above"), one of the two frames was selected in 92.2% of cases.

It may be speculated that errors may derive from a conflict between representations of space. In this case, a necessary condition for an error to be made is that the activation of a particular representation would last until an appropriate motor response is programmed and/or executed. In other words, a given representation of space should include both perceptual and motor elements. Hence one could speculate that the presentation of a stimulus in a subspace would activate the appropriate representation of that space (activation), which would remain active until a motor

response is emitted and, possibly, feedback of that action are checked for (implementation). If during the implementation of such a representation a second stimulus were presented in a different portion of the space, a capture phenomenon may occur, which associates the newly activated representation with the motor programme pertaining to the old representation (as the latter is still going to be implemented) and cancels out, or postpones, the motor programme pertaining to the new representation. This account is quite similar to Duncan's (1999) integrated competition hypothesis, and represents its extension to the temporal domain. In fact, Duncan's hypothesis is aimed at explaining functioning when objects overlap in space, while our explanation is based on time overlapping. Also, competition occurring when the same properties of different objects are integrated resembles the concept of simultaneous activation of schemata competing for implementation (Norman, 1981). Moreover, as reported by Duncan (1999, p. 114), "as an object gains dominance in any one system, responses to this same object are supported elsewhere", and this would strongly support our claim that competition between representations may directly affect the subsequent action (see also Magen & Cohen, 2002, for a recent account in this direction). It is worth noting that such a mechanism seems to be able to account for the action slips that occur when motor responses are needed to objects sequentially presented into different portions of the space, and that the characteristics of the representations that are required in order to make them able to explain why errors occur make them also quite similar to Arbib's motor schemata (Arbib, 1985, 1992) dealing with motor commands and their control.

Concluding, the present results strongly support the idea that a boundary between peripersonal and extrapersonal spaces really exists, and that crossing such a demarcation line can—under some circumstances—lead us to err.

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