Coding of Far and Near Space During Walking in Neglect Patients

Anna Berti
Università di Torino

Nicola Smania
Ospedale Borgoroma

Marco Rabuffetti and Maurizio Ferrarin
Centro di Bioingegneria, Fondazione Don Carlo Gnocchi ONLUS IRCCS—Politecnico di Milano

Lucia Spinazzola
Azienda Ospedaliera, Sant’Antonio Abate

Alessandra D’Amico
Università di Torino

Emanuele Ongaro
Ospedale Borgoroma

Alan Allport
Oxford University

Previous studies have shown that far space can be remapped as near when reached by a stick that artificially prolongs the participants’ personal space. In the present study, the authors asked whether a similar remapping occurs when far space is reached not by using a tool but by locomotion. Neglect patients showed more severe neglect in far than in near space in bisection tasks executed from different distances either by pointing to a target line with a projection light pen or by walking across the line. A kinematic study of the walking performance of one of those neglect patients showed that, contrary to the prediction of remapping during locomotion, the walking trajectories were rectilinear. The authors interpreted these results as evidence that in their patients—at least for short, linear trajectories—no remapping of space took place during locomotion. The location of far objects was coded at the beginning of the movement, and the error in the bisection computation was generated within the 1st representation that was activated.

In everyday life, both animals and humans need to reach for objects around them. Depending on the distance away of a given object, different types of action are afforded. For instance, if the object of interest is close to the body (in near or peripersonal space), manual reaching may be performed. If the object is beyond manual reach (in far or extrapersonal space), two different possibilities are available. The subject can use a tool to reach for a far object, or he or she can reach the far object by locomotion. To accomplish such tasks successfully, the brain has to compute the distance of the object from the agent’s body correctly. Neurophysiological studies in animals have shown that near and far space (behaviorally defined as the space within and beyond hand reach) are, indeed, differentially coded by the brain. Far space is apparently coded in two regions of the monkey brain (area 8 and area LIP) that are physiologically similar and richly connected with one another (Colby, Duhamel, & Goldberg, 1996; Latto & Cowey, 1971). Near space seems to be represented in frontal area 6 and in the rostral part of the inferior parietal lobe, area 7b (Leinonen, Hyvarinen, Nymani, & Linnankoski, 1979) and area VIP (Colby, Duhamel, & Goldberg, 1993; Duhamel, Bremmer, Ben Hamed, & Graf, 1997).

Particularly important are the coordinate systems in which the different circuits code space. The representation of far space is mainly subserved by oculomotor circuits, in which spatial information derives from neurons whose receptive fields (RFs) are coded in retinal coordinates. The spatial position of an object is reconstructed either by computing the position of an object on the retina and the position of the eye in the orbit (Zipser & Andersen, 1988) or, alternatively, by a computation of impending saccade motor vectors (Bruce, 1988; Goldberg & Bruce, 1990). In contrast, near space (i.e., the space in which there is direct interaction between the object and the body during a reaching movement) is coded in egocentric coordinates at a single neuron level. The egocentric coordinate system is related not only to the body midline but also to body parts. Indeed, some “peripersonal” neurons fire both when a tactile stimulus is delivered to the animal skin and when a visual stimulus is presented in the space near the part of the body.
where the tactile field is located (Fogassi et al., 1996; Gentilucci et al., 1988; Graziano & Gross, 1995; Graziano, Yap, & Gross, 1994). It is important to note that when the stimulus is too far away for the monkey to reach, peripersonal neurons stop firing. Conversely, when the stimulus enters peripersonal space, neurons start firing, showing that the reaching distance is a crucial factor in the activation of near space representation.

Neuropsychological studies provide evidence that discrete representations for far and near space also exist in humans. Halligan and Marshall (1991) described a patient who, following a right-hemisphere stroke, showed marked left spatial neglect in line bisection in near space but greatly reduced neglect when the task was carried out in far space. Cowey, Small, and Ellis (1994, 1999) and Vuilleumier, Valenza, Mayer, Reverdin, and Landis (1998) reported the opposite dissociation: more severe neglect in far space than in near space (see Shelton, Bowers, & Heilman, 1990, for further dissociations within near space). Moreover, evidence in favor of the existence of a visuotactile peripersonal space in humans has been recently found in studies on cross-modal extinction (e.g., di Pellegrino, Lădavas, & Farnè, 1997; Lădavas, di Pellegrino, Farnè, & Zeloni, 1998). The dissociation between near and far space coding in humans recently has been confirmed by a positron emission tomography (PET) study that showed an activation of dorsal visuomotor processing areas when actions are performed in near space and an activation of ventral visuoperceptual areas when actions are performed in far space (Weiss et al., 2000).

It is worth noting that the studies in which dissociation between peripersonal and far space neglect was found used tasks, such as line bisection, that were not only perceptual but also visuomotor. Therefore, it was tentatively suggested that the motor component of the task was crucial for yielding asymmetry between far and near space neglect. A recent study by Pitzalis, Di Russo, Spinelli, and Zoccolotti (2001) showed, however, that this is not necessarily true. These authors found a dissociation between near and far space in purely perceptual tasks also. This finding supports the notion that, within a given space sector, the activity of the same brain circuit subserves both perceptual and visuomotor tasks.

Together, these studies have shown that (a) the brain constructs different maps according to far and near space and (b) “far” and “near” are computed on the basis of reaching distance. This last point seems to be confirmed by the fact that in monkeys, the representation of peripersonal space is activated when an object is reachable, whereas the representation of far space is activated when the object is out of reach. Very recently it has been shown that the activation of near and far space representations also can be modulated by actions that change the effective spatial relationship between the body and the object. For instance, when subjects reach for a distant object by using a tool, the spatial representation can switch from far to near. This has been demonstrated in monkeys by Iriki, Tanaka, and Iwamura (1996) and in humans by Berti and Frassinetti (2000).

Iriki et al. (1996) found that, when monkeys performed a reaching movement with a rake, the visual receptive field of parietal bimodal neurons (Fogassi et al., 1996; Gentilucci et al., 1988; Graziano et al., 1994) was expanded to include the entire space accessible by the rake. In other words, in that experiment, the use of a tool altered the body schema—the tool was assimilated to the hand and became part of the hand representation (Agioti, Smania, Manfredi, & Berlucchi, 1996). As a consequence, peripersonal space was expanded and far space was remapped as near. Berti and Frassinetti (2000) indirectly demonstrated a similar effect in humans. They studied a patient who, after damage to the right hemisphere, was affected by visual neglect, a disturbance that impairs the processing and the exploration of the space contralateral to the brain lesion. The patient showed a dissociation within the manifestation of neglect. In a line bisection task, neglect was apparent in near space, but not in far space, when the line bisection was performed with a projection light pen. However, the striking finding was that when far lines were bisected with a stick, used by the patient to reach the line, neglect also appeared in far space and was as severe as neglect in near space. This observation showed that when the patient used the stick to reach for the object of interest in far space, the tool was coded as part of the patient’s hand and, as in monkeys, caused an expansion of the representation of the body schema. This affected the spatial relation between far space and the body. The structure of peripersonal space was altered, and peripersonal space expanded to include the far space reachable by the tool. The reaching of far space with a tool determined a switch between spatial representations, so that the representation of near space was then activated. Because near space representation was affected by the brain damage, the remapping of far space as near affected the patients’ performance in line bisection, and neglect reappeared (see also Farnè & Lădavas, 2000; Maravita et al., 2001). Iriki et al. (1996) and Berti and Frassinetti (2000) showed that the coding of spatial positions can be a dynamic operation, not only related to the computation of the distance of an object from the agent’s body, but also sensitive to the agent’s action of reaching.

In the present study, we asked the question of whether space can be remapped when far objects are reached not by tool use but by locomotion.

**Experiment 1**

**Method**

**Participants**

Six neurologically intact participants and 7 right-brain-damaged patients, affected by ischemic stroke, were included in our study. Patients were selected on the basis of their ability to walk. None of them needed any help from the experimenters for accomplishing the walking task (see the following), nor did they use an external aid. On neurological examination, only one of them had a very mild distal paresis in the left lower limb. Exclusion criteria consisted of presence of other neurological disorders, psychiatric illness, dementia, or confusional state. All patients gave informed consent to participate in the experiment. The patients were asked...
to perform a number of tests for the diagnosis of neglect: the Albert (1973) test, the Bell test (Gauthier, Dehaut, & Joanette, 1989), and the Diller test (Diller & Weinberg, 1977); they also were asked to draw, both by immediate copying and from memory. A patient was included in the neglect group if he or she showed neglect in at least one of the tests we used. Clinical data are reported in Table 1.

Three right-brain-damaged patients had left unilateral neglect (RBD+N+), 3 did not show any sign of spatial disorders (RBD+N–), and 1 patient presented with mixed right- and left-sided neglect (Patient GE). Two of the 4 neglect patients also had a left cerebral lesion that was not documented before the patients’ clinical evaluation for the right-hemisphere lesion. A line bisection task, executed by means of a projection light pen, was part of our experimental testing (see the following). Three out of 4 neglect patients showed left neglect in this test. However, 1 neglect patient (Patient GE, with bilateral cerebral damage) showed a displacement of the subjective midpoint to the left of the objective midpoint of the line, that is, in the bisection task she showed a right neglect. Furthermore, all 3 patients with consistent left neglect (Patient GE, with bilateral cerebral damage) showed a displacement of the subjective midpoint to the left of the objective midpoint of the line was indicated with the plus sign, whereas the minus sign indicated leftward displacement. The bisection errors are indicated as the percentage of deviation with respect to the line length.

**Task A.** This task was a line bisection task. Patients were asked to point to the objective midpoint of the line, at a distance of approximately 3.0 m, 1.5 m, and 0.5 m from the patient. Three different line lengths were used, at the three different distances, to hold visual angle constant. Lines at 0.5 m distance (near space) were 23.5 cm long; lines in far space (1.5 m and 3.0 m) were 75 cm and 148 cm long, respectively. Patients sat on a chair and were requested to indicate the midpoint of each line by means of a projection light pen. There were 10 trials for each distance (3.0 m, 1.5 m, 0.5 m), for a total of 30 trials. Bisec tion errors were measured as deviations in millimeters: A deviation of the subjective midpoint to the right of the objective midpoint of the line was indicated with the plus sign, whereas the minus sign indicated leftward displacement. The bisection errors are indicated as the percentage of deviation with respect to the line length.

**Task B.** The patients’ task was to bisect a doorway. Indeed, they were asked to walk, with their eyes open, through a doorway and were explicitly requested to cross the doorway in the middle, as if bisecting the doorway with their body. Two plastic sticks, 90 cm high, represented the edges of the door. The width of the doorway was 148 cm. The starting points were at 3.0 m, 1.5 m, and 0.5 m from the doorway. As a body reference point, the midpoint between the feet was used (approximately corresponding to the sacrum and, therefore, to the body midline). There were 10 trials for each condition (3.0 m, 1.5 m, and 0.5 m), for a total of 30 trials. At each passage through the doorway, the deviation of the body reference point from the doorway midpoint was measured in millimeters. A deviation of the subjective midpoint to the right of the objective midpoint of the line was indicated with the plus sign, whereas the minus sign indicated leftward deviation.

**Procedure**

The two tasks, the pointing task and the walking task, were presented in an A to B to B to A sequence. The patient started with 15 trials of Task A, continued with 30 trials of Task B, and finished with 15 trials of Task A. In each block of 15 trials, there were 5 trials per condition.

Table 1

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (years)</th>
<th>Gender</th>
<th>Education (years)</th>
<th>Lesion</th>
<th>Handedness</th>
<th>L-hemianopia</th>
<th>Time from stroke (days)</th>
<th>Left neglect</th>
<th>Test</th>
<th>L</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE</td>
<td>18</td>
<td>M</td>
<td>11</td>
<td>L/R</td>
<td>dx</td>
<td>–</td>
<td>76</td>
<td>–</td>
<td>Bell</td>
<td>17/17</td>
<td>14/17</td>
</tr>
<tr>
<td>BE</td>
<td>71</td>
<td>F</td>
<td>10</td>
<td>PO/R</td>
<td>dx</td>
<td>–</td>
<td>77</td>
<td>–</td>
<td>Diller</td>
<td>52/52</td>
<td>29/52</td>
</tr>
<tr>
<td>AL</td>
<td>58</td>
<td>M</td>
<td>10</td>
<td>PO/R</td>
<td>dx</td>
<td>–</td>
<td>27</td>
<td>–</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BO</td>
<td>76</td>
<td>F</td>
<td>11</td>
<td>FrP/R</td>
<td>dx</td>
<td>+</td>
<td>24</td>
<td>+</td>
<td>Albert</td>
<td>18/18</td>
<td>5/18</td>
</tr>
<tr>
<td>MA</td>
<td>63</td>
<td>M</td>
<td>5</td>
<td>FrTPO/R</td>
<td>dx</td>
<td>+</td>
<td>809</td>
<td>+</td>
<td>Bell</td>
<td>17/17</td>
<td>14/17</td>
</tr>
<tr>
<td>LS</td>
<td>72</td>
<td>M</td>
<td>13</td>
<td>TP/R</td>
<td>dx</td>
<td>+</td>
<td>166</td>
<td>+</td>
<td>Albert</td>
<td>9/18</td>
<td>0/18</td>
</tr>
<tr>
<td>GE</td>
<td>79</td>
<td>F</td>
<td>10</td>
<td>PO/R</td>
<td>dx</td>
<td>+</td>
<td>26</td>
<td>+</td>
<td>Bell</td>
<td>6/17</td>
<td>2/17</td>
</tr>
<tr>
<td>AB</td>
<td>70</td>
<td>F</td>
<td>3</td>
<td>O/R</td>
<td>BG/R</td>
<td>+</td>
<td>90</td>
<td>+</td>
<td>Albert</td>
<td>6/17</td>
<td>0/18</td>
</tr>
</tbody>
</table>

*Note.* L = left; R = right; M = male; F = female; Ln = lenticular nucleous; P = parietal; O = occipital; Fr = frontal; T = temporal; Tal = talamus; BG = basal ganglia; dx = right-handed; + = presence; – = absence; Bell = the Bell test; Diller = the Diller test; Albert = the Albert test.
Predictions

In the pointing task, we predicted that the bisection errors would indicate whether right-brain-damaged patients with neglect showed dissociation between the performance executed in far and near space. A dissociation would imply a different degree of neglect when the task is executed in different space sectors.

In the walking task, we addressed the question of whether coding of space is modulated when the spatial relation between the body and the external objects is changed by the participant’s movement toward the far space. Two different hypotheses can be advanced: First, space is remapped in the course of one’s approaching the doorway from far space. Different spatial representations are activated in sequence: far space representation at first and near space representation later. The final representation activated is the one responsible for the actual bisection performance at the doorway. Second, space is coded at the start of walking and is not updated while one approaches the doorway. Thus, the representation activated at the beginning of walking is the one responsible for the bisection performance at the doorway.

These two hypotheses give rise to two different predictions in relation to the bisection error in the walking task. Given that the 3 left neglect patients showed more severe neglect in far than in near space in the line bisection task (see the following), the possible, competing predictions for these 3 patients are as follows: If the representation of space is updated during walking, our neglect patients should activate an impaired representation at the beginning of each walking path and a less impaired, or unimpaired, representation toward the end, in the two longer distance conditions. Therefore, their walking trajectories should deviate at the beginning of each path, especially with the most distant starting point. As they approach the doorway, with the activation of better representations, the walking trajectories should be corrected. As a consequence, the passage through the doorway (i.e., the actual displacement error) should be similar from all three starting points. On the contrary, if space is not updated, then the first representation that is activated, at the beginning of each path, is the one responsible for the final bisection performance. Therefore, if the spatial neglect is more severe in far than in near space (as in all 3 of these neglect patients), we should expect to find worse performance with the starting point in far space (activation of far space) than with the starting point in near space.

Results

Group Analysis

The results are shown in Figure 1. Patient GE was not included in the general analysis because she presented a bisection pattern that was the opposite to that of the other neglect patients (see the following).

To perform the statistical analysis, finally we transformed the means percentages by applying the arcsine operator (e.g., Zar, 1996). We then performed a repeated measures analysis of variance (ANOVA), with one between-subjects factor, group (with three levels: normals, RBD+N−, RBD+N+), and two within-subjects factors, modality and distance. The modality factor had two levels (pointing and walking), and the distance factor had three levels (3.0 m, 1.5 m, and 0.5 m).

The analysis showed a significant main effect of group, F(2, 9) = 10.30, p < .005; distance, F(2, 9) = 32.27, p < .00001; and the following significant interactions: Group × Distance, F(4, 18) = 23.26, p < .00001; Group × Modality, F(2, 9) = 5.40, p < .05; Modality × Distance, F(2, 18) = 6.15, p < .01; and Group × Modality × Distance, F(4, 18) = 6.30, p < .005. The effect of group indicates that both normals (bisection error = −0.05%) and RBD+N− (bisection error = 0.30%) were accurate in both tasks, whereas neglect patients presented with a rightward bisection error significantly different from the bisection performances of the other two groups (bisection error = 10.80%).

A post hoc analysis (Newman–Keuls) showed no difference between normals and RBD+N−, whereas both groups differed from RBD+N+ (p < .001). The main effect of distance shows that the performance was less accurate from the distances of 3.0 m and 1.5 m than it was from the distance of 0.5 m (3.0 m = 5.23%, 1.5 m = 3.90%, 0.5 m = 1.90%; p < .005 for all comparisons). However, the Group × Distance interaction showed that this was true only for the neglect group. In particular, bisection errors were more severe when the task was executed at (or with the starting point at) the distance of 3.0 m (bisection error = 14.0%) than when the task was executed at (or with the starting point at) the distance of 1.5 m or at the distance of 0.5 m (bisection error = 11.6% and 5.9%, respectively).

A post hoc analysis with the Newman–Keuls method showed that in the neglect group bisections performed at (or with the starting point at) 3.0 m were significantly different from the other two distances (p < .001 for both comparisons). Moreover, the bisection performed at (or with the
starting point at) the distance of 1.5 m differed significantly from those executed at the distance of 0.5 m (p < .001). The Modality × Distance interaction showed that the performance tended to be more severe in the pointing task and at the distances of 1.5 m and 3.0 m, and the Group × Distance and Group × Modality × Distance interactions showed that this was especially true for the neglect group (see Figure 1). A post hoc analysis (Newman–Keuls) on the Group × Modality × Distance interaction showed that in the neglect group, both in the pointing modality and in the walking modality, the bisection performed with the starting point in near space (0.5 m) significantly differed from those performed with the starting point in far spaces (p < .01 for all comparisons).

To show that the arcsine transformation did not change the data so much to find significant effects that might not be found with the analysis of the raw data, we also performed an ANOVA with the percentage errors: The results confirmed the analysis carried out with the arcsine transformation. The analysis showed a significant main effect of group, F(2, 9) = 30.98, p < .0001; distance, F(2, 9) = 20.55, p < .0001; and the following significant interactions: Group × Distance, F(4, 18) = 13.87, p < .0001; Modality × Distance, F(2, 18) = 17.07, p < .0001; and Group × Modality × Distance, F(4, 18) = 7.87, p < .005. In addition, the post hoc analysis was confirmed.

Single-Case Analysis

Figure 2 shows the means of the percentage of bisection errors for each patient for each condition. We conducted an ANOVA for each RBD+N+ patient on the arcsine transformed percentages of displacement errors. The factors and levels were the same as the group analysis.

Patient MA

In this patient, both factors, modality, F(1, 5) = 214.42, p < .0001, and distance, F(2, 10) = 32.04, p < .0001, were significant. Moreover, the Modality × Distance interaction was also significant, F(2, 10) = 4.15, p < .05. Bisection errors in the walking modality (9.1%) were less severe than in the pointing modality (29.1%). Moreover, bisection errors tended to be more severe when the task was executed at (or with the starting point at) the distance of 3.0 m (24.0%) than they were when the distance was 1.5 m (21.0%) or 0.5 m (12.5%). The post hoc analysis showed that, for pointing, the displacement toward the right was greater when the task was executed at the distance of 3.0 m (31.5%) and 1.5 m (32.5%) than when it was executed at the distance of 0.5 m (23.2%; p < .05 for both comparisons). These data show that, in this patient, neglect for near space was less severe than was neglect for far space (3.0 m and 1.5 m). In the walking modality, the post hoc analysis showed that the bisection error was more severe when walking started from far space (3.0 m = 16.3%, 1.5 m = 9.0%) than when it was started from near space (0.5 m = 10.0%; p < .005 for both comparisons). Moreover, in the walking modality, bisection with the starting point at 3.0 m also differed from bisection with the starting point at 1.5 m (p < .01).

Patient BO

The analysis showed that distance, F(2, 18) = 24.75, p < .000001, and the Modality × Distance interaction, F(2, 18) = 6.70, p < .01, were significant. The post hoc analysis showed that in the pointing modality, the bisection error was more severe when the task was executed in far space (3.0 m = 11%, 1.5 m = 12.3%) than when it was executed in near space (0.5 m = 6.2%), even if the distance at 1.5 m was significantly different from the distance at 0.5 m (p < .05). In the walking modality, the bisection error was more severe when locomotion started from far space (3.0 m = 16.9%, 1.5 m = 8.2%) than when it was started from the near space (0.5 m = 5.6%; p < .01 for both comparisons). Moreover, in the walking modality, when the starting point was at 3.0 m, the bisection also was significantly different from the condition of the starting point at 1.5 m (p < .01).

Patient LS

The analysis showed that modality, F(1, 9) = 15.18, p < .005, and distance, F(2, 18) = 17.27, p < .0001, were significant. In the pointing modality, the bisection error in far space (3.0 m = 7.7%, 1.5 m = 5.6%) was more severe than the bisection in near space (0.5 m = 3.3%). Similarly, in the walking modality, the worst bisection performance was observed with the starting point at 3.0 m (5.6%)
and 1.5 m (2.2%), with respect to the starting point at 0.5 m (0.6%). The post hoc analysis showed that the bisection performed at (or with the starting point at) 3.0 m differed significantly from the conditions at 1.5 m.

Discussion of Experiment 1

First of all, the data of this experiment show that right-brain-damaged patients who presented with dissociation between near and far space neglect in a bisection task using a laser pointer also showed neglect in a bisection task in which bisection had to be performed through a walking task. In this study, we asked whether a possible remapping of space can be observed when neglect patients with this particular kind of dissociation had to reach for a far object through locomotion. According to the prediction stated in a previous section of the article, remapping should allow correction of trajectories and therefore the same displacement error at the doorway level. On the contrary, different bisection performance at the doorway level would imply that the patients computed space at the beginning of locomotion, producing a bisection error dependent on the severity of neglect that they experienced at the different starting points. Our data seem to favor this latter hypothesis (space is not remapped during walking) because the results of the first experiment indicate that patients characterized by a more severe neglect in far space showed a larger bisection error when the starting point of locomotion was in the far space.

However, an alternative explanation can be advanced for the results obtained in the walking task. The bisection error might simply be due to an unspecific tendency to veer toward the right during locomotion, as suggested by previous studies (Robertson, Tegnér, Goodrich, & Wilson, 1994; Tromp, Dinkla, & Mulder, 1995). Therefore, in the walking modality, the increasing of the bisection error as a function of starting distance might be interpreted as being due to the fact that the longer the distance to be walked, the greater the deviation toward the right. If so, the results in the walking modality should be ascribed to a particular neglect walking pattern and should not be interpreted as the consequence of an impaired bisection computation operated by the patients.

We tried to answer this objection in two ways. First, we presented the data of Patient GE, which strongly suggest that the performance in the walking task was guided by a bisection computation and not by other cognitive processes. Second, we conducted a kinematic study on patients’ walking, described in Experiment 2.

Patient GE

As already mentioned, this patient showed a left neglect in the conventional clinical tests we used. However, she presented with a right neglect in the bisection test in both modalities, pointing and walking (see Figure 2), and for this reason she was not included in the general analysis. She, like the other patients, performed the test in both far and near space and therefore the analysis was performed with the same factors. The ANOVA showed that the only significant factor was modality, $F(1, 9) = 11.20, p < .01$, with the tendency for bisection performed by walking being more accurate than bisection performed by pointing.

Discussion of Patient GE

Patient GE’s performance, although not showing a dissociation between far and near neglect, clearly showed that the walking task was executed as a real bisection task. Patient GE, after bilateral cerebral damage, showed the usual left neglect pattern in all the screening tests we used for the diagnosis of neglect. However, in the bisection test with the pointing modality, she showed a deviation of the subjective midpoint to the left (right neglect) of the objective midpoint of the lines. The crucial finding was that in the walking task we observed the same pattern (i.e., the patient showed a leftward deviation at the passage through the doorway). This would mean that the same kind of computation (i.e., bisection of a linear length) underlies both performances. In other words, this pattern of results strongly suggests that the walking task was interpreted by our patients in the same way as the pointing task and that both tasks activated the same cognitive system responsible for the operation of the bisection computation. It is interesting that Patient GE, who did not show a clear-cut dissociation between far and near space neglect in the pointing task, did not show any dissociation in the walking task, suggesting again a strong similarity between the two different tasks of the first experiment.

Experiment 2

The results of Experiment 1 seem to suggest that in a bisection task performed by walking, at least for short and unperturbed trajectories, space is not remapped. This conclusion was based on the fact that bisection performances at the doorway level in the walking modality were different depending on the starting distance, implying that space was coded at the beginning of each walking trajectory and was not remapped while one approached near space. Another way of testing this hypothesis was to study the shape of the walking trajectories. This was achieved using an optoelectronic motion analyzer (ELITE system, BTS, Milano, Italy; Pedotti & Ferrigno, 1985). We studied one patient, AB, and three neurologically intact participants. Patient AB had a clinical neglect very similar to the one described in the patients of the first experiment, that is, more severe neglect for far than for near space (see Table 1 for clinical data).

Method

Apparatus and Procedure

Bisection performance. The participants had to perform two bisection tasks. The first one was a line bisection task to be performed using a projection light pen. The second one was a line bisection task to be performed by walking. In both tasks, the lines to be bisected were always placed on the ground and consisted of a white tape of different length. The length of the line placed on the ground was standardized to the participant height and distance.
from the line itself, in order to obtain a constant angle width of the line at retinal level (of approximately 24.5°, corresponding to a line of 1.5 m at a distance of 3.0 m for a participant whose height is 1.700 mm). In both modalities, the lines were placed at three different distances from the participants: 750 mm, 1,500 mm, and 3,000 mm. There were 8 trials per each condition, for a total of 48 trials per experiment. Instructions to the participants were the same as in Experiment 1. As in Experiment 1, bisection errors were calculated as the percentage of displacement to the right or left of the objective midpoint of the line.

Recording of the walking trajectories. The measurement of the walking trajectory was performed in a laboratory equipped with four TV cameras focused on a calibrated volume (length = 5.0 m; height = 1.7 m; width = 1.2 m), inside which the experiment involving walking must take place (Frigo, Rabuffetti, Kerrigan, Deming, & Pedotti, 1998). A set of anatomical landmarks, on either the right or left side of the body, was marked with small (diameter = 15 mm) passive reflective hemispheres. The points were the posterior superior iliac spine, the posterior face of the calcaneous, the acromion, and a lateral point on the head. Each participant was dressed and wore his or her shoes. The optoelectronic system is able to detect the presence of a marker in the calibrated volume and to measure its three-dimensional position with an accuracy that is about 1/3,000 of the volume's largest dimension. In the present study, the accuracy was about 2 mm. Data were acquired at a 100-Hz sampling rate and low pass filtered (cutoff frequency 2 Hz). The midpoint of the posterior superior iliac spines was assumed as the body reference point and the walking trajectory was identified by the second-order polynomial curve, which best fits the body reference point trajectory in the horizontal plane during walking (second order is the minimum required for a polynomial to eventually identify a trajectory curvature). The bisection error was measured as the percentage of rightward deviation from the target line midpoint of the intersection of the line itself and the walking trajectory.

Predictions

For the bisection error, the predictions were the same as in Experiment 1. In patients with neglect for far space, both the non-remapping hypothesis and the hypothesis of the neglect walking pattern predict that bisection errors should be deviated more to the right when the bisections are executed from (or with the starting point at) the distance of 3.0 m.

For the shape of the trajectories, predictions are different in relation to the remapping and nonremapping hypotheses and to the hypothesis of the neglect walking pattern. There are three different possibilities: First, performance depends on a neglect walking pattern (i.e., to a general tendency of veering continuously toward the right) and not on a bisection performance related to near or far space coding: In this case, the patient's trajectories are expected to deviate toward the right with deviations that should increase as the distance from the target increases. Therefore, the trajectory shape should be similar to the one presented in Figure 3a. Second, space is not remapped during walking and the bisection error at the doorway level is not due to a neglect walking pattern: In this case space is not updated and the deviation in the trajectory should be generated at the beginning of the walking pattern. No correction or any other further deviation is expected during locomotion. The trajectory shape should be similar to the one presented in Figure 3b. Third, space is remapped during walking: If the patient updates his or her space representation during walking then the trajectories should be corrected as the patient goes from far to near space and the shape should be similar to the one presented in Figure 3c.

Results

Bisection Performance

The results of the bisection performance are presented in Figure 4. An ANOVA with two within-subject factors was conducted on the arcsine transformed percentage of bisection errors. As in the previous experiment, the factors were modality (pointing and walking) and distance (3.0 m, 1.5 m, 0.75 m). Normal participants did not show any significant difference between the experimental conditions. In Patient AB, the distance factor was significant, F(2, 14) = 18.16, p < .0001. No other factor or interaction was significant. Bisection errors to the right of the objective midpoint of the line were more severe when the task was executed at (or with the starting point at) the distance of 3.0 m (15.80%) than they were when the distance was 1.5 m (13.47%) or 0.75 m (7.4%). The post hoc analysis showed that, for both modalities, the bisection executed at (or with the starting point at) the distance of 3.0 m significantly differed from the other two distance conditions (p < .0005 for both comparisons).

Trajectory Shape

In Figure 5, normal participants' average trajectories and standard deviations are shown. The trajectories were rectilinear and repeatable, as demonstrated by the particularly small standard deviation confidence intervals.

Patient AB’s average trajectories and standard deviations are shown in Figure 6. It is clear that the patient neither deviates continuously, as the neglect walking pattern hypothesis would predict, nor corrects his trajectory during walking, as the remapping hypothesis would predict. On the contrary, his trajectory is similar to the one hypothesized in Figure 3b (i.e., a rectilinear trajectory). Walking trajectories have been approximated by parabolas, second-order curves:
Second-order coefficient describes veering. Patient AB showed second-order coefficients of his trajectories that were included among the ones of controls, which were rectilinear.

**Discussion of Experiment 2**

Patient AB presented with a neglect pattern similar to the patients we tested in the first experiment. Indeed, he had neglect more severe for far than for near space in the pointing task. Moreover, in the walking task, he bisected the line to the right of its objective midpoint with a greater bisection error when the starting point was in far space. The trajectory shape did not indicate the presence of a continuous veering pattern during walking; its linearity indicates, instead, that once far space was coded at the starting point, no remapping took place while he approached the target stimulus.

**General Discussion and Conclusion**

Iriki et al. (1996) and Berti and Frassinetti (2000) showed that space coding is not related in an absolute way to the coding of the reaching distance but that the activation of near and far space representation also is influenced by actions that modify the spatial relation between the subject and the object on which a task has to be performed. In those studies, the use of a tool to perform a task in a space that was not reachable by the subject’s hand was the factor that modulated space representations. In the present study, we asked the question of whether and how the activation of different space representations can be influenced by walking toward far space.

We studied this problem in right-brain-damaged patients with neglect. Because modulation of space representations is better seen when patients show dissociations in coding near and far space, the first aim of this study was to look for such dissociations. That was achieved by testing patients on line bisection, using a pointing task that had to be executed at three different distances from the target stimulus. In this task, 4 patients showed more severe neglect in far than in near space, a neglect pattern similar to that described by Cowey et al. (1994, 1999) and Vuilleumier et al. (1998). It is interesting that these patients also showed neglect in the walking test. Indeed, they bisected the doorway to the right of the objective midpoint. This tendency was more evident when the starting point was at 3.0 m than when the starting point was at 1.5 m, and in 2 out of 3 patients (MA and BO), the difference between the two starting points was significant. This indicates that bisection performance in the walking task depended on the space where the patients computed the position of the target stimulus before the beginning of each walking path, and according to our predictions, this pattern of performance supports the hypothesis that, during walking toward a target to accomplish a definite task (bisection of the doorway), space is not remapped.

We did not test the patients’ capacity for estimating their body midline. However, although it would be interesting to see whether the estimation of body midline correlates with neglect in pointing tasks and in walking tasks, what is crucial in our findings is that all these aspects are related to
the position in space. Therefore, if body midline estimations were altered in our patients, this alteration also would have depended on the distance at which space was computed.

Another point that emerged from the present study is that neglect in the walking modality tended to be less severe than neglect in the pointing modality. This effect might be due to the fact that walking through a doorway is a more ecological task than bisecting lines with a projection light pen and, therefore, is easier to accomplish. Moreover, the execution of bilateral movements during walking might cause a bilateral cerebral activation resulting in nonspecific improvement in the bisection performance. The activation would not simply be due to the operation of motor areas but also to the strong proprioceptive feedback coming both from muscles and joints, and from the vestibular system, which is continuously stimulated during movement.

Thus, the important point that emerged from the bisection tasks of both experiments is that bisection performances were in keeping with the possibility that during walking, at least for short and unperturbed pathways, remapping of object position in space was not necessary. However, as already mentioned, an alternative explanation can be advanced for these results. In the walking test, our findings conform to previous studies showing that neglect patients may sometimes (although not always) veer toward the right during locomotion when asked to pass through a doorway (Robertson et al., 1994; Tromp et al., 1995). Therefore, in the walking modality, the increasing of the bisection error, as a function of starting distance, might be interpreted as being due to the fact that the longer the distance to be walked, the greater the deviation toward the right. If so, the results in the walking modality should be ascribed to an aspecific neglect walking pattern and should not be interpreted as the consequence of an impaired bisection computation. However, there are reasons to believe that, in our experiment, walking through a doorway was executed as a bisection task. First, in the instructions we gave to the patients, we explicitly asked them to cross the doorway line in the middle. Second, Patient GE’s performance clearly showed that the walking task was executed as a real bisection task. Patient GE, after bilateral cerebral damage, showed the usual left neglect pattern in all the screening tests we used. However, in the bisection test with the pointing modality, she showed a deviation of the subjective midpoint to the left (right neglect) of the objective midpoint of the lines. The crucial finding was that in the walking task we observed the same pattern (i.e., the patient showed a leftward deviation at the passage through the doorway). This pattern of results clearly demonstrates that the walking task was interpreted by our patients in the same way as the pointing task and that both tasks activated the same cognitive system responsible for the operation of the bisection computation.

The results obtained in the second experiment confirmed that remapping did not take place. The patients we studied presented with more severe neglect in far space than in near space and, therefore, when they started their locomotion from a distance of 3.0 m from the target stimulus, they activated the worse space representation available to them, causing a deviation to the right of the walking trajectory. The remapping hypothesis predicts that while one approaches near space, better representations should be activated. Therefore, the recoding of space should cause a correction of the trajectories while one approaches the stimulus, in order to correct the bisection error at the doorway level. Contrary to this prediction, the kinematic study of Patient AB’s walking performance clearly showed that when going from far to near space, the trajectories were rectilinear and not corrected and the patient continued to follow a path that was related to the first computation of space carried out at the starting point.

In conclusion, our data show that during locomotion, at least for short, linear, and unperturbed trajectories, space representation was not remapped. The spatial position of the target object was coded at the beginning of the movement, and the error in the bisection computation was produced within the first representation that was activated.

The evidence of the present study was collected in brain-damaged patients. Therefore, the absence of space remapping in the locomotion task might be due to a specific deficit in shifting from one representation to another caused by the lesion. Although we cannot infer from this negative finding (absence of remapping) that normal participants also do not remap space during locomotion, we would suggest a similar pattern for normals. We find it very reasonable that for relatively short distances and for unperturbed pathways, our brain constructs a single, stable representation of the spatial position of an object for the execution of a particular task during movement, instead of continuously changing the representation as the participant passes across different sectors of space. As already mentioned, it is likely that updating during walking may become necessary for distances greater than those we used, or when a rapid change in some characteristic of the target or a perturbation in the walking trajectory is introduced during the participant’s walking.

---

1 It is worth noting that to veer toward the right during locomotion is not in contrast with the usual report of neglect patients bumping into the left side of a doorway or bumping into objects on the left. When they bump into the left side, we do not know what part of space or of an object these patients are considering, whereas in our task (where bisection of the doorway was explicitly requested), and in other walking experiments with neglect patients, they had to take the doorway as the object to be bisected; therefore, if they neglected the left side of the doorway, they necessarily passed through it (bisected it) to the right of the objective midpoint.

References


