Goal-Directed Hand Movements Are Not Affected by the Biased Space Representation in Spatial Neglect

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Abstract

■ Patients with spatial neglect exhibit a severe shift of spontaneous explorative movements to the right side, indicating a bias of long-living representations of space. Whether or not goal-directed movements likewise are affected by this rightward bias has been controversially discussed throughout the last decade. Unfortunately, substantial differences regarding patient selection and data analysis prevented a direct comparison of these results. We thus studied pointing movements in a new sample of subjects covering all different patient groups previously investigated on this issue. We analyzed all the different measures of hand path curvature used so far and, in addition, suggest a new measure that avoids the disadvantages of the previously used parameters. Despite their severe bias for exploratory movements, we did not find systematic, direction-specific deviations of goal-directed hand movements that were specific for the patients with spatial neglect. The results strongly suggest that the disturbance of long-living spatial representations underlying the bias of exploratory behavior in patients with neglect does not influence the performance of goal-directed movements. The data support the view of a dual mode of space representation in the posterior parietal and the superior temporal cortex. ■

INTRODUCTION

Clinical evidence has been reported suggesting dissociated space representations underlying exploratory and goal-directed motor behavior in humans. On the one hand, patients with optic ataxia and posterior parietal lobe lesions demonstrate severe misreaching of goal-directed movements to visual, contralesionally located targets. The same patients show unimpaired exploratory movements when they are searching for objects in their peripersonal space (Perenin, Revol, & Rode, 1998). On the other hand, patients with spatial neglect and more ventro-rostral lesions, in the superior temporal cortex, demonstrate a severe distortion of their exploratory movements. If they search for an object or person in their surroundings, they show a stable shift of ocular and tactile search movements to the ipsilesional right side (Karnath, Niemeier, & Dichgans, 1998; Karnath & Perenin, 1998).

There is no dispute that patients with spatial neglect do not show the misreaching for visual targets that is observed in patients with optic ataxia. Even with severe spatial neglect in the acute stage of the stroke, the patients' goal-directed movements precisely land on target with or without visual feedback about actual hand position (Jackson, Newport, Husain, Harvey, & Hindle, 2000; Karnath, Dick, & Konczak, 1997; Perenin, 1997). However, contradictory findings have been reported concerning the shape of the movement path between start and target position. Two studies (Harvey, Milner, & Roberts, 1994; Goodale, Milner, Jakobson, & Carey, 1990) reported a rightward deviation of goal-directed movements in patients with right brain damage. None of their patients showed clinical neglect at the time of the experiments, but they suggested that the deviation might be due to subtle spatial neglect. Karnath et al. (1997) investigated patients with acute and severe spatial neglect. They did not find a direction-specific deviation of the patients' goal-directed movements, neither to targets on the left nor to targets on the right side of space. Jackson et al. (2000) reported that pointing movements were more curved in two patients with right brain damage and neglect (as this was the case in the only control patient without neglect in that study). The trajectories had more rightward curvature in one neglect patient, but not in the other. In a more recent study, the same group investigated the grasping behavior of four patients with neglect in comparison to three right brain-damaged patients without neglect and healthy controls (Harvey et al., 2002). Now, in agreement with the findings of Karnath et al. (1997), they did not find a deviation of the hand trajectory that specifically occurred only when the patients had spatial neglect.

Unfortunately, the contradictory studies conducted so far cannot easily be compared. Whereas Harvey et al. (2002), Jackson et al. (2000), and Karnath et al. (1997) investigated patients with spatial neglect, Harvey et al.

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(1994) and Goodale et al. (1990) investigated patients who had fully recovered from spatial neglect by the time of the experiments. Further, different measures of hand path curvature were used in the different studies. The present study thus aimed to (i) directly compare all clinical patient groups tested in the previous studies, (ii) compare all the different measures of hand path curvature used so far, and (iii) suggest a new measure of hand path curvature that avoids the disadvantages of previously used parameters. The purpose was to clarify whether or not systematic deviations of goal-directed hand movements toward the ipsilesional side are characteristic for patients with spatial neglect.

We examined 17 consecutively admitted patients with right brain damage: 6 patients with severe spatial neglect after a unilateral stroke in the right hemisphere, 4 patients who had already recovered from spatial neglect by the time of testing, and 7 stroke patients without spatial neglect throughout their clinical history. The subjects sat in front of a vertical board. They were required to make an accurate pointing movement from a fixed starting position to one of eight targets (red LEDs) located on the left and right sides of the board. Every subject underwent two conditions pointing three times to each LED with room lights turned on (closed-loop) and pointing in darkness (open-loop), resulting in 24 trials per condition. The sequence of target presentation was randomized within the two conditions.

RESULTS

Each trajectory was standardized to allow a quantitative analysis and a direct comparison of individual trajectories to different target positions at different movement velocities. First, trajectories were adjusted to the straight line between the starting position and the respective target by means of translational and rotational transformations. Second, each trajectory was divided into 30 intervals of equal temporal length. For each interval, we calculated the mean deviation of actual finger position from the straight-line path along the horizontal and vertical axes. Mean standardized trajectories of each subject for both experimental conditions are presented in Figure 1.

Terminal Accuracy

The mean terminal accuracy along the horizontal and the vertical axis of all groups in both conditions is presented in Figure 2. The measure represents the distance between the target and the fingertip at the time of the kinematic end of the movement. The individual means of endpoint deviations along the horizontal and vertical axes were subjected to repeated-measures ANOVAs with the within-subject factors Condition (closed- vs. open-loop) and Side (left-sided vs. right-sided targets) and the between-subject factor "group." Along the horizontal dimension, we found a significant main effect of factor Side, $F_1 = 4.988$, $p = .036$, indicating a more leftward terminal error for movements to targets on the right side and a more rightward terminal error for targets on the left side of space in all subject groups.

Along the vertical dimension, we found significant two-way interactions for Side with Group, $F_3 = 12.458$, $p < .001$, and for Side with Condition, $F_1 = 7.017$, $p = .015$. We thus conducted individual repeated-measures ANOVAs for both sides with factors Condition and Group. These analyses revealed a significant main effect of Condition, indicating larger terminal errors for open-loop than for closed-loop movements to both sides of space (left: $F_1 = 18.94$, $p < .001$; right: $F_1 = 21.353$, $p < .001$). For targets on the right side, we found a significant main effect of factor Group. Post hoc Scheffé tests revealed a significant difference between recovered neglect patients and healthy control subjects ($p = .013$),

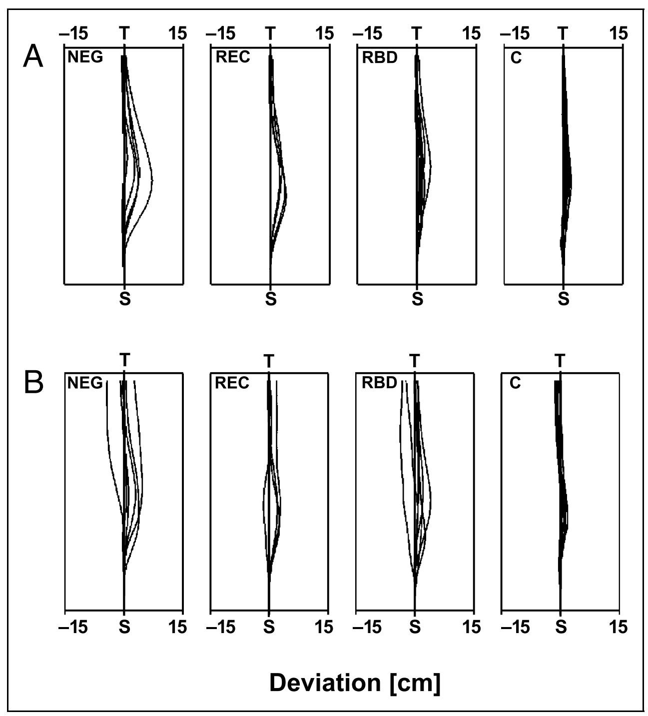
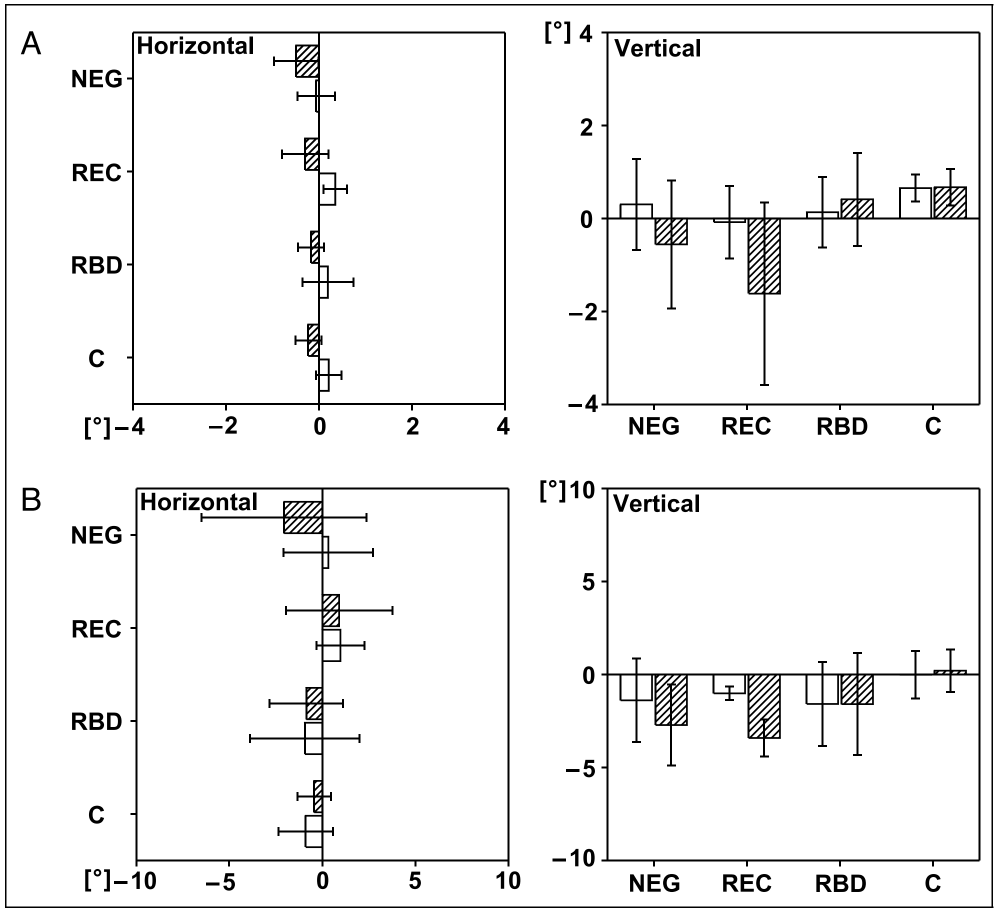


Figure 1. Horizontal deviation of standardized mean trajectories from the straight connection between the start and the target positions. Negative values denote leftward deviations, positive values denote rightward deviations. Individual trajectories from each subject were spatially and temporally adjusted (please see the text for details) and averaged for each condition. Presented are the resulting mean trajectories of each subject in closed-loop (A) and open-loop (B) movement conditions. The straight line in the center of each panel represents the straight connection between the start (S) and the target (T) positions. NEG=patients with severe spatial neglect; REC=patients who had recovered from spatial neglect by the time of testing; RBD=right brain-damaged patients without spatial neglect; C=non-brain-damaged controls.

Figure 2. Mean terminal accuracy and standard deviations along the horizontal and the vertical axis of space for all groups in the closed-loop (A) and the open-loop (B) conditions. Negative values denote leftward or downward deviations, positive values denote rightward or upward deviations. Open bars indicate movements to targets positioned on the left side, hatched bars movements to targets positioned on the right. Please note the different scales in conditions A and B. Abbreviations NEG, REC, RBD, and C as in Figure 1.



indicating a lower elevation of the terminal hand position in the recovered neglect patients.

Hand Path Curvature

To analyze ''hand path curvature'' (i.e., the shape of the movement path between start and target position), we calculated four different parameters (Figure 3). As the indices HPC_{sign} and HPC_{cum} take the direction of deviations into account, we termed them ''directionally sensitive.'' In contrast, the so-called absolute indices HPC and STR are not sensitive to specific directional changes (Figure 3). All horizontal curvature parameters were subjected to repeated-measures ANOVAs with the within-subject factors Condition (closed- vs. open-loop) and Side (left-sided vs. right-sided targets), and the between-subject factor Group.

Absolute Indices (Figure 4)

To directly compare the present data with those reported by Harvey et al. (2002) and Jackson et al. (2000), we computed the absolute distance between the movement path and the straight connection between start and target position at the point of maximum lateral deviation (Figure 4). This value was divided by the distance between start and target. This measure (HPC, Figure 3A) has two disadvantages. It is not capable to differentiate between rightward and leftward deviations and takes into account just one single point of the whole trajectory.

A second parameter was calculated in order to directly compare the present data with those reported by Karnath et al. (1997). This ratio (STR, Figure 3B) between the overall length of the movement path and the shortest distance between the starting position and the target was calculated with nonstandardized trajectories. Although STR takes into account the whole trajectory and not just one single point as the HPC ratio, it likewise does not differentiate between leftward and rightward deviations.

The STR index showed a significantly larger deviation from the straight path for movements under open-loop than under closed-loop conditions, $F_1 = 6.667, p = .017$, and for leftward than for rightward movements, $F_1 = 10.437$, $p = .004$, in all subject groups. There were no specific differences between the groups. The analysis of the HPC index revealed a significant main effect of Side, indicating a higher curvature for rightward movements in all groups, $F_1 = 14.796$, $p = .001$. In addition, we found a significant interaction of factors Condition and Group, $F_3 = 3.915$, $p = .022$. We thus conducted individual ANOVAs for both experimental conditions. The analysis of closed-loop movements revealed a significant effect of factor Group, $F_3 = 3.723$, $p = .026$. Post hoc Scheffé tests showed a significant difference only between patients with spatial neglect and healthy control subjects ($p = .047$), indicating a higher absolute curvature of movements in neglect patients irrespective of the direction of the curvature.

Directional Indices (Figure 5)

Harvey et al. (2002) and Jackson et al. (2000) reported a further analysis of the sign of movement path deviation in patients with spatial neglect (Figure 5). To directly compare the present data with their findings, we computed the ratio between the maximum lateral deviation and the distance between start and end with sign to denote the direction of deviations (HPC_{sign}, Figure 3C). However, like the parameter HPC, this measure takes into account just one single point of the whole trajectory and works well only for unidirectionally curved trajectories. Any additional, but smaller, deflection to the side opposite of the maximum deviation is neglected.

To avoid the disadvantages of the previously used parameters HPC, STR, and HPC_{sign}, we calculated a new measure of curvature in the present study (HPC_{cum}, Figure 3D). The deviations of standardized trajectories at each data point were added up regarding sign to denote the direction of deviations. This cumulative value was divided by the distance between movement start and end. The procedure provided us with a deviation value, which takes into account the entire movement path and not only a single point of maximum deviation. This new measure (HPC_{cum}) results in high positive or negative values for movements with a largely unidirectional deviation, whereas deviations to both sides will cancel out each other. Therefore, it is sensitive especially for systematic direction-specific changes as they were assumed to occur in patients with spatial neglect.

The HPC_{sign} index did not reveal significant effects neither for factor Group, $F_3 = 1.193$, $p = .335$, nor for any interactions including this factor. A significant difference between the sides of target presentation, $F_1 = 51.315$, $p < .001$, indicated a larger rightward curvature for movements to right-sided than for movements to left-sided targets in all subject groups. The analysis of HPC_{cum} revealed the same significant overall difference between left-sided and right-sided targets, $F_1 = 50.036$, $p < .001$, as HPC_{sign}. In addition, there was a significant three-way interaction of Condition, Side, and Group, $F_3 = 3.769$, $p = .025$, which necessitated to carry out individual ANOVAs for each condition. These analyses revealed a significant interaction of Side and Group for open-loop movements. However, the subsequent univariate ANOVAs for factor Group, carried out for left- and

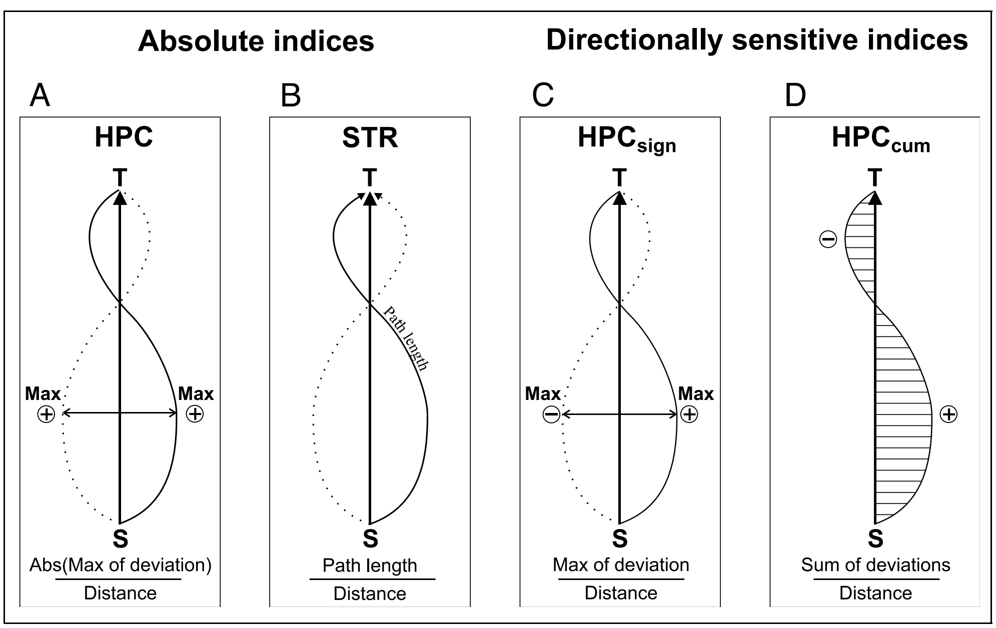


Figure 3. Illustration of the different measures of curvature. Each diagram shows two possible hand trajectories (slim solid and slim dotted lines) along the straight connection between the start (S) and the target (T) positions. (A) The hand path curvature index (HPC) represents the absolute distance between the trajectory and the straight connection between the start and the target positions. It takes into account only one data point, namely, the point of maximal lateral deviation (Max), and does not regard the side to which this deviation occurs. Both depicted trajectories are represented by the same HPC value, although they deviate to different sides. (B) The straightness index (STR) is the ratio between the length of the hand path and the shortest distance between start and target. Again, this measure is insensitive to the direction of deviations. Both depicted trajectories are represented by the same STR value, although they deviate to different sides. (C) The HPC_{sign} index corresponds to the HPC value at the point of maximum deviation, but with sign denoting the direction of the deviation. However, like the HPC index, it takes into account only one data point, namely, the point of maximal lateral deviation (Max). Additional deviations to the opposite side of the maximum deviation are neglected by this measure. (D) The cumulated HPC_{cum} index is computed by the summation of the deviations at each data point of the standardized trajectory. Therefore, the entire hand movement is represented by this variable, not just one single point of it. Also, it regards sign to denote the direction of deviations.

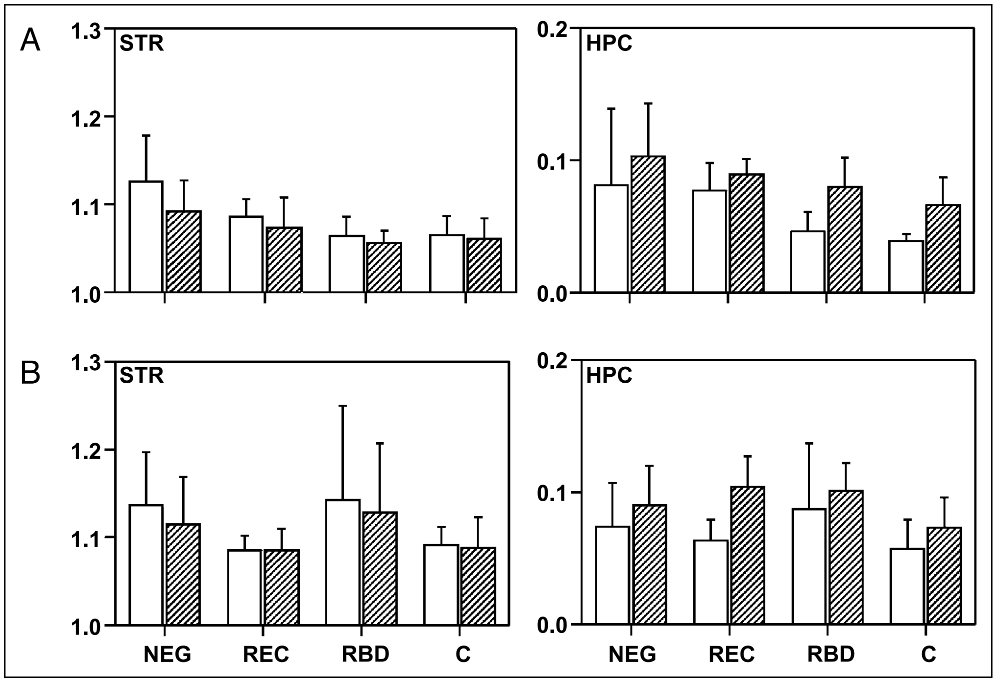


Figure 4. Mean values and standard deviations of the absolute curvature indices STR and HPC for all groups in the closed-loop (A) and open-loop (B) conditions. Open bars denote movements to targets positioned on the left side, hatched bars denote movements to targets positioned on the right. Abbreviations NEG, REC, RBD, and C as in Figure 1.

for right-sided targets separately, did not reveal a significant effect (left: $F_3 = 1.499$, $p = .243$; right: $F_3 = 1.013$, $p = .406$).

DISCUSSION

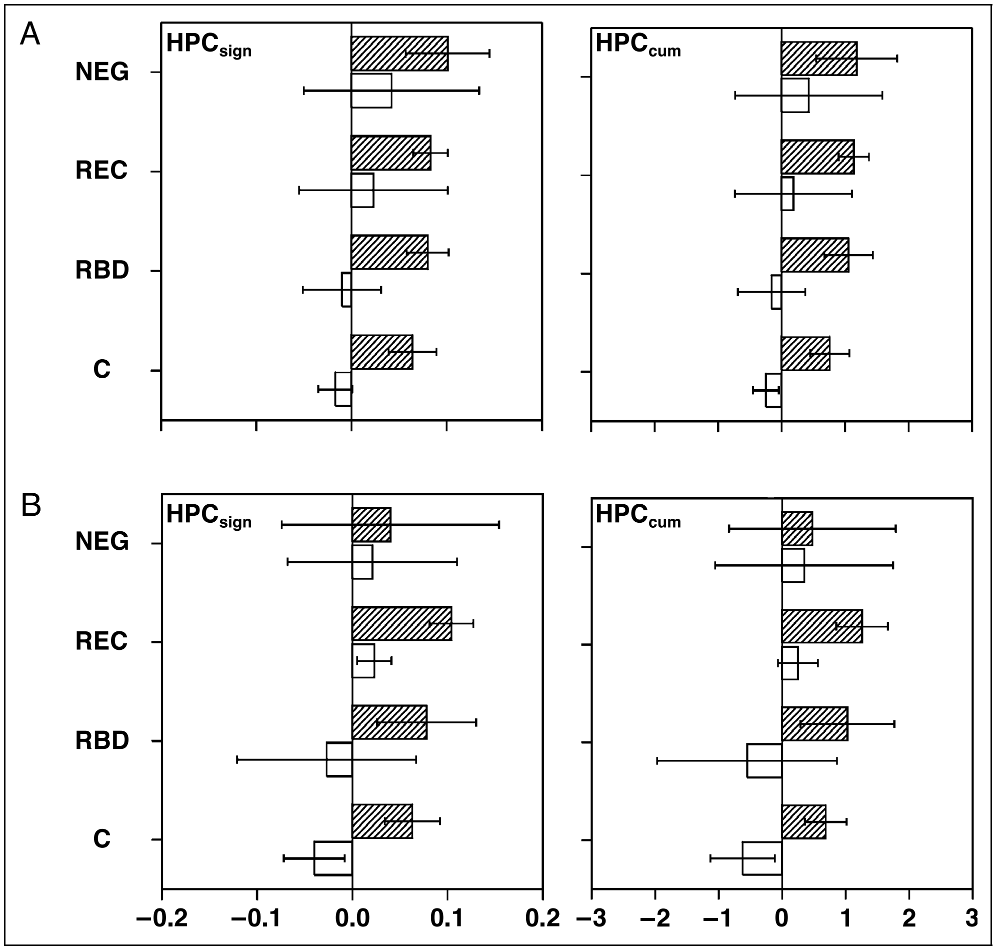
The present study aimed to clarify whether or not systematic deviations of goal-directed hand movements toward the ipsilesional side are characteristic for patients with spatial neglect. We investigated all different patient groups and calculated all indices of hand path curvature used so far in previous studies on that issue. We also tested a new measure of hand path curvature (HPC_{cum}) that avoids the disadvantages of the previously used parameters.

Consistent with previous observations (Jackson et al., 2000; Karnath et al., 1997; Perenin, 1997), we found no systematic bias of ‘‘terminal accuracy’’ in patients with acute spatial neglect in comparison to other subject groups. The neglect patients’ pointing movements precisely landed on target. The present study also clearly showed that there were no systematic deviations of ‘‘hand path curvature’’ to one side of space that could be specifically attributed to spatial neglect. We found a significant difference of curvature only between patients with acute neglect and healthy controls and only for one of the four indices calculated. However, this significant HPC index represents general, but not direction-specific, variability of movements, that is, it does not differentiate between rightward and leftward deviations. Moreover, this measure was not different between the groups of right brain-damaged patients with and without neglect, indicating that the higher variability of movement curvature is not a specific consequence of spatial neglect. All other comparisons, especially those based on the two indices which differentiate between rightward and leftward deviations and thus reflect directionally specific biases (HPC_{sign}, HPC_{cum}), revealed no systematic differences between the groups that could be specifically attributed to spatial neglect.

The present difference between healthy subjects and neglect patients on the HPC index in the closed-loop condition can directly be compared to the findings of Jackson et al. (2000). The authors analyzed the same index in a visually and a proprioceptively guided pointing task and compared three brain-damaged patients with healthy controls. They found an increase of the mean HPC in two patients, one patient with spatial neglect and one patient, who had recovered from spatial neglect, in the visual condition. Our present findings confirm this HPC difference between patients and healthy subjects in a visually guided pointing task. However, the present results also clearly show that this higher variability of hand path curvature is neither direction-specific nor a specific consequence of spatial neglect. There was no significant difference between patients with spatial neglect and right brain-damaged control patients without neglect.

In a third patient with spatial neglect, Jackson et al. (2000) found a direction-specific increase of hand path curvature to the ipsilesional right side. However, this direction-specific change of hand movements was not observed in another patient with spatial neglect. Nevertheless, these contradictory results led the authors to conclude that, ‘‘reaching movements may reveal the distorted topography of spatial representations after neglect’’ (i.e., the ipsilesional, direction-specific bias of

Figure 5. Mean values and standard deviations of the directionally sensitive curvature indices HPC_{sign} and HPC_{cum} for all groups in the closed-loop (A) and open-loop (B) conditions. Negative values denote leftward deviations, positive values denote rightward deviations. Open bars indicate movements to targets positioned on the left side, hatched bars movements to targets positioned on the right. Abbreviations NEG, REC, RBD, and C as in Figure 1.



egocentric spatial representations). The present study clearly showed in a group of six patients with acute and four patients with recovered neglect that all measures which take the spatial direction of deviations into account (HPC_{sign}, HPC_{cum}) did *not* reveal a direction-specific increase of movement curvature between the patients with spatial neglect and the other subject groups. There was a generally larger rightward curvature for movements to right-sided than for left-sided targets in *all* subject groups. Thus, it has to be concluded that spatial neglect is not specifically associated with a systematic bias of goal-directed hand movements toward the ipsilesional side.

This conclusion is further supported by a recent study that compared the effect of vestibular stimulation on exploratory and on goal-directed behavior in healthy subjects (Karnath, Himmelbach, & Perenin, in press). We know that vestibular stimulation is very efficient in reducing the spatial bias in patients with spatial neglect (Rubens, 1985), and induces neglect-like spatial shifts of ocular exploration in healthy subjects (Karnath, Fetter, & Dichgans, 1996). In line with these observations, Karnath et al. (in press) found a strong rightward bias of manual exploration following cold caloric stimulation to the right vestibular organ. In contrast, goal-directed movements to visual targets remained unaffected by the same manipulation. Asymmetric vestibular stimulation thus produced a neglect-like behavior in healthy subjects with a similar dissociation between impaired exploratory and nonimpaired goal-directed hand movements as observed in patients with spatial neglect in the present study.

It was assumed that the dissociation of goal-directed and of explorative movements in optic ataxia and in spatial neglect represents a functional dissociation within the parietal lobe. Recent anatomical findings suggested that this functional dissociation rather concerns the posterior parietal lobe and the superior temporal cortex. Patients with spatial neglect showed a typical lesion overlap in the superior temporal gyrus (STG) or subcortically in the putamen, caudate nucleus, and pulvinar (Karnath, Ferber, & Himmelbach, 2001; Karnath, Himmelbach, & Rorden, 2002). These cortical and subcortical structures are directly interconnected forming a coherent cortico-subcortical network (Karnath, 2001). The present study shows that lesions of this origin lead to a deficit in space exploration, but obviously not to deficits in goal-directed hand movements.

Because the inferior parietal lobule (IPL) and the temporo-parieto-occipital junction were widely accepted as the typical lesion sites provoking spatial neglect (Vallar & Perani, 1986; Heilman, Watson, Valenstein, & Damasio, 1983), previous studies interpreted any motor deficit following lesions which enclosed the right IPL to be due to the syndrome of spatial neglect, even if no clinical neglect was observed by the time of the experiments (Jackson et al., 2000; Harvey et al., 1994; Goodale et al., 1990). Our recent anatomical findings shed new light on this interpretation and can resolve the discrepancies between several studies concerning goal-directed movements in patients with spatial neglect. In many neglect patients, the lesion does not affect the STG exclusively. We hypothesize, that in those cases with spatial neglect who have additional deficits of goal-directed hand and/or eye movements, both neural structures, the IPL as well as the STG, are affected. This could explain why direction-specific deficits in goal-directed movements can occur in single patients with neglect, but—as the present study documents—are not characteristic for a group of neglect patients, who differ concerning the precise localization and extension of their lesions.

Recent studies showed that lesions of the inferior parietal cortex can result in deficits of goal-directed hand or eye movements. Darling, Rizzo, and Butler (2001) reported one patient with a lesion confined to the right IPL with a large variable direction error in pointing to remembered target positions. Consistent with the present findings, this patient did not show spatial neglect. Ro, Rorden, Driver, and Rafal (2001) demonstrated an ipsilesional bias in saccade execution in patients with inferior parietal lesions without clinical symptoms of spatial neglect. Their patients tended to execute saccades to the ipsilesional target in a situation with two asynchronously appearing visual stimuli in the left and right hemifields. Moreover, Milner, Paulignan, Dijkerman, Michel, and Jeannerod (1999) investigated a patient with optic ataxia after posterior parietal lesions. They found gross deviations when the patient pointed to visible targets and a considerable improvement of misreaching when she was pointing to remembered target positions. These results seemed to confirm Milner's (1998) suggestion, that the IPL might play a role in goal-directed movements to remembered or imagined targets, whereas the superior parietal lobule dominates visuomotor processing in situations with visible targets.

All these recent data demonstrate that visuomotor dysfunction can occur with lesions of the IPL independently of the presence of spatial neglect. The present study provides complementary evidence. It shows that spatial neglect does not induce direction-specific deviations in goal-directed movements. These patients rather show a bias of exploratory movements. Taken together, the data support the view of a dual mode of space representation in the posterior parietal and superior temporal cortex subserving direct coding of space for action on the one hand and representations for spatial cognition and exploration on the other.

METHODS

Subjects

All subjects were right-handed. Visual field defects were excluded using standardized neurological examination and/or Tübingen perimetry. Spatial neglect was diagnosed when the patients showed the typical clinical behavior such as (i) a spontaneous deviation of the head and eyes toward the ipsilesional side, (ii) orienting towards the ipsilesional side when addressed from the front or the left, and (iii) ignoring of contralesionally located people or objects. In addition, all patients were further assessed with the following four clinical tests: the "Letter cancellation" task (Weintraub & Mesulam, 1985), the "Bells test" (Gauthier, Dehaut, & Joanette, 1989), the "Baking tray task" (Tham & Tegnér, 1996), and a copying task (for details concerning test analysis and criteria used for the diagnosis of neglect, see Karnath et al., 2002). Demographic and clinical data of all subjects are reported in Table 1. In addition to the brain-damaged patients, we examined nine age-matched healthy controls (median age: 63 years; range: 53–80). All subjects gave their informed consent to participate in the study which has been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Procedures

The subject sat at a distance of 45 cm in front of a vertical board. Their sagittal mid-plane was aligned with a green LED positioned in the middle of the board at eye level. Four horizontally arranged red LEDs were located on the left and on the right side of this central LED. The distance between all LEDs was 5°, resulting in a distance of 20° from the central LED to the most peripheral LED on either side. The board was covered with black textile. An LED therefore was visible only when it was switched on. The head of the subject was fixated with a helmet in a position aligned with the body mid-sagittal plane. At the beginning of each trial, the subjects placed their ipsilesional right hand on a fixed starting position located on their body mid-sagittal plane in front of them. The subjects were instructed to fixate on the central green LED while switched on. We checked accurate fixation by means of an infrared eye-tracking device providing on-line display of eye position. After a random delay between 1000 and 2000 msec, the fixation light turned off and one of the peripheral red target LEDs appeared. The subjects were required to make an accurate movement at a comfortable speed with their right index finger to the target. The movements of the hand were measured with an ultrasonic 3-D tracking device (ZEBRIS) with a sample rate of 150 Hz and a marker at the tip of the index finger.

Table 1. Demographic and Clinical Data of the Right Brain-damaged Patients

Patients	*Sex*	*Age*	*Etiology*	*Lesion location*	*Lesion volume (% of RH)*	*Time since lesions (days)*	*Letter cancellation*		*Bells test*		*BTT*		*Copying (%)*
							Left	*Right*	*Left*	*Right*	*Left*	*Right*	
NEG1	F	69	Infarct	F/T/P	6.1	7	0	9	0	5	6	10	75
NEG2	M	29	Infarct	T/P/I	14.6	12	8	28	6	15	8	8	25
NEG3	F	77	Infarct	F/P	4.2	432	0	21	0	5	0	16	50
NEG4	F	80	Infarct	F/T/P/BG/I	31.0	155	2	22	1	13	0	16	87.5
NEG5	M	56	Hemorraghe	Th	0.7	11	0	10	0	9	0	16	50
NEG6	M	63	Infarct	BG	0.9	15	0	13	2	13	8	8	50
REC1	F	46	Infarct	F/T/P/BG/I	13.1	389	30	30	15	15	7	9	0
REC2	M	78	Infarct	F/T/P/Th	8.7	781	30	30	15	15	6	10	0
REC3	F	47	Infarct	T/I	2.7	371	28	28	15	14	9	7	0
REC4	M	46	Infarct	T/P	17.9	435	28	29	15	14	9	7	0
RBD1	M	75	Infarct	P	1.5	9	30	29	15	15	6	10	0
RBD2	F	60	Hemorraghe	T/I	7.4	6	30	30	15	15	7	9	0
RBD3	F	74	Hemorraghe	BG	2.3	3	28	30	13	15	7	9	0
RBD4	M	64	Infarct	BG	0.5	3	30	30	15	15	8	8	0
RBD5	M	54	Surgery (glioma)	F	4.5	15	30	30	15	15	9	7	0
RBD6	M	36	Hemorraghe	P	2.8	13	30	30	14	15	8	8	0
RBD7	M	50	Infarct	F/T/I/BG	9.8	10	28	28	14	13	7	9	0

NEG1–6 = patients with severe neglect; REC1–4 = patients who had recovered from neglect by the time of testing; RBD1–7 = right brain-damaged patients without neglect. *Sex:* F = female, M = male; *Lesion location:* F = frontal, T = temporal, P = parietal, I = insula, BG = basal ganglia, Th = Thalamus; *Lesion volume:* determined by using MRIcro (Rorden & Brett, 2000); *Letter cancellation* and *Bells test* = number of cancelled items within the left and right half of the test sheet; *BTT* = Baking tray task, number of placed items on the left and right half of the sheet. *Copying* = percentage of items omitted.

Data Processing and Analysis

All data were digitized and stored on a PC for off-line analysis. The data were filtered with a low-pass butterworth filter and a cutoff frequency of 10 Hz. Missing data points of the finger marker were interpolated linearly for a period up to 15 samples (i.e., 100 msec), when the marker got lost (e.g., due to a tilted orientation of the hand with respect to the receiving microphones). The position data of the right index finger of each trial were adjusted to the straight line between the starting position and the respective target by means of translational and rotational transformations. Positive values thus indicate a rightward or an upward deviation from the straight path between the starting position and each of the eight targets. Negative values denote a leftward or a downward deviation. Kinematic start and end of movements were defined as the time when hand velocity reached 5% of tangential peak velocity or a velocity of less than 50 mm/sec.

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