Space exploration in neglect

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Summary
The present study investigated the gaze as well as the head and the eye-in-head movements of neglect patients while they were exploring their surroundings. A random configuration of letters was presented on the inner surface of a sphere that surrounded the subject, requiring free exploratory eye and head movements. The subjects were requested to search for a single (non-existent) target letter. The co-ordination of eye and head movements in patients with neglect resembled the pattern usually observed in healthy subjects orienting to eccentric visual targets. They performed hypometric head movements with additional shifts of eye-in-head position. Moreover, like healthy subjects, the patients with neglect explored space with gaze, with head and eye-in-head movements that were symmetrically distributed around preferred orientations in space. However, in contrast to controls, these centres of exploration were shifted towards the right. The average horizontal position of gaze and of head movements lay right of the body’s mid-sagittal plane, the average eye-in-head position right of the head midline. The preferred orientations were located far away from the anatomical limits of horizontal gaze, head and eye-in-head movements. The decrease of exploration towards more eccentric locations left and right of these orientations thus could not be explained by anatomical restrictions. The results argue against a model of neglect that proposes a lateral gradient of attentional orienting towards the ipsilesional side. Exploring the surroundings, the patients did not orient gaze, the head or the eyes in the head towards the extreme ipsilesional side, nor even close to it. The results favour a deviation model suggesting a shift of the whole frame for exploratory behaviour towards the ipsilesional side. In addition to this shift, we found a second component of altered visual exploration in neglect. The patients’ head and gaze movements exhibited a reduced variability around the deviated centre of exploration. The variability was not generally reduced but rather concerned specifically the horizontal dimension. The latter was found even when the area of exploration was paralleled between the groups, requiring the control subjects to search only in that part of the letter array that the neglect patients had explored spontaneously. Possible mechanisms, such as a disturbed ability to update the spatial representation of visual targets or an altered neural representation of space in the horizontal dimension, are discussed.

Keywords: spatial neglect; brain damage; eye movements; head movements; parietal lobe; space representation

Abbreviation: AD = average deviation

Introduction
Patients with neglect typically fail to report or respond to stimuli located contralateral to the lesion. We know that this deficit is predominantly associated with lesions involving the right inferior parietal and adjacent temporal lobe (Vallar and Perani, 1986; Samuelsson et al., 1997). The underlying mechanism leading to this behaviour, however, is still an issue of lively debate (Halligan and Marshall, 1994).

Clinical tests for neglect, like the cancellation tasks (Albert, 1973; Mesulam 1985), frequently show that neglect patients not only ignore the target stimuli on the contralesional side but also tend to cancel repeatedly the targets on the extreme ipsilesional side. This behavioural pattern of hypo-attention on the contralesional and hyper-attention on the ipsilesional side corresponds with the idea of a lateral gradient of attentional orienting, as suggested by Kinsbourne’s (1977, 1987) model of neglect. The author argued that attention is directed along the vector that is the resultant of the interaction of paired opponent processors that are controlled by the right and left hemispheres, each of which directs attention towards the opposite end of the visual display. Activation imbalance in neglect patients biases the vector and elicits ipsilesional shifts of attention and gaze. A crucial prediction of this model is that orienting is not intact within either hemispace in neglect (Kinsbourne, 1993). Rather, a lateral gradient of attention sweeps across both hemispaces such that attention is always biased in the ipsilesional direction. Following the
gradient, the probability of detecting a target is very low or zero on the extreme contralesional side and increases along the horizontal axis towards the ipsilesional side. The pattern of spontaneous exploration of space should thus exhibit a continuous increase of visual search along the horizontal axis, with a minimum on the extreme contralesional side and a maximum on the extreme ipsilesional side.

Some recent studies were aimed at determining the pattern of visual exploration along the horizontal axis in patients with neglect. They recorded the patients’ exploratory eye movements while searching for a (non-existent) target in complete darkness (Hornak, 1992; Karnath et al., 1996; Karnath, 1997). These studies consistently found a pattern in contrast to the prediction of the gradient model. In a registration field of ±50°, exploratory eye movements showed a symmetrical, bell-shaped distribution with a maximum around +15° right of the body’s mid-sagittal plane and decreasing frequencies towards more eccentric positions on the left and on the right.

However, it was argued that the patients’ exploratory behaviour might be quite different in complete darkness, when no visual stimulus attracts the patients’ attention, compared with normal lighting conditions when they scan a visual scene. In fact, Behrmann et al. (1997) recently reported evidence for such a view. In light, the authors recorded eye movements during visual search in an array of randomly presented letters. From the left to the right of the search field, they found a steep gradient in the patients’ eye movement pattern. The patients made more fixations and spent more time searching. The authors interpreted the finding in favour of Kinsbourne’s (1977, 1993) model of neglect. They argued that the gradual fall-off in frequency of fixations from the right to the left supports the notion that the imbalance between the opposing leftward and rightward vectors following right-sided brain damage results in a smooth gradient of attention from the right to the left.

However, in contrast to the exploration studies carried out in darkness, Behrmann et al.’s (1997) investigation used a much smaller search area with a horizontal extent of ±22.5°, which was about half the field of registration of the previous studies. Nevertheless, the distribution of eye movements obtained in that narrow area corresponded to the distribution seen in darkness in much larger registration fields. Behrmann and co-workers observed a maximum of visual exploration around ±18° with decreasing frequencies of eye movements towards the left and towards the right side of this maximum. However, due to the small area of registration, the decisive question whether the start of the decrease right of the +18° peak continues further towards the right (which would argue against the Kinsbourne hypothesis) or whether it is followed by an increase of visual search towards more eccentric locations on the right (as predicted by the Kinsbourne hypothesis) remained unanswered.

A first aim of the present study was to clarify this question. We decided that, in contrast to both Behrmann et al.’s study and the cancellation tasks used in a clinical bedside situation, visual search should not be restricted to a small area presented in front of the patient. We therefore used a large stimulus array that surrounded the patient and required free eye and head movements, as in an everyday situation. As eye and head movements are tightly coupled during normal orientation in space, such an experimental setting makes it possible to study exploratory behaviour in a more natural situation than when the head is kept in a fixed position, as in the previous studies recording visual search in neglect patients.

We argued recently that patients with neglect explore the attended part of space similarly to healthy subjects, but with the centre of exploration shifted to the ipsilesional right side (Karnath, 1997). According to this assumption, the pattern of eye–head co-ordination of patients with neglect should be similar to that of healthy subjects who concentrate their visual search on the right side of a scene and disregard the leftward parts. From studies with healthy subjects, we know that final head positions during orientation to peripheral targets are usually hypometric, requiring an additional shift of eye-in-head position that increases with the eccentricity of the target (e.g. Gresty, 1974; Uemura et al., 1980; Delreux et al., 1991). According to the above hypothesis, we would thus expect in patients with neglect a rightward shift of their exploratory head movements as well as of the eye-in-head position.

However, it is also possible that patients with neglect show an abnormal interaction of exploratory eye and head movements. From clinical observation, it has long been known that patients with neglect tend to deviate their head to the ipsilesional side. The neglect of stimuli on the contralesional side could thus result from a shifted head position with respect to the trunk while the eye movements with respect to the head are carried out symmetrically to both sides of the shifted head midline. To clarify this question and to understand the mechanism leading to spatial neglect, the present investigation analyses not only gaze positions in space and head movements with respect to the trunk but also the patients’ eye-in-head movements when the orientation of the head is decoupled from the orientation of the trunk. In two experiments, we examine the subjects’ eye–head coordination when exploring the surroundings searching for a visual target stimulus.

Method

Subjects

All neglect patients and control subjects gave informed consent to participation in the study, which was approved by the Ethics Committee of Tübingen University. None of the subjects had oculomotor palsies or visual field defects, as assessed by standard neurological examination. We recorded the gaze and head movements of four consecutively admitted patients with right hemispheric lesions and neglect, aged 48–65 years (median = 57 years). Demographic and clinical
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Table 1 Demographic and clinical data of the four right-brain-damaged patients with neglect (NEG)

<table>
<thead>
<tr>
<th>Patient</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Aetiology</th>
<th>Lesion location</th>
<th>Days since first clinical symptoms</th>
<th>Hemi-anopia</th>
<th>Extinction*</th>
<th>Letter cancellation†</th>
<th>Line bisection‡</th>
<th>Copying§</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEG1</td>
<td>F</td>
<td>50</td>
<td>Infarct</td>
<td>Temporo-parietal</td>
<td>148</td>
<td>No</td>
<td>v/a</td>
<td>1</td>
<td>24</td>
<td>0.24</td>
</tr>
<tr>
<td>NEG2</td>
<td>M</td>
<td>63</td>
<td>Infarct</td>
<td>Temporo-parietal</td>
<td>2</td>
<td>No</td>
<td>v/a/t</td>
<td>12</td>
<td>25</td>
<td>0.96</td>
</tr>
<tr>
<td>NEG2</td>
<td>M</td>
<td>64</td>
<td>Infarct</td>
<td>Parieto-occipital</td>
<td>18</td>
<td>No</td>
<td>v/a/t</td>
<td>0</td>
<td>11</td>
<td>5.92</td>
</tr>
<tr>
<td>NEG4</td>
<td>M</td>
<td>48</td>
<td>OP astrocytoma grade III</td>
<td>Parietal</td>
<td>−125</td>
<td>No</td>
<td>v</td>
<td>0</td>
<td>11</td>
<td>3.02</td>
</tr>
</tbody>
</table>

OP = operation/surgery. *v = visual; a = acoustic; t = tactile. Target letters marked on each half of the test sheet (n\text{\textsubscript{max}} = 30 on either side) (Mesulam, 1985). †Average rightward deviation (in centimetres) of horizontal lines with 24 cm length (five trials). ‡Complete copy of all objects; (−) = omission of elements located at the objects’ left side; − = complete omission of at least one object on one side of the test sheet.

Data are given in Table 1. We compared their performance with that of 10 control subjects without neglect (six male, four female), aged 27–74 years (median = 60.5 years). Six of these subjects were neurological patients without brain damage. The other four subjects suffered from right hemispheric lesions but had no symptoms of neglect (median time since lesion = 115 days). One of these patients had sustained a haemorrhage in the right frontal cortex and underlying white matter. Two patients had a temporal lesion and another a frontal lesion due to surgery on a grade IV glioma.

Apparatus

Subjects were seated in a light bulb-shaped cabin that was dimly illuminated. The head of the subject was located in the centre of the upper spherical part of the bulb (diameter 190 cm) and could be freely moved. The rest of the body was immobilized by belts and shoulder straps. On the inner surface of the spherical part of the cabin, a random array of letters was presented (Fig. 1). The whole array consisted of 340 letters (each 2° high). They covered an area of 280° of visual angle in the horizontal plane (140° right and left of the body’s mid-sagittal plane) and of 100° in the vertical plane (50° above and below the subject’s eye level).

Gaze and head positions were recorded using the magnetic field-search coil technique (Robinson, 1963). Three orthogonal alternating magnetic fields were generated by three pairs of Helmholtz coils mounted in a cube-like configuration on the outer surface of the spherical part of the cabin. For the measurement of gaze position, the subject wore a 3D search coil (Skalar Medical, Delft, The Netherlands), i.e. a coil embedded in a silicone rubber ring, which adhered to the sclera by suction. Head position was measured with another 3D annulus attached to the subject’s forehead. The sampling rate was 100 Hz. Data were stored on hard disk for off-line analysis. The eye-in-head position, which is the difference between gaze and head positions, was determined by multiplying the rotation matrices of gaze positions with the inverse rotation matrices of head positions.

To contrast the subject’s spontaneous exploratory movements with the most eccentric positions actually possible due to anatomical restrictions, we determined the maximum horizontal range of gaze, head and eye-in-head positions at the end of the second experiment (see below). Subjects were instructed verbally to direct their gaze as far as possible to the left and to the right while head and gaze movements were recorded.

Figures and data analyses in this paper present head and gaze positions in cabin coordinates, i.e. in allocentric coordinates of the letter array. Since the subject’s trunk position was fixed in the cabin, the coordinates of head and gaze positions were also trunk-centred. Head and gaze coordinates 0°/0° were defined as the position of the subject’s mid-sagittal body axis in the horizontal plane and the individual eye level in the sagittal plane. Eye-in-head coordinates were head-centred with coordinates 0°/0° aligned with the head’s mid-sagittal axis at eye level.
Experiment 1

Procedure
All subjects participated in this experiment. The task was to search for a single target letter ‘A’ while gaze and head movements were recorded. At the beginning of each trial, the subject was blindfolded and told that a single target letter ‘A’ would be presented ‘somewhere in the sphere’. Subsequently, exploratory eye and head movements were recorded for 20 s. The subject was then blindfolded again. Each subject carried out three of these search trials. While eye and head positions were being recorded, no ‘A’ was in fact presented in the sphere.

We employed a search task with a non-existent target to prevent a target stimulus attracting the subject’s attention and thus influencing the distribution of spontaneous exploratory movements in space. To maintain the subject’s motivation to search for the non-existent letter ‘A’, an additional trial was carried out between the second and the third experimental trials without recording any data. In this trial, a letter ‘A’ was actually presented in the central area of the sphere. If the subject did not find the target in the 20 s allowed, the experimenter identified its location by pointing to the target.

Results
In Fig. 2, the mean percentage of exploration time along the horizontal axis is given in discrete 5° sectors of visual angle. Since there were no relevant differences between the control subjects with and without brain lesions, the figure presents the data of the whole control group. The distributions of gaze, eye-in-head and head positions are plotted separately. Negative gaze or head positions indicate locations left of the trunk’s mid-sagittal plane; positive values indicate locations on its right side. Irrespective of the head’s actual position in the cabin, negative eye-in-head positions indicate locations left of the head’s mid-sagittal plane and positive values indicate locations on its right side. The distance between the two vertical dotted lines in Fig. 2 represents the subjects’ maximum horizontal range of gaze, eye-in-head and head positions.

While searching for the target letter, the control subjects showed a flat, symmetrical distribution of gaze positions covering a broad part of the space up to ~130° left and right of the body’s mid-sagittal plane (Fig. 2). They explored the surroundings by rotating the head, and the eyes relative to the head, symmetrically to both sides (Fig. 2). The patients with neglect explored a much smaller part of the letter array. Gaze positions, head positions and also eye-in-head positions deviated towards the ipsilesional, right side (Fig. 2). To compare the exploratory behaviour of the two subject groups statistically, we averaged the positions of each of the three variables along the horizontal axis. The variables were analysed by repeated measures analyses of variance with ‘patient group’ as the between factor and ‘experimental trial’ as the within factor. The three analyses revealed significant main effects of ‘patient group’ (gaze: $F = 41.01$, $P < 0.001$; eye-in-head: $F = 16.20$, $P = 0.002$; head: $F = 30.32$, $P < 0.001$), indicating a rightward deviation of exploratory gaze, eye-in-head and head movements in patients with neglect. No other effects or interactions proved to be significant.

In contrast to the spontaneous exploratory movements, we found no differences between the two subject groups concerning the maximum horizontal ranges of gaze, eye-in-head and head positions. Statistical analysis of each of these variables using repeated measures analysis of variance with ‘patient group’ as the between factor and with ‘side’ (left versus right) as the within factor revealed no significant effects. The results suggested that, on command, patients with neglect were able to direct gaze, the head and the eyes in the head as far to the left and right side as the controls.
investigate whether this difference is simply the consequence of the rightward shift of the exploration centre or whether it has its own pathogenetic origin, we conducted the following experiment. The control subjects were guided to attend to the same part of space that the patients with neglect had explored spontaneously. The area of exploration was thus paralleled between the groups. This allowed us to examine whether the same spatial shift and the same distribution of exploration would occur in the control subjects as had been observed for the patients with neglect in Experiment 1.

**Procedure**

The same 10 control subjects tested in the first experiment participated in Experiment 2. Again, the subjects’ task was to search for a (non-existent) target letter ‘A’ using the same experimental procedure as before. In contrast to the first experiment, the subjects were told that the target letter ‘A’ would be presented ‘only in a certain area in the sphere’. This area was indicated by two vertical lines presented −55° left and +125° right of the body’s mid-sagittal plane. This restriction of the area of exploration corresponded with the part of the letter array that the patients with neglect had explored spontaneously in Experiment 1. All their gaze positions had fallen into that area of the surrounding letter array.

**Results**

Analogously to Fig. 2, Fig. 4 presents the mean percentage of exploration time along the horizontal axis in discrete 5° sectors of visual angle. The hatched fields indicate the areas of the letter array that the subjects were told should not be explored. One subject ignored the statement that the target letter would be presented ‘only in a certain area in the sphere’. He explored the array up to ±130° towards the left and right sides. His data were excluded from the analysis. The remaining nine subjects searched for the target in the area indicated. They directed their gaze beyond these borders only for 3.9% of the exploration time.

The control subjects’ orientation of the head, the eyes in the head and the gaze indeed showed deviations towards the right similar to those seen in the patients with neglect in the first experiment (Fig. 4). Figure 5 presents the average horizontal positions of the three variables. The data for the control subjects obtained in Experiment 2 are plotted as shaded diamonds. These data are contrasted with those obtained for the same nine control subjects and for the neglect patients in the first experiment (open and closed circles, respectively, in Fig. 5). In comparison with the first experiment, the control subjects explored space further towards the right. As in the patients with neglect, this shift was seen in all three variables. Statistical comparison between the control subjects’ data obtained in the first and second experiments demonstrated a significant rightward deviation of gaze position ($t = 12.90, P < 0.001$), head...
Fig. 4 Mean percentage of exploration time registered for the group of control subjects while searching for the target letter in the restricted area of space ranging from –55° to the left to +125° to the right of the body’s mid-sagittal plane. Data are shown separately for gaze, eye-in-head and head movements. Exploration is plotted in discrete 5° sectors along the horizontal axis. The grey curve superimposed on each graph represents the result of a smoothing procedure using moving averages that include five data points on either side of each value. The hatched areas indicate the parts of the letter array that the subject was told should not be explored.

However, in contrast to the induced rightward shift, the shapes of the distributions of gaze and of head positions in the controls were quite different from those for the neglect patients obtained in Experiment 1. Figure 4 demonstrates that these distributions were flat in shape and had no marked peak, as in the patients with neglect. The control subjects’ head positions showed a slightly bimodal distribution. To compare the apparent differences in variability statistically, we determined the mean of absolute distances between each measured position and the average positions of gaze, eye-in-head and head [i.e. the average deviation (AD)]. Compared with the more common measure of variability, the standard deviation, AD provides a more robust estimation for broad distributions (Press et al., 1992). AD was calculated for the horizontal as well as for the vertical dimension in order to examine whether the apparently reduced variability along the horizontal axis might be a consequence of generally reduced exploratory behaviour in the patients with neglect (Fig. 6). For each of the three variables (ADgaze, ADeye–in–head, ADhead), a repeated measures analysis of variance was carried out with ‘patient group’ as the between factor and ‘dimension’ (horizontal versus vertical) as the within factor. (The analyses excluded the 3.9% of exploration time in which the subjects directed their gaze beyond the borders of the restricted area.)

For both variability of gaze and variability of head position, we found significant effects for the factors ‘patient group’ and ‘dimension’ and for the interaction of the two factors (gaze: patient group × dimension, $F = 5.78$, $P = 0.035$; head: patient group × dimension, $F = 12.61$, $P = 0.005$). Post hoc analyses compared the two groups of subjects using the t test and Holm’s correction for the overall alpha
level. In neglect patients, significantly reduced variability of gaze and head positions was found only in the horizontal plane (gaze: \( t = 4.39, P = 0.018 \); head: \( t = 5.38, P < 0.001 \)). In the vertical plane, variability of gaze and head positions did not differ between the two subject groups (gaze: \( t = 1.91, P = 0.145 \); head: \( t = 0.72, P = 0.519 \)). The findings indicate that the reduced variability of gaze and head movements in patients with neglect cannot be explained by a generally reduced amount of exploratory behaviour, but specifically concerns the horizontal dimension of space.

The analysis of the variability of eye-in-head position revealed a significant effect for the factor ‘patient group’ (\( F = 8.82, P = 0.013 \)), indicating generally reduced variability of exploratory eye-in-head movements in patients with neglect. The factor ‘dimension’ (\( F = 2.13, P = 0.172 \)) and the interaction (\( F = 3.47, P = 0.090 \)) were not significant.

To examine whether the reduced variability of visual search in the patients with neglect might result from local differences in saccadic performance along the horizontal axis, we computed the duration of fixations and the amplitudes of the saccades and compared them between the controls (Experiment 2) and the neglect patients (Experiment 1). Successive points of measurement were combined into ‘fixations’ if they fell into a gliding window of 1.5° of visual angle and had a minimum duration of 120 ms. Consistent with previous results (Karnath et al., 1996), the patients with neglect performed smaller saccadic amplitudes than the controls (\( t = 2.75, P = 0.019 \)). Moreover, patients with neglect showed significantly longer mean durations of fixation (\( t = 2.87, P = 0.015 \)). However, as illustrated in Fig. 7, this difference of saccadic parameters characterized ocular exploration along the horizontal axis independently of the position from which a saccade was initiated. No local maxima or minima were found around the centre of exploration.

**Discussion**

The present study investigated the gaze as well as the head and eye-in-head movements of neglect patients while exploring their surroundings. To study space exploration in its natural course, we used a large stimulus array that surrounded the patients and allowed them to move the head freely.

We found a marked discrepancy between the neglect patients’ orientation of gaze, of the eyes relative to the head and of the head relative to the trunk when they spontaneously explored the surroundings compared with their ability to direct the line of sight to that side when explicitly instructed. While searching spontaneously, the patients’ gaze and head positions as well as their eye-in-head positions were deviated towards the ipsilesional side. In contrast, the patients were able to direct their gaze, the head and also the eyes in the head as far to the left and right side as the controls when this was requested by the experimenter. This observation corresponds with previous findings of reduced neglect symptoms due to cueing procedures of various kinds (e.g. Riddoch and Humphreys, 1983; Karnath, 1988; Halligan et al., 1992). The finding also demonstrates that the deviated pattern of spontaneous exploratory movements in the patients with neglect was not simply the result of a basic motor or oculomotor deficit causing an inability to direct gaze, the head or the eyes in the head towards the far left or right.

The deviation of eye-in-head positions in addition to the deviated head positions observed in patients with neglect corresponded to the pattern of eye–head co-ordination found in the control subjects when required to search only in that part of the letter array that the neglect patients had explored spontaneously. The co-ordination of eye and head movements in patients with neglect thus appears to resemble the pattern usually observed in healthy subjects orienting to eccentric visual targets, namely to perform hypometric head movements in combination with additional shifts of eye-in-head position (Gresty, 1974; Uemura et al., 1980; Delreux et al., 1991).

The patients’ distributions of gaze, of the eyes in the head and of the head with respect to the trunk were roughly bell-shaped along the horizontal axis with the centre of exploration on the ipsilesional right. With respect to these maxima, neglect patients oriented gaze, the eyes in the head and the head symmetrically and with decreasing frequency towards more eccentric positions on the right and the left sides. The decreasing frequencies for movements to both sides could not be explained by anatomical restrictions. The average positions of gaze, eye-in-head and head movements were located far away from the patients’ anatomical limits. Also,
the decrease of frequency did not coincide with a point beyond which visual search would have caused such effort and inconvenience that even control subjects would have shown significantly reduced exploratory activity. In fact, to direct the line of sight with a combined eye–head movement beyond +40° to the right is a quite common event for normal subjects in everyday situations.

The present findings do not conflict with those reported by Behrmann et al. (1997). Rather, they show that the continuous increase of ocular exploration that these authors observed from the left side of the search field up to about +20° to the right of the patient’s sagittal midline is followed by a continuous decrease towards more eccentric positions on the right. The experimental setup used by Behrmann and co-workers, i.e. the narrow field of eye movement registration up to only +22.5° to the right, simply did not allow observations and decisions about the frequency of patients’ exploratory movements beyond this border further towards the right side of space. Accordingly, the present findings suggest conclusions different than those drawn by Behrmann and colleagues. The findings provide evidence against a model of neglect that proposes a lateral gradient of attentional orienting towards the ipsilesional side (Kinsbourne, 1977, 1987).

Kinsbourne’s model regards neglect not as a spatial but rather as a directional phenomenon. Each hemisphere generates one of a pair of opponent processors that interact in a mutually inhibitory manner in the sense of a ‘difference-minimizing feedback’ connection (Kinsbourne, 1993). Neglect following brain damage is due to a lesion of one of these processors leading to a functional imbalance within the system. The result is an attentional bias or a turning tendency in the ipsilesional direction. It leads to hypo-attention on the contralesional side and orienting ‘to the end of the structured environment. Kinsbourne (1993) interpreted this behaviour as being due to neglect induced by these lesions and as evidence for the attentional gradient model. The fact that human patients with neglect are not observed in such states of rightward circling was not considered to be an argument against the validity of the gradient model in humans, but rather was attributed to ‘associated deficits that limit mobility’ in brain-damaged patients with neglect (Kinsbourne, 1993).

The present data are not in agreement with such predictions. They do not support the assumption that neglect is associated with imbalance leading to a tendency to turn more and more to the right when exploring the visual surroundings. Even though the patients neglected most of the contralateral left side of space, they did not orient excessively towards the extreme ipsilesional right side to spend most of the time searching in this area of space. Rather, we found the patients’ attentional orienting to be centred around a location on the ipsilesional side of egocentric space, far away from the borders of the visual array and from anatomical limits of eye and head movements. The average orientation of gaze lay ‘only’ +40.6° and the average orientation of the head ‘only’ +26.3° right of the body’s mid-sagittal plane. The orientation of the eyes in the head also showed a shift towards the ipsilesional, head-centred right. Like gaze and head positions, the eyes did not deviate to a position close to the anatomical limit on the right but were preferentially oriented ‘only’ +13.2° to the right.

One could speculate that it might be possible to modify Kinsbourne’s model in such a way that it would be compatible with the present distribution of exploratory movements. For example, by choosing appropriate gains and delays for the inhibitory connections between the opponent processors, a model could be found in which the lesion of one of the processors would not lead to the continuous orienting of attention in the ipsilesional direction but rather would lead to a new state of equilibrium. However, as in Kinsbourne’s original model, such a modified version would again be a purely directional model that has no information about egocentric positions in space. It would represent directions (‘to the left’, ‘to the right’), but would have no knowledge about positions relative to the subject. Equilibrium thus could occur at any point in egocentric space, depending on factors such as the initial state of activation of both processors or the starting position of visual search.

To obtain an equilibrium of exploration occurring reliably at a certain position on the ipsilesional side, as observed in the present experiment, it is necessary to supply the system with additional information about the actual orientation of attention in egocentric space. Proprioceptive signals of the eyes in the head and of the head on the trunk, for example, would have to be assumed to modulate the activity of the processors. Whenever the eyes in the head or the head on the trunk are directed along the horizontal dimension, the proportion of activity between the two processors could be assumed to be changed in favour of one of the opponent processors. However, including such proprioceptive signals as afferent input into the model would change the character of Kinsbourne’s original concept completely. Such changes would lead to a model that represents spatial information. The decisive aspect would be resolved, namely that neglect is assumed to be a directional phenomenon, suggesting that the ‘relative position of a stimulus is a major determinant of its standing on the attentional hierarchy, its absolute location is not’ (Kinsbourne, 1993). In summary, it seems to be difficult to reconcile the present data of patients with neglect even with a modified concept of a directional model of opponent processors.

The patients’ distribution of eye and head movements during space exploration rather favour a deviation model,
suggesting that the whole frame for exploratory behaviour is rotated around an earth-vertical body axis to a new equilibrium on the right (Karnath, 1997). As in healthy subjects, this position represents the centre of exploratory activity. Its location, however, is shifted towards the ipsilesional right side. A possible mechanism that might lead to such a horizontal shift of exploratory behaviour is an altered neural representation of space in patients with neglect (Ventre et al., 1984; Karnath, 1994). This concept corresponds with recent neurophysiological findings supporting the assumption that the posterior parietal cortex combines visual, vestibular, neck-proprioceptive and auditory input to elaborate an abstract representation of space (Andersen, 1997). In neglect patients, the transformation of the inputs from the multiple sensory systems into this abstract representation seems to work with a systematic error resulting in rotation of the spatial reference frame to the ipsilesional side (Karnath, 1994, 1997).

Instead of rotation around an earth-vertical body axis, Valler et al. (1995) suggested translation of the spatial reference system towards the side of the lesion. In an auditory localization task, the authors found in patients with neglect a displacement of the auditory median plane to the ipsilesional right in the front half-space and in the back half-space. They interpreted their results in favour of translation of the whole coordinate system to the patients’ ipsilesional side. However, since eye position was not restricted in the experiment, it is also plausible that their findings had an origin different from a distortion of space representation. A bias of horizontal eye position, as observed in the present study, could well account for the ‘translation’ of the subjective auditory median plane to the ipsilesional side. As was demonstrated by Lewald and Ehrenstein (1996) in healthy subjects, the subjective auditory median plane shifts with the spatial direction of gaze position. Thus, a bias of horizontal eye position towards the ipsilesional side in patients with neglect would physiologically, but not pathologically, lead to a shift of the auditory median plane in the same direction (as is the case in healthy subjects with their gaze directed to that side).

Beyond this discussion of translation versus rotation, it would be interesting to find out whether the present findings about the patients’ deviated visual exploration of space are specific for exploration via eye movements or might characterize neglect patients’ exploratory behaviour in general. One might ask whether the outcome of the present study would have been different if the task had been, for example, to mark motorically a certain letter on the inside of the cabin instead of visually searching for it. More generally, it might be asked in which way the present results are related to and might explain the neglect of contralateral stimuli in visuomotor tasks such as the copying of stimuli distributed on a test sheet, in cancellation tasks such as those introduced by Albert (1973) or Mesulam (1985), or simply in the clinical situation in which a neglect patient is sitting at a table and searches for but does not find an object when it is located on the contralateral side.

To clarify this question, Karnath and Perenin (1998) examined neglect patients’ tactile exploration of space by recording hand movements when the patients searched for a tactile target in peripersonal space. In parallel with the present distribution of exploratory eye movements, the authors found the whole distribution of patients’ exploratory hand movements shifted to the right. The median activity lay 17.7 cm right of the body’s mid-sagittal plane. The frequency of tactile exploration decreased towards the periphery of peripersonal space on the right and the left sides. As in the present exploration of space by eye movements, the tactile search of neglect patients showed no skewed distribution with a minimum on the far contralesional left and a maximum on the far ipsilesional right side. The patients did not orient their hand excessively towards the extreme right. Rather, the median activity was found far away from the rightmost reachable location in peripersonal space. Together with the present findings, the results favour a deviation of the whole frame for exploratory behaviour towards a new equilibrium on the right. The character of this frame appears to be supramodal in that it determines the distribution of exploratory movements irrespective of whether the subject explores the surroundings visually or tactually.

Beyond their implications for the assumption of a deviation model of exploration in neglect (Karnath, 1997), the present data uncover an additional aspect of the exploratory behaviour of neglect patients. We found marked differences in the shape of the distributions of gaze and of head positions along the horizontal axis. Even when the control subjects in the second experiment explored the same part of space that the patients with neglect had explored spontaneously, the distributions of the two groups still differed markedly in the horizontal dimension. The control subjects’ distributions of gaze and head positions were flat in shape and showed no marked peaks, as was the case in the patients with neglect. This indicates that, even when the spatial area to be explored is paralleled between controls and neglect patients, the control subjects scan space along the horizontal axis with head and gaze movements that are broader and thus more ‘efficiently’ distributed in order to find the target.

One could assume that the reduced variability of the neglect patients’ visual search around the centre of exploration on the ipsilesional side might result from local differences of saccadic performance along the horizontal axis. Indeed, the neglect patients scanned the scene, performing longer mean durations of fixation and smaller saccadic amplitudes than the controls. However, these differences characterized the patients’ exploratory behaviour along the whole horizontal axis, i.e. the differences were found independently of the egocentric horizontal position of saccade initiation. Saccades initiated around the centre of exploration showed the same characteristics as those initiated in the periphery.

The assumption of a generally reduced ‘vivacity’ of exploratory behaviour to explain the neglect patients’ reduced variability of visual search is also unconvincing. We found that the variability of visual search was selectively reduced
in the horizontal dimension. Along the vertical axis, the variabilities of gaze and head movements were indistinguishable from those of controls.

Other explanations seem more reasonable. It has been argued that the parietal cortex is involved in the elaboration of a constant representation of visual space across shifts of gaze. Lesions of the parietal cortex should thus lead to a reduced ability to elaborate such representations. In accordance with the idea of defective visual updating, Zihl and Hebel (1997) found repetitive scanning patterns in patients with parietal lesions (without clinical signs of neglect) while visually exploring dot patterns. The authors attributed this finding to a defective ‘working memory for executed fixation locations’. The reduced variability of visual search observed in the present patients with neglect might be interpreted as a consequence of such a deficient representation of fixation locations causing a qualitatively different strategy of visuospatial guidance of the scan path during space exploration. If so, the present results are remarkable since they would demonstrate that in patients with neglect this deficit specifically concerns the horizontal dimension of visual search.

A further possible explanation for the reduced variability of the patients’ exploratory movements is an altered neural representation of space along the horizontal axis. It has been argued that neglect of contralateral stimuli following brain damage might be associated with a compressed neural representation of space along the earth-horizontal axis. Halligan and Marshall (1991) argued for a linear, uniform compression of subjective visual space along the horizontal axis, while Milner (1987) suggested that this compression might progressively increase from the right to the left side.

To conclude, the present findings clearly argue against a lateral gradient of attentional orienting in patients with neglect (Kinsbourne, 1977, 1987, 1993). Exploring their surroundings, the patients demonstrated no hyper-attention of the extreme ipsilesional side by orienting gaze, the head with respect to the trunk or the eyes in the head excessively in that direction spending most of the time searching in that area of space. The distribution of eye and head movements rather favour a deviation model, suggesting that the whole frame for exploratory behaviour is rotated around an earth-vertical body axis to a new equilibrium on the right (Karnath, 1997). Like healthy subjects, patients with neglect explore space with gaze, i.e. with head and eye-in-head movements, that are symmetrically distributed around preferred orientations in space. However, in contrast to controls, these centres of exploration are shifted towards the right side of the body’s mid-sagittal plane. The character of the deviated frame for exploratory behaviour seems to be supramodal in that it determines the distribution of exploratory movements irrespective of whether the subject explores the surroundings visually or tactually (Karnath and Perenin, 1998).

Further, we found a reduced variability of the patients’ exploratory head and gaze movements around the deviated centre of exploration, specifically restricted to the horizontal dimension. The underlying mechanism leading to this aspect of the exploratory behaviour of neglect patients’ is still unclear. A disturbed ability to update the spatial representation of visual targets or an altered neural representation of space in the horizontal dimension are first hypotheses that need further elaboration.

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References
Gresty MA. Coordination of head and eye movements to fixate continuous and intermittent targets. Vision Res 1974; 14: 395–403.


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