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NOTE

OCULAR SPACE EXPLORATION IN THE DARK AND ITS RELATION TO SUBJECTIVE AND OBJECTIVE BODY ORIENTATION IN NEGLECT PATIENTS WITH PARIETAL LESIONS

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Abstract—Eye movements of neglect patients with right parietal lesions were recorded during ocular searching for a (non-existent) target in complete darkness. With respect to the objective orientation of the sagittal midplane, ocular exploration was biased toward the ipsilesional side. However, in relation to the patients' subjective localization of the sagittal midplane in space, exploratory eye movements were symmetrically distributed to the subjective "left" and "right" as observed in non-brain-damaged controls. The present results further support the hypothesis that the essential aspect leading to spatial neglect is a disturbance of those cortical structures that are crucial for computing egocentric, body-centred coordinates that allow use to determine our body position in space and that are necessary for visuomotor coordination and exploration of space. In neglect patients the central coordinate transformation seems to work with a systematic error resulting in a deviation of the spatial reference frame to the ipsilesional side. Consequences of this deviation are a displacement of subjective localization of body orientation and—to the same degree—of the spatial area in which motor behavior (here exploratory eye movements) is executed.

Key Words: human; eye movements; neglect; body orientation; space exploration; egocentric spatial reference frame.

INTRODUCTION

Eye movement recordings in right brain-damaged patients with clinically manifest neglect show that they predominantly fixate on the right side of the stimuli during visual searching [2, 6], viewing of a horizontal line or a rectangle [5], text reading [10] or scanning while describing simple drawings [8].

Even in darkness, i.e. without any visual stimulus, neglect patients show a bias toward the right side in their exploratory eye movements [4]. Patients with right posterior brain lesions and neglect were seated in a darkened room and asked to determine whether any light was present. Fixations were confined almost entirely to the right of the sagittal midplane and biased rightwards within that area. In contrast, a control group consisting of left and right brain-damaged patients without neglect searched equally on both sides with eye movements symmetrically distributed around the sagittal midplane.

When right brain-damaged neglect patients were asked to determine the position which they felt to lie exactly "straight ahead" of their body, they localized their sagittal midplane markedly right of its objective orientation [3, 9]. In contrast, subjective body orientation in normal subjects closely corresponds to the objective position in the horizontal as well as in the vertical plane [9].

The present study investigates whether the ipsilesional bias of ocular space exploration seen in neglect patients with respect to the *objective* orientation of the sagittal midplane also exists in relation to the patients' *subjective* localization of body orientation. We asked whether ocular exploration of space is symmetrically distributed around or biased toward the ipsilesional side of subjective body position.

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Table 1. Clinical data of the brain-damaged neglect patients

Case	Etiology	Location of lesion (side)	Paresis (side)	Time since first clinical symptoms (weeks)
N1	Grade IV glioma	R parietal	L moderate	4
N2	Infarct	R fronto-temporo-occipital	L moderate	3
N3	Infarct	R parietal	L moderate	1
N4	Grade IV glioma	R parieto-occipital	—	24
N5	Infarct	R parietal	—	2

METHODS

Subjects

The group of neglect patients consisted of five subjects (4 male, 1 female), aged 49–79 years (median = 56 years). Clinical data are given in Table 1. Neuropsychological examination including confrontation testing, copying, line bisection, cancellation and picture comparison revealed a marked left-sided neglect in each of these subjects. Perimetry showed normal binocular visual fields. Moreover, none of the subjects had a history of or suffered from oculomotor abnormalities.

Five non-brain-damaged neurological patients, aged from 42 to 62 years (median = 52 years), served as a control group. All subjects gave informed consent to participate in the study.

Apparatus and procedure

Subjects were seated in an opaque, light bulb-shaped cabin with the head in the center of the upper spherical part of the bulb (diameter 190 cm). The investigation was conducted in complete darkness. Subjects sat upright in a chair which was located in the center of the cabin and provided adjustable support for the back. In addition, the experimenter stabilized the head by grasping it. A red laser spot covering 0.5° of visual angle was reflected onto the inner surface of the cabin by a mirror galvanometer system situated directly above the subject's head. The control patients moved the laser point by pressing one of four small directional buttons (up/down/left/right) mounted crosswise on a small box (8.5 × 5 × 4.5 cm). Each button was 1.5 cm from the center of the box. The position of the buttons on the box corresponded with the direction in which the laser point would be steered. When a button was pressed, the laser point moved smoothly in the indicated direction with a velocity of 1°/sec. To prevent any possible interaction between the effect of brain lesion, i.e. paresis and/or neglect, and the handling of the box, for the brain-damaged patients the laser point was directed by the experimenter according to the instructions (up/down/left/right) given by the patients.

The objective position of the body's spatial orientation was defined by laser position 0°/0° which was aligned with the center of the chair in the horizontal plane and the individual eye level of the subject in the sagittal plane. The testing procedure started with the laser spot being pseudo-randomly presented in one of four eccentric positions (+10°/+10°, −10°/−10°, +10°/−10°, −10°/+10°). (Directions were defined with respect to objective body position and named in the conventional way: up and right as positive, down and left as negative.) The subject then had to direct the laser to the position which was felt to lie exactly "straight ahead" of the body's orientation. Subjects verbally indicated when the position was reached. No time limit was used.

The laser spot was then extinguished and the subjects were asked to search for the "new location" of the spot which was stated to be located "somewhere" in the cabin. In fact, no spot was presented within the next 30–40 sec and the subjects thus searched in complete darkness with their eye movements being recorded at the same time. The scanning period was terminated by presenting the laser spot at a random location on the inner surface of the cabin, where it was immediately noticed and reported by all subjects.

Eye movements were recorded using the magnetic field-search coil technique [15] to measure angular positions of the left eye, relative to the bulb housing the subject, in two dimensions. The sampling rate was 100 Hz. Three orthogonal magnetic fields were generated by three pairs of Helmholtz coils mounted in a cubelike configuration on the outer surface of the upper spherical part of the bulb. Since the search coil technique requires uniform, orthogonal magnetic fields at the location of the subject's head, the cabin was constructed of fiberglass using a minimum of metal, which was kept far from the subject's head.

Subjects wore a 2D-Skalar search coil, i.e. a coil inbedded in a silicone rubber ring, which adheres to the sclera by suction. Signals from the eye search coil were sent to a preamplifier at the bottom of the bulb and were then conveyed by slip rings to a decoding unit which computed the two-dimensional position of the eye. The data were stored on hard disk for off-line analysis.

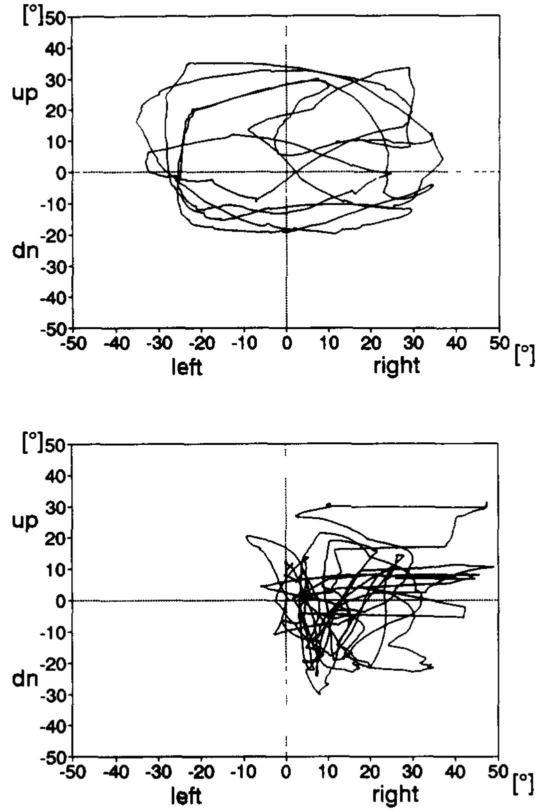


Fig. 1. Eye scan paths of a control subject (top) and a neglect patient (bottom) while searching for a non-existent target in complete darkness. Directions up and right of objective straight ahead body position (0°/0°) were defined as positive, down (dn) and left as negative.

RESULTS

Figure 1 shows scan paths of a control subject and a neglect patient (patient N5) searching for the (non-existent) laser spot in complete darkness. The quantitative analysis for the two subject groups is given in Figs 2 and 3. Presented is the average percentage of exploration in discrete 5° sectors along the horizontal and vertical axes in relation to objective straight ahead body position (position 0°/0°). The control subjects explored space with eye movements ranging up to −40° to the left and +40° to the right of objective sagittal midplane (Fig. 2). In neglect patients, the area of ocular exploration was shifted to the ipsilesional (right) side, extending from −25° left to +50° right (Fig. 2). The maximum of exploration lay around 0° in the control group and between +10° and +15° right of the sagittal midplane in the group of neglect patients.

The distribution of exploratory eye movements along the vertical axis revealed no marked differences between the two subject groups (Fig. 3). However, in both groups there was a skewed distribution of ocular exploration with a clear maximum above the subject's eye level.

The subjective "straight ahead" of the control patients was close to the objective straight ahead body position (laser position 0°/0°). The five subjects steered the laser to an average position of +4.3° (S.D. 2.6°) in the horizontal plane and +0.4° (S.D. 4.3°) in the vertical plane. In contrast to controls ($t = 3.45$, $P = 0.005$, one-tailed), subjective and objective body orientation of the five neglect patients differed markedly in the horizontal plane. Their "straight ahead" was on average +15.4° (S.D. 2.6°) to the right of the objective body position. In the vertical plane, the "straight ahead" judgements of the neglect patients were close to those of the control group ($t = -1.50$, $P = 0.172$, two-tailed). They directed the laser point to an average vertical position of −3.0° (S.D. 4.8°).

As illustrated in Fig. 2, ocular scanning of controls was symmetrically distributed to the left (44.2%) and right of the objective sagittal midplane, whereas in neglect patients the area of exploratory eye movements was shifted to the ipsilesional side. Only 12.5% of their exploratory eye movements were directed to spatial locations left of the objective sagittal midplane (Fig. 4a). However, if ocular space exploration was related to the subject's "straight

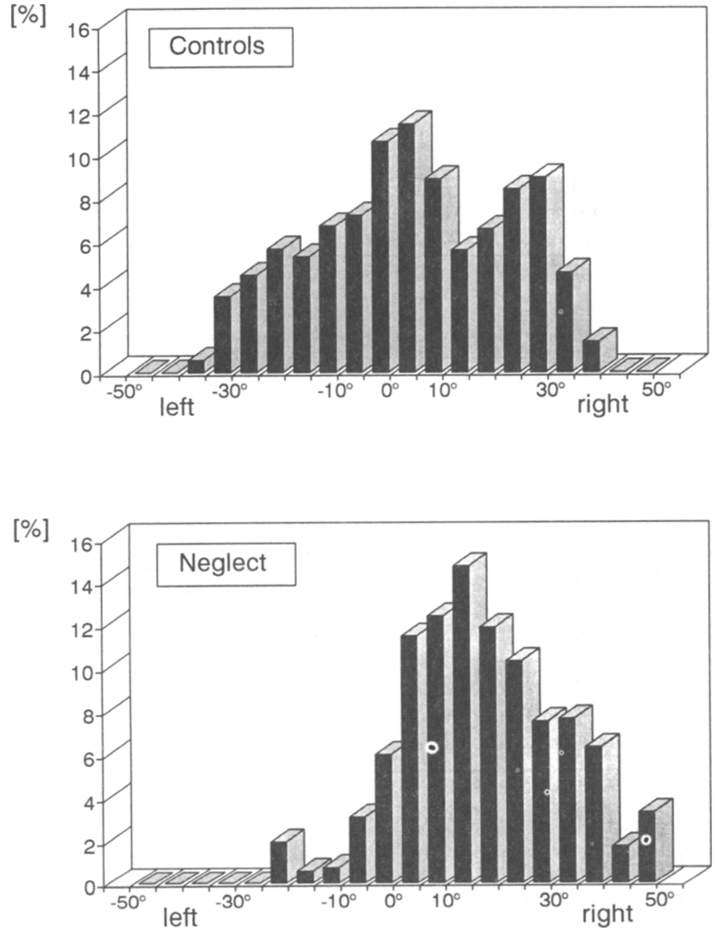


Fig. 2. Average percentage of exploration registered for the two subject groups in discrete 5° sectors along the horizontal axis with the objective position of the body's sagittal midplane at position 0°.

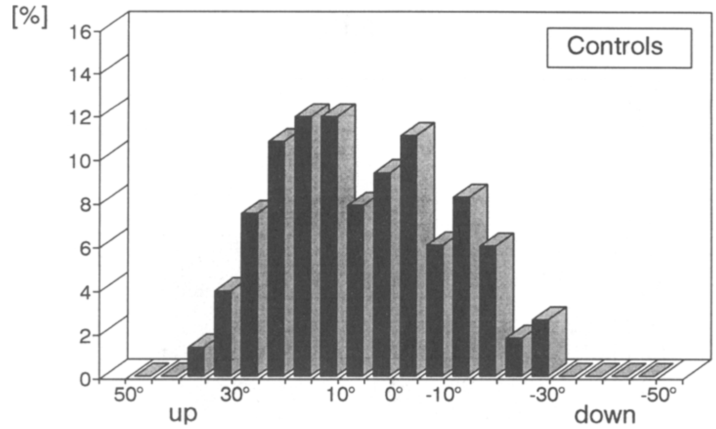
ahead", i.e. the subjectively perceived orientation of sagittal midplane in space, for controls as well as for neglect patients eye movements were symmetrically distributed to their subjective "left" and "right" (Fig. 4a). To test whether, patient by patient, the degree of displacement of the subjective body midline correlated with the spatial bias in exploratory eye movements, the Pearson product–moment coefficient was calculated between the "straight ahead" position in the horizontal plane and the median of ocular exploration along the horizontal axis; the coefficient was 0.93.

In the control group (Fig. 4a), no significant difference was found for ocular exploration relative to the objective vs the subjective sagittal midplane (paired-samples: $t=-2.50$, $P=0.067$, two-tailed).

No significant differences were found between neglect patients and controls in the distribution of eye movements in the vertical plane (objective: $t=0.74$, $P=0.478$/subjective: $t=1.22$, $P=0.258$, two-tailed). In both groups, about 70% of ocular exploration was located above the subjects' objective eye level as well as above their subjective "straight ahead" position (Fig. 4b). In neglect patients as well as in controls the percentage of exploration above the objective vs subjective body position did not differ significantly (paired-samples: $t=-1.18$, $P=0$ 304/$t=-0.99$, $P=0.379$; two-tailed).

DISCUSSION

Subjective body orientation of the non-brain-damaged control patients was close to the objective body orientation. A close correspondence has also been found in brain-damaged patients without neglect [9]. In contrast,



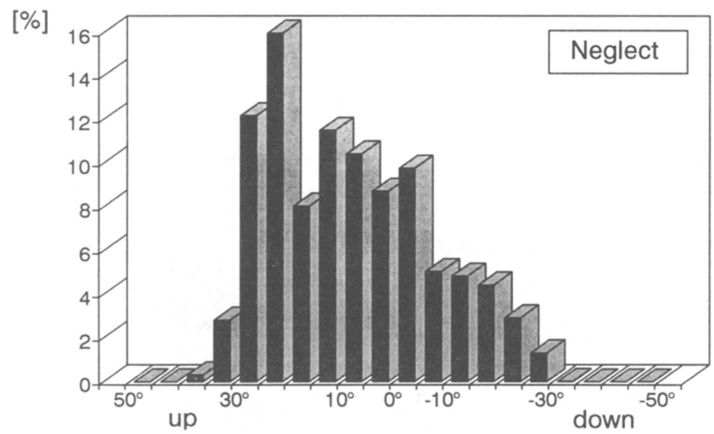


Fig 3. Average percentage of exploration registered for the two subject groups in discrete 5° sectors along the vertical axis with the subject's objective eye level at position 0°

subjective and objective body orientation differed significantly in the neglect patients. They localized their sagittal midplane markedly to the right of its objective position, as found in previous studies [3, 9, 13].

During ocular searching for a non-existent target in complete darkness, the control patients explored space with eye movements symmetrically distributed on both sides of the sagittal midplane (whether objectively or subjectively defined) up to eccentricities of about 40°. With respect to the objective position of the sagittal midplane, ocular exploration of neglect patients was biased toward the ipsilesional right side, as was also found by Hornak [4]. However, exploratory eye movements were symmetric about the patients' subjective localization of sagittal midplane.

From investigations using visual stimulation [12, 14] one could have expected a general deficit of the neglect patients to orient attention (here in its overt form by eye movements) into the contralesional direction irrespective of the current point of fixation and of the hemispace involved. Another expectation might have been a skewed distribution of ocular exploration with a maximum on the ipsilesional right side and a minimum on the contralesional left forming a more or less continuously decreasing gradient of exploratory eye movements [1, 11].

However, the patients eye movements during space exploration in complete darkness did not correspond with these expectations. In contrast, a symmetrical and, compared to controls, quasi "normal" distribution of exploratory eye movements to both sides of the subjective position of sagittal midplane in space was observed. In relation to the patients' subjective "straight ahead" body orientation, eye movements were carried out in all spatial directions (i.e. from right to left, up to down, etc.) exploring equally the subjective "left" and "right".

The present results support the hypothesis of a disturbed neural computation of the egocentric, body-centered frame of reference necessary for visuomotor coordination and exploration of space. Karnath [7, 9] argued that an

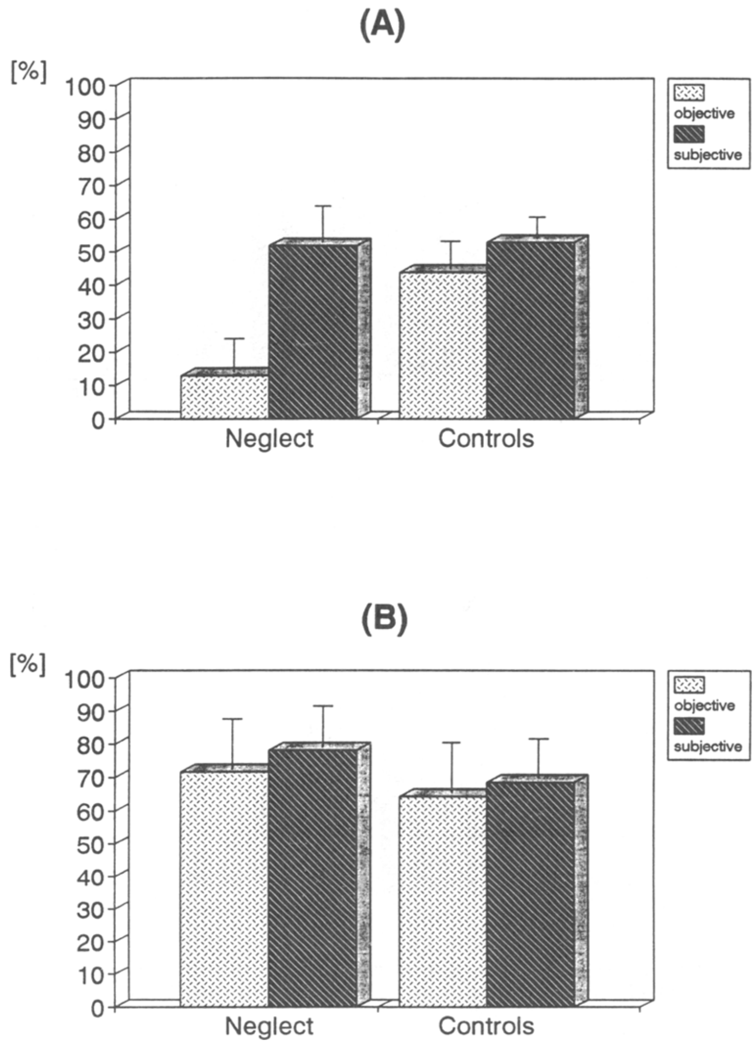


Fig. 4. (A) Average percentage of exploration left of the objective vs subjective orientation of sagittal midplane in the two subject groups. (B) Average percentage of exploration above the objective (=eye level) vs subjective orientation of "straight ahead" in the vertical plane of the two subject groups.

important and possibly the essential aspect leading to spatial neglect in brain-damaged patients is a disturbance of the central transformation process that converts the sensory input coordinates from the peripheral organs (e.g. the retina, neck muscle spindles, cupulae) into an egocentric, body-centered coordinate system. It was further argued that in neglect patients this coordinate transformation is working with a systematic error resulting in a horizontal deviation of the spatial reference frame to the ipsilesional side.

Directly connected with the frame of reference underlying the subject's mental representation of space seems to be the localization of body orientation [9, 16]. In the case of neglect syndrome, the disturbed coordinate transformation thus leads to a disturbed perception of body orientation, i.e. to a disparity of subjective and objective body orientation with a displacement of subjective "straight ahead" to the ipsilesional side.

It can be hypothesized that the region of space subjects spontaneously explore with eye movements while searching in complete darkness is a direct function of the subject's egocentric, body-centered frame of reference. If so, the present results indicate that, in the horizontal plane, subjective body orientation marks the center of this spatial reference frame. We found a symmetrically distributed scanning pattern on both sides of this perceived position of sagittal midplane. The symmetry of exploratory motor behavior was found in controls as well as in neglect patients. The difference between both groups was that in normal subjects objective and subjective localization of body orientation correspond closely whereas they differ in neglect patients. In other words, it appears that in neglect patients the represented spatial frame of reference, and thus the spatial area in which motor behavior (here exploratory eye movements) is executed, is shifted to the objective right due to a systematic error in the central computation of egocentric, body-centered spatial coordinates.

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