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Rotation or translation of auditory space in neglect ? A case study of chronic right-sided neglect

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Abstract

Egocentric models of neglect explain the lateralised omission of stimuli in neglect patients by an ipsilesional shift of a subjective reference frame. However, they differ in the direction of shift (*rotation* around the midsagittal plane vs. *translation* in front/back space). We tested this hypothesis in a patient (AJ) with persistent right-sided neglect following a left temporo-parieto-occipital and hypoxic lesion and in six age-matched healthy subjects. AJ showed visual neglect in line bisection, size matching, reading and visual search. Auditory localization was tested by using two different psychophysical techniques based on binaurally simulated stimuli for the horizontal plane in front and back space. Eye position was continuously monitored during stimulus presentation in all subjects. AJ revealed a significant ipsilesional, leftward shift of his auditory subjective median plane (ASMP) in *front space* (mean: -22.6°), and a rightward shift of the ASMP in *back space* (+14.5°). This pattern of results was replicated with a different psychophysical technique in a retest 10 months later. The rotational shift of AJ´s ASMP contrasted with normal performance in the healthy subjects. Monaural hearing deficits can not account for these differential findings as all subjects (including AJ) performed normally. In conclusion, a *rotation* of the egocentric spatial reference frame may occur in the auditory modality for right-sided neglect.

1. Introduction

Spatial neglect is a neurological disorder characterized by a failure to detect or respond to sensory stimuli in one hemispace or act motorically on such stimuli. Although neglect is predominantly found after right temporo-parietal lesions (Karnath, Milner, & Vallar, 2002) it may also occur after left-hemispheric (Beis et al., 2004) or bilateral cerebral lesions (Weintraub, Daffner, Ahern, Price, & Mesulum, 1996). Transformational theories explain neglect by assuming a lesion-induced, ipsilesional processing error within an egocentric reference system (Vallar, 1997; Karnath, 1997). These two theories differ in one important aspect. Vallar´s model (Vallar, 1997), based on results from right brain-damaged patients with auditory neglect in front- and back space (Vallar, Guariglia, Nico, & Bisiach, 1995), postulates a *translation* of the egocentric reference frame for spatially oriented behaviour to the ipsilesional side in front *and* back space. This account is based on the observation of patients with left neglect showing an ipsilesionally rightward deviation of their auditory subjective median plane in front- and back space. In contrast, Karnath ´s theory assumes a rotation of the egocentric reference frame around the trunk midsagittal plane (Karnath, 1997). This account is based on a study assessing visual subjective straight ahead judgments in neglect patients, taken at different distances from the observer (Ferber & Karnath, 1999). The results suggest an angular clockwise shift in front space and an opposite shift in back space.

At present, it is unclear whether the rotation or translation model of neglect is more appropriate since there is conflicting evidence on this topic, as described above. We recently investigated auditory localization judgments in front and back space in a patient with right-sided visual neglect. We aimed to evaluate the rotation/translation hypotheses in neglect by assessing the auditory subjective median plane (ASMP) in front and back space with binaural sound sources (Kerkhoff, Artinger, & Ziegler, 1999). After a short case history of patient AJ including his visual neglect phenomena we report AJ´s results, as well as those of six age-matched healthy control subjects, in binaural and monaural auditory experiments.

2. Material and methods

2.1 Case history

AJ, a right-handed carpenter with 9 years of schooling, was involved in a car accident at the age of 26. He experienced head trauma with a left temporo-parietal subdural hematoma, which was immediately treated in a nearby hospital. In addition, he suffered fractures of his left knee and of two ribs. One day after the operation, during an attempt to stand up, cardiac arrest occurred. Despite immediate reanimation AJ suffered multiple organ failure (liver and renal) and was tracheotomized. Subsequently, artificial respiration was applied to him for 7 weeks. Apart from a marked left parieto-temporo-occipital lesion - possibly as a sequel of the space-occupying subdural hematoma that had been removed - AJ also showed diffuse encephalopathy in the white matter of both hemispheres (Fig. 1). These widespread diffuse lesions probably result from the hypoxic, hepatic and uraemic coma. Following intensive care, AJ received 10 months neuropsychological rehabilitation in two different clinics. After discharge, he lived partially independent and worked 3-4 hours per day in a sheltered workplace.

Fig. 1 here

All experiments reported below were carried out 7-8 years after the accident (when AJ was 33/34 years). Binocular visual fields (Tübingen perimeter) were normal for white test stimuli. Colour and form perception were slightly impaired in the right hemifield (20°; cut-off: 32°) and more in the left hemifield (4°; cf. Fig. 2A). Decimal visual acuity was 0.80 (0.4 m viewing distance) and 0.70 (6 m). The results of an initial orthoptic screening showed spasmodic fixation, hypometric saccades and disrupted pursuit eye-movements to the left and right hemispace one year after the trauma. At seven years post-onset, AJ´s fixation was normal. Saccades to the left side were executed normally, but were still hypometric and slower to the right side. Smooth pursuit remained slightly impaired to both hemispaces. Neither gaze palsies nor diplopia were observed. AJ still showed marked right-sided visual neglect in horizontal line bisection (deviation from midline: -33 to -37 mm to the left, normal cut-off: +/- 5mm, cf. (Kerkhoff & Marquardt, 1998); Fig. 2B), as well as in a visual search task. In the latter test, 40 household objects were placed on a 0.8 x 0.6 m cardboard in front of the patient. The patient was sequentially presented with 20 target objects and was asked each time to point to the same object on the cardboard as quickly as possible. Each of the four quadrants contained five target objects. The summed search times for the objects detected in each quadrant by AJ (cf. details in (Kerkhoff, Münβinger, & Meier, 1994) showed marked right-sided visual neglect (Fig. 2C). In visual size matching (Fig. 2D) where a left horizontal bar (size: 60 x 10 mm) was shown as the target stimulus and a bar on the right side of the computer screen had to be adjusted perceptually to the same size (Kerkhoff et al., 1998), AJ showed an average error of +27.5 mm (46 % size distortion; cut-off: +/- 1.6 mm= 2.6 % distortion). Standardised reading tests (Kerkhoff, Münβinger, Eberle-Strauss, & Stögerer, 1992) showed right-sided neglect dyslexia (12 errors, time: 12:14 minutes; cut-off: max. 2 errors; max. 2 min,not shown). In addition, AJ showed visuospatial/visuoconstructive deficits, but no aphasia.

Fig. 2 here

2.2. Normal control subjects

Six right-handed healthy control subjects, 3 males and 3 females (age range: 26-38 years, median: 32) were tested in exactly the same way as AJ. None of the subjects showed evidence of neurological or ear disease.

2.3. Peripheral (monaural) hearing tests

AJ and all normal subjects were screened with a Philips HP 8741/31 pure-tone audiometer for monaural peripheral hearing functions in a sound-shielded room. Hearing sensitivity (loss in dB) was measured for each ear separately for the following frequencies: 0.125, 0.25, 0.5, 0.75, 1, 1.5, 2, 3, 4, 6 and 8 kHz.

2.4. Auditory Subjective Median Plane (ASMP) in front and back space

Broad-band (white-noise), 3 s single pulse signals with a sound pressure level of 75 dB, as measured by an audiometer (manufacturer: Kjaer) were delivered sequentially by an AKG K240 headphone with a similar frequency range as used in the HRTF-measurements (see below). Signal pulses were passed through digital linear minimum phase filters (FIR-filter design) with directional dependent head-related transfer functions (HRTF, cf. (Wightman & Kistler, 1989a; Wightman & Kistler, 1989b; Wenzel, Arruda, Kistler, & Wightman, 1993) to simulate virtual sound locations at a 5° resolution along the azimuth plane in front and back space (for details see (Kerkhoff et al., 1999). There were 37 sound source positions in the front space (including the objective midline position at 0°, and 37 sound source positions in back space (including the objective midline position at 0°). The starting positions of all stimuli were pseudorandomized across these 37 possible positions *separately* for front and back space. Three trials were presented for each source position, resulting in a total of 111 trials in normal subjects. In AJ, two trials were presented for each source position, resulting in 74 trials per test. This was done to avoid fatigue due to prolonged testing. Subjects were instructed to indicate whether or not a stimulus came from the subjective midline position (either in front or back space). If the subject reported a deviation from the midline he/she was asked in which direction (left, right) the sound source had to be modified by the experimenter until it was finally judged as coming from the subject´s auditory subjective median position (ASMP). Note, that with this psychophysical method 74 valid judgments of the ASMP were obtained for front and back space in separate sessions in AJ (accordingly 111 for every normal subject). The procedure was explained in 12 practice trials, which were not rated.

Each subject was seated in an experimental chair in front of a Tübingen perimeter, fixating a small red spot in the centre (diameter: 30 minutes of arc, luminance: 3.2 cd/m^2; background luminance: 3.2 cd/m^2). The subject´s head was aligned perpendicular to the trunk and supported by a head- and chinrest to prevent any head movements. Measurements of the ASMP for front and back space were performed separately in random order across individual subjects to avoid confusion between the two hemispaces and reduce front-back-confusions. Short breaks were given every 5-10 minutes. No feedback was given on the results.

2.5. Retesting the ASMP with the method of limits

Ten months after the initial experiment we re-tested all subjects with the same auditory stimuli and experimental conditions, but with different instructions and the psychophysical method of limits (Engen, 1971). This method allowed for revalidating the results of the first session by presenting sound positions closer to the objective midline position in all trials as in the first test. Furthermore, front-back-confusions were counted. Subjects were now a priori informed that they would hear auditory stimuli in *front space* and were to indicate verbally, whether the current stimulus came directly from the auditory subjective median plane (ASMP) in front of them. If they perceived a sound as coming from the back (front-back-confusion) they were instructed to respond with “back” and this trial was voided and later in the experiment repeated. Otherwise, the adjustment procedure was identical to the first experiment. To compute the Point of Subjective Equality (PSE) the stimuli were delivered in a fixed sequence starting from the mid-left (-45°, -40°, -35°, -30° etc.) to 0° (midline position) up to the mid-right side (+45°) and back 20 times. Table 2 shows the mean of these 20 threshold measurements. In a separate session, the same procedure and psychophysics were used for *back space.* Subjects were instructed that they would hear sounds from the back and had to indicate when a stimulus came directly from the ASMP in their back space. If they perceived a sound as coming from the front in this condition (front-back-confusion) they were instructed to respond with “front” and this trial was voided and later in the experiment repeated. Otherwise, the adjustment procedure was identical in both experiments.The PSE was computed as described above. The percentage of front-back-confusions is reported in table 2. The order of the front only/back only blocks was random across subjects.

2.6 Eye position monitoring

During all tasks and experimental conditions the experimenter monitored permanently the correct eye fixation of all subjects through the telescope of the perimeter. For every trial, the stimulus was only released when eye fixation rested centrally on the fixation point. The experimenter could see the subject´s pupil centred over crosswires. Trials were voided if the subject moved his/her eyes during presentation of the auditory stimulus (duration: 3 s) and repeated after correct fixation was re-established.

3. Results

3.1. Peripheral (monaural) hearing tests

Table 1 summarizes the data of AJ and the normal control subjects. AJ showed normal peripheral hearing sensitivity comparable to that of the six normal subjects. T-tests over all frequencies and separately for each ear revealed no significant difference between AJ´s and the normal control subjects´ hearing sensitivity (smallest P= 0.117, largest t=-1.896, n.s.).

Table 1 here

3.2. Auditory subjective median plane in front and back space (ASMP)

AJ shifted his ASMP in front space substantially towards the left side (mean: -22.6°), which is compatible with right-sided, auditory neglect. In contrast, none of the 6 controls showed average deviations larger than 5.2° in front space to either side in the ASMP (see Fig. 3 and Table 2). Moreover, AJ´s frequency distribution was shifted towards the left side. There was nearly a complete divergence of the frequency distributions of AJ and the normal subjects, indicating a clear difference in performance. AJ´s deviation in front space clearly exceeded the performance of the worst control subject (22 normal subjects; range: -7° to the left to +3° to the right; see (Kerkhoff et al., 1999).

Fig. 3 here

In back space AJ showed a considerable right-sided shift (+14.5°), larger than that of any normal subject in this study. There was also a difference in the distribution pattern with AJ's frequency distribution skewed to the right side, and that of the normal subjects slightly skewed to the left. The normal controls showed no systematic shift in their ASMP in back space. Their average errors were less than 5° (except subject 5, who showed larger errors), indicating that the ASMP-task in back space was not too difficult. For a more detailed comparison, table 2 lists the mean data of every subject separately for front and back space. We also split the data according to the hemispace where the first stimulus was displayed (starting position, see table 2), to evaluate possible cueing effects (Riddoch & Humphreys, 1983).

Table 2 here

A comparison of the ASMP depending on the initial starting position of the stimulus showed a significant difference in the 6 normal subjects when pooled together as one sample (t = 3.770, $P < 0.001$). Hence, normal subjects showed a greater leftward shift of their ASMP when the first stimulus was displayed in the left hemispace, and a greater shift of their ASMP to the right side when the auditory stimulus was displayed first in the right hemispace. However, the difference was quite small (1.1°, see mean values in table 2). In contrast, there was no influence of the starting position on the final ASMP in back space (t = 0.9, $P > 0.05$, n.s.).

AJ showed neither effects of starting position in front space (t = 1.1, $P > 0.05$, n.s.)

nor in back space ($t = 0.8$, $P > 0.05$, n.s.; Table 2). In order to evaluate whether AJ´s spatial estimates were statistically different from those of the normal group we performed one-sample t-tests comparing AJ´s data with the mean ASMP-values of the six normal controls separately for front and back space. The results confirmed a clear difference of ASMP values in front space between AJ and the normal group (AJ: -22.6°, controls: -1.9 °; $t = 22.033$, $P < 0.001$). AJ´s mean ASMP in back space was also significantly different from the mean ASMP of the six controls (AJ: +14.5°, controls:-2.5°, $t = 11.596$, $P < 0.001$). In summary, AJ´s performance in the ASMP clearly differed from that of the normal subjects in front and back space, and was not influenced by the starting position of the auditory stimulus.

However, it is interesting to note, that not only AJ's (15.4° vs. 9.9°, Wilcoxon-test, $z=-2.107$, $P< 0.03$, two-tailed), but also the normal subjects' variability of localization (indexed by the standard deviations) was significantly higher in back than in front space (6.1° vs. 3.3°, $z = -2.201$, $P < 0.028$, two-tailed). Hence, AJ and all six normal subjects showed a more variable and thus less precise spatial resolution of the ASMP in back space as compared to front space (see 4.2 for discussion).

3.3 Retest of the ASMP and quantification of front-back-confusions

The re-examination of the ASMP with the method of limits and with all stimuli covering more central azimuth positions revealed similar results (table 2). In all subjects, the Point of Subjective Equality (PSE) was close to the mean values obtained in the first assessment of the ASMP (ASMP in front space: AJ: -25.4°, normals: -1.6°; ASMP in back space: AJ: +15.4°, normals: -1.8°). AJ´s Point of Subjective Equality (PSE) was significantly different from that of the normal subjects in front space ($t=21.07$, $P<0.001$) and back space ($t=12.433$, $P<0.001$). This cross-validation of our data supports the validity of our measurements in the first test, irrespective of the methodological differences (more central sound positions and different psychophysics in the re-examination).

Finally, the percentage of front-back-confusions was quantified in the re-test (Table 2). On average the normal subjects showed between 3.6 % and 10.8 % front-back-confusions in both hemispaces which was not significantly different from those of AJ (front space: $t=-1.736$, $P>0.05$; back space: $t=-0.565$, $P>0.05$). These data are quite comparable to those reported from other studies using HRTF-stimuli (5-10%, cf. (Wightman et al., 1989a).

4. Discussion

The present study yielded the following results: 1) AJ displayed a significant *left-sided* shift of his ASMP in front space but a *right-sided*, smaller shift in back space, supporting the interpretation of a rotation of his auditory egocentric reference frame in azimuth. This result was replicated with a different psychophysical threshold technique. 2) Normal subjects did not show a rotation/translation of the ASMP (errors < 5°) but were less precise in their spatial resolution in back versus front space. 3) These results can not be confounded by eccentric eye position since central fixation was established in every subject.

4.1. Rotation versus translation of egocentric reference frames in neglect

AJ is to our knowledge the first reported case with a *rotational* shift of the auditory egocentric reference frame in visual neglect. This result differs from the translational shift previously reported in *left-sided* neglect in a group of patients with unilateral vascular, right-hemispheric lesions using free-field auditory stimuli in front and back space (Vallar et al., 1995). Since the HRTF-generated stimuli used in our study are comparable to free-field auditory stimuli as both are perceived in *external* space the different pattern of results can not be due to the methods used. However, as only mean deviations were reported in the study by Vallar et al (1995) it is difficult to know whether some of their patients may have shown a rotation pattern despite the group result reporting a pattern of translation. Nevertheless, differences in the aetiology of the lesions (bilateral in AJ, unilateral right-hemispheric, vascular in Vallar´s et al´s study) might contribute to the differences in results. This issue can be resolved with subsequent group studies.

4.2. Front versus back space

Interestingly a common observation between our study and Vallar et al.'s (1995) were the smaller deviations in the auditory midline task in back space as compared to front space (AJ: 14.5° vs. 22.6°; Vallar et al.'s neglect patients: about 13° vs. 20°). One possible explanation could be that deviations in back space are smaller or 'obscured' since the auditory sensitivity is lower in back versus front space (Middlebrooks & Green, 1991). This conclusion is strengthened by the fact that the variability (as indexed by the standard deviations) was significantly higher in back versus front space in our normal subjects (front:

3.3°, back: 6.1°, table 2) and in AJ as well (front space: 9.9°, back space: 15.4°;). Hence, *systematic* shifts of the subjective midline may be masked by larger *unsystematic* errors in auditory back space. A possible reason for this reduced auditory resolution in back space may lie partially within the peculiarities of the auditory system, which depends on visual calibration for sound source localisation – at least during development (Knudsen & Brainard, 1995). Thus, it seems likely that visually controlled regions of space such as front space reach a higher auditory spatial resolution than regions without visual control, such as back space.

Front-back confusions are well-known in auditory experiments regardless of the technique and stimuli used (Middlebrooks et al., 1991). Such confusions are smallest when the ambiguity of the task is low and broad-band stimuli are used (Middlebrooks et al., 1991). We employed both strategies to reduce front-back-confusions which resulted in similar percentages (5-10%) as reported by others using HRTF-stimuli (Wightman et al., 1989a). This means that our normal subjects and AJ perceived the auditory stimuli in more than 90% of trials in the correct spatial region (front or back).

Although our present case may be special regarding his aetiology, his right-sided neglect is by no means different from that reported in left hemisphere stroke patients (Beis et al., 2004), but clearly his auditory results need validation in vascular lesioned patients with left or right neglect. Since quantitative studies on auditory neglect are relatively new as compared to visual neglect the concept of auditory neglect is still emerging and such investigations might clarify its nature (for review see (Pavani, Husain, Ladavas, & Driver, 2004).

Possible „anchors“ for the elaboration of an egocentric reference frame in audition are eye- and head-position which influence auditory sound localization (Mazzoni, Bracewell, Barash, & Andersen, 1996; Stricanne, Andersen, & Mazzoni, 1996). Manipulation of eye- and head-position should therefore influence the ASMP in neglect.

4.3. Possible eye position effects

It is well known that eye movements (Robinson, McClurkin, & Kertzman, 1990) and orbital eye position (Andersen, Snyder, Bradley, & Xing, 1997; Lewald & Ehrenstein, 1996; Sparks, 1988) modulate auditory-spatial judgments and their underlying neural activity in the superior colliculus, area LIP and many other cortical areas of the dorsal stream (Battaglini, Galletti, & Fattori, 1997). In neglect patients, an ipsilesionally shifted pattern of ocular exploration has often been observed, at least in the early phase of the disease (i.e.

(Ishiai, Sugishita, Mitani, & Ishizawa, 1992; Girotti, Casazza, Musicco, & Avanzini, 1983; Barton, Behrmann, & Black, 1998; Karnath, Niemeier, & Dichgans, 1998). Accordingly, it is plausible that a similar, ipsilesionally shifted ocular fixation pattern may occur during an auditory task if eye movements are not restrained. If present, a rightward shift of eye fixation would lead to a corresponding shift of the ASMP in the same direction (Lewald et al., 1996) – in front *and* back space. This could feign a pattern of translation. We therefore delivered auditory stimuli on a trial-by-trial-basis, while viewing the subject´s eye through the telescope of a perimeter. With this method, it was possible to detect fixation shifts beyond 1-2° and saccades so that void trials could be excluded. Hence, eccentric eye-position is highly unlikely to account for the observed rotational shift of the ASMP in AJ. The same holds true for head movements because these were eliminated by fixating the head.

In conclusion, *rotation* of an egocentric reference frame may be found in right-sided visual neglect, as reported here for the first time for acoustic stimuli. Subsequent studies should clarify whether stroke patients with left or right neglect show comparable results when tested in the same way (including eye fixation control). Moreover, the visual and auditory modality could be compared to gain insights into the organization of space in different modalities and sectors (visible front space vs. nonvisible back space).

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Captions, Figures 1-3

Fig. 1: AJ´s magnetic resonance imaging scans as taken at 2 years after the lesion. Note the large left temporo-parietal-occipital lesion (long arrows), and the small white, diffuse-disseminated lesions in the left and right hemisphere (short arrows), probably due to cerebral hypoxia. The left side of the MRI scans corresponds to the left cerebral hemisphere.

Fig. 2 **A**: Binocular visual field plot from AJ. The numbers indicate the degree of visual field sparing on the relevant meridian. Note left-sided constriction (beyond 4°) and slight right-sided constriction (beyond 20°, normal cut-off: 32°) of the colour and form visual field, but normal fields for white light stimuli. **B:** AJ´s performance in horizontal line bisection. The grey area indicates the complete range of 40 normal subjects. Note profound right-sided neglect, irrespective of the starting position of the slit in the bar (indicated by the arrows) **C:** Mean visual search times (in sec) for the left and right hemispace in the object search test; the dotted line indicates the cut-off of normal subjects (for details see text). Note profound right-sided neglect during visual search. **D**: Visual, horizontal size matching deficit in AJ (+27.5 mm error in reproduction, normal subjects (n=40) show an average error of +1.6 mm; grey box depicts total normal range)

Fig. 3: Complete frequency distributions of AJ´s and the six normal subjects´ auditory subjective median plane (ASMP) judgments in front space (top) and in back space (below). += deviation to the right side; -= deviation to the left side. Note AJ´s leftward shift in front space and the rightward shift, albeit of smaller magnitude, in back space. No significant shift was observed in the normal subjects.

Figures 1-3

Figure 1:

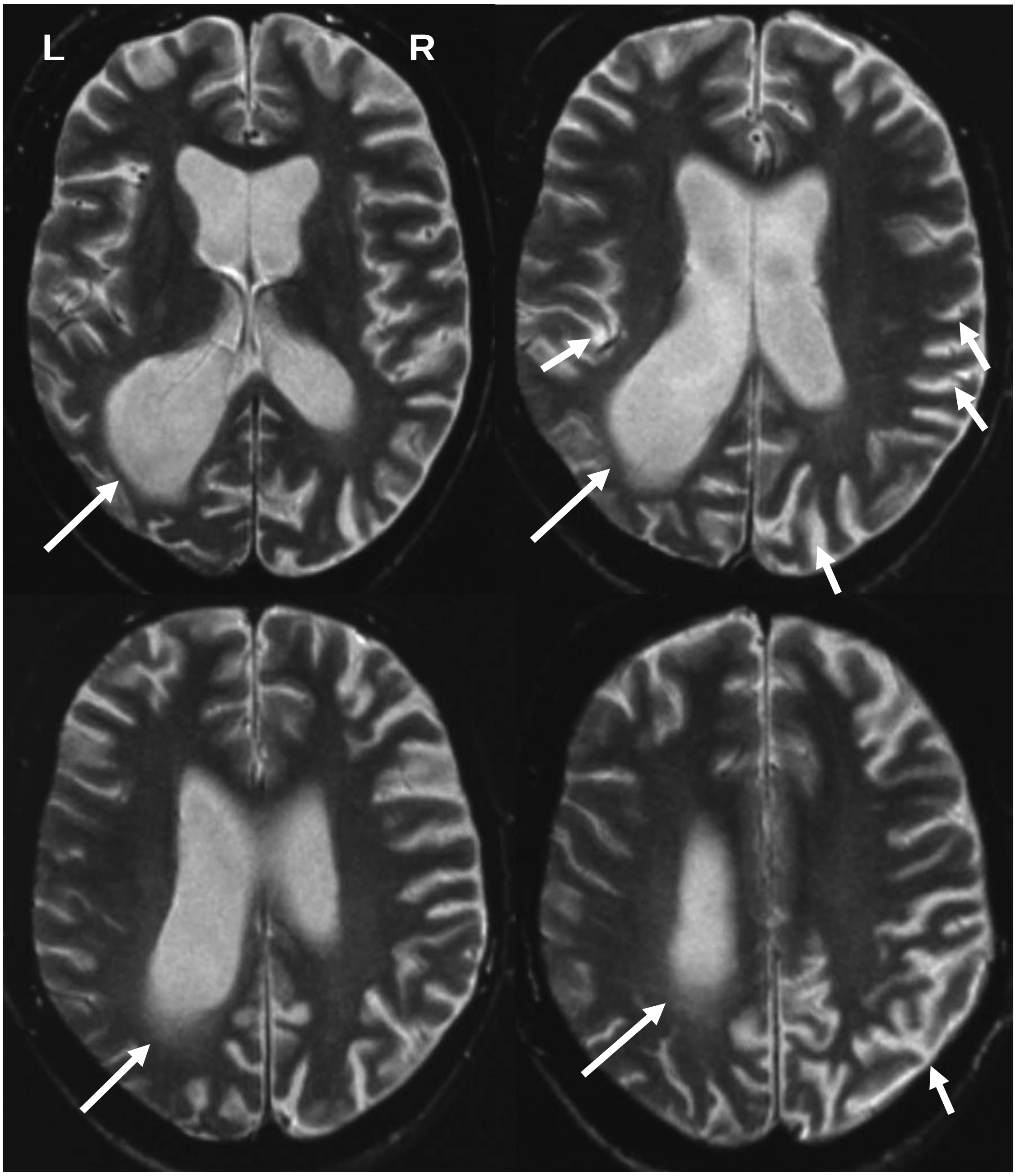
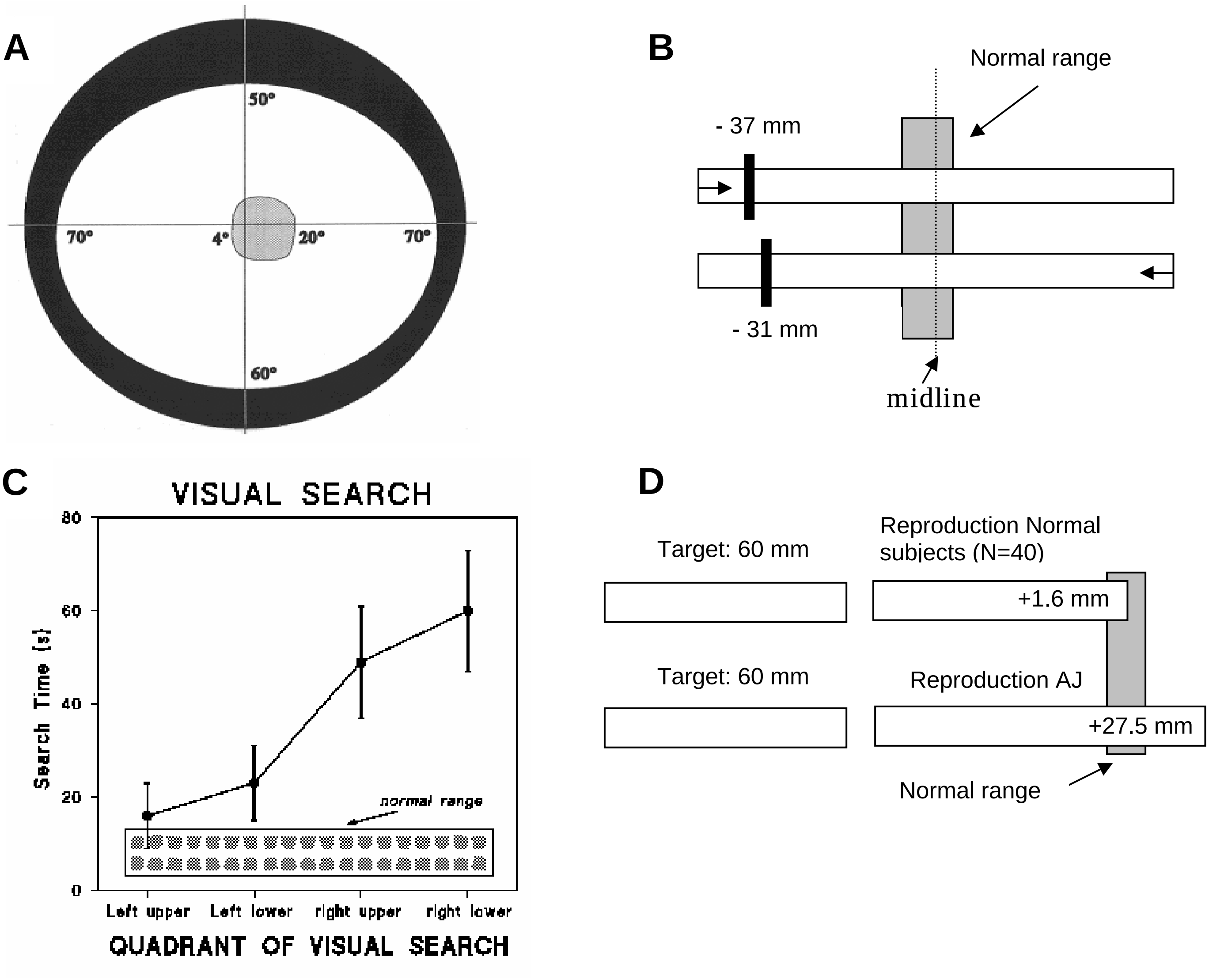


Figure 2


A
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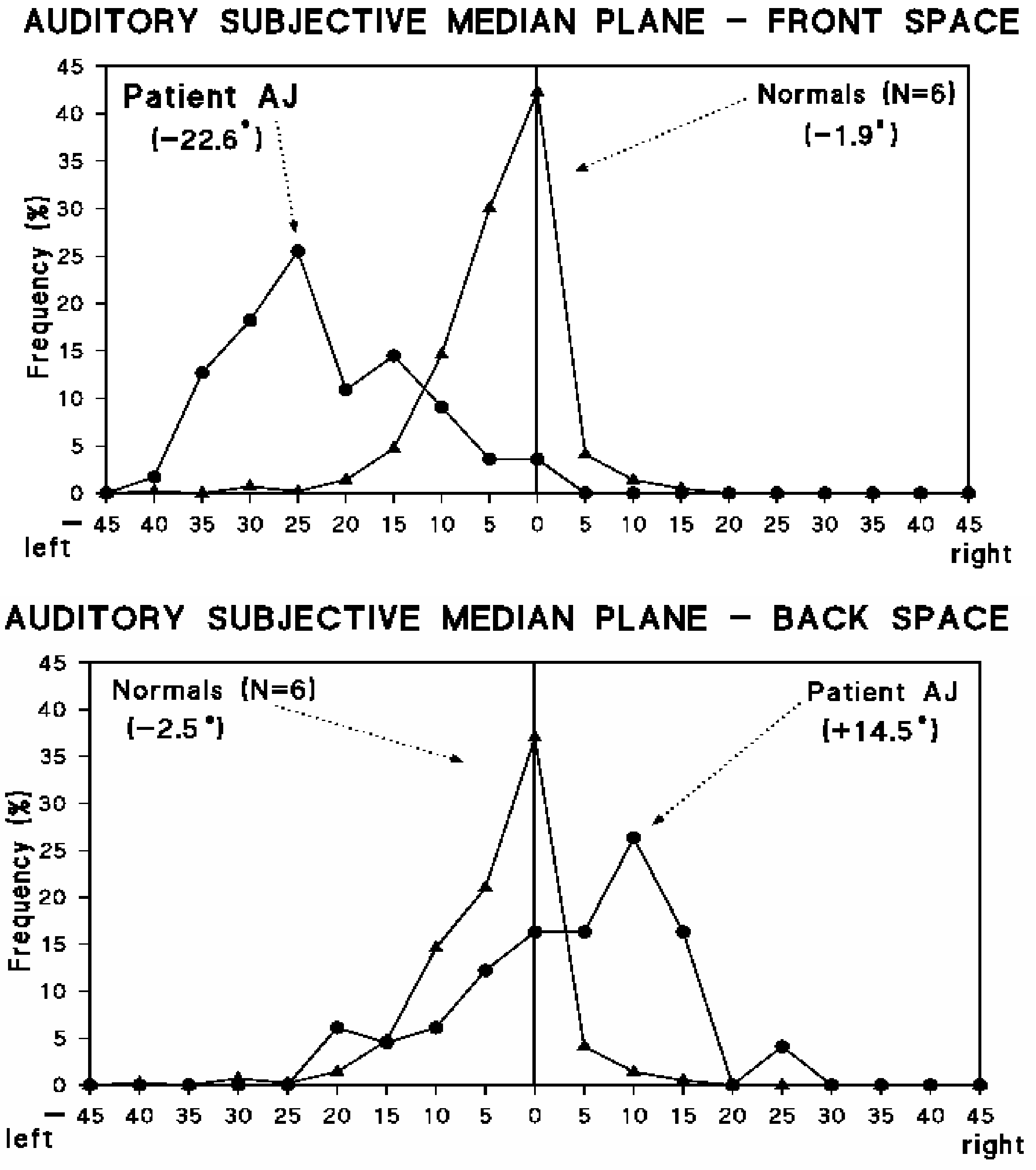
Target: 60 mm
Reproduction AJ
+27.5 mm
Normal range

Figure 3:



AUDITORY SUBJECTIVE MEDIAN PLANE – FRONT SPACE

AUDITORY SUBJECTIVE MEDIAN PLANE – BACK SPACE

Tables

Table 1: Mean peripheral (monaural) hearing acuity (sensitivity loss in dB) in AJ and six age-matched normal control subjects. For the normal subjects the min/max values are shown in brackets.

Subject	Ear	Frequency (kHz)										
		0.125	0.25	0.5	0.75	1	1.5	2	3	4	6	8
AJ	L	14	12	10	9	9	20	20	15	21	20	26
AJ	R	17	16	11	10	9	16	19	23	24	25	29
Normals (N=6)	L	15 (4-17)	16 (5-19)	17 (7-19)	13 (9-18)	10 (6-20)	17 (8-24)	16 (10-24)	20 (12-25)	21 (13-26)	23 (11-28)	24 (15-30)
Normals (N=6)	R	16 (3-21)	15 (4-20)	16 (6-21)	14 (7-23)	12 (6-20)	19 (7-23)	20 (10-28)	21 (11-27)	22 (13-28)	22 (14-29)	24 (17-30)

L=left, R=right

Table 2: Mean judgments of the auditory subjective median plane (ASMP, in °) in AJ and six age-matched normal subjects in front- and back space. Data are split depending on the starting position of the auditory stimulus (left or right hemispace). The standard deviation (SD) is given in brackets for AJ and the normal control group. In addition the PSE (Point of Subjective Equality) obtained in the retest examination and the percentage of front-back-reversals in the retest are shown (see text for details)

Subject	Front Space					Back Space				
	Left	Right	Left and Right	PSE (Retest)	Front-Back-Reversals (%)	Left	Right	Left and Right	PSE (Retest)	Front-Back-Reversals (%)
Patient AJ	-21.9 °	-23.3°	-22.6° (9.9°)	-25.4°	10.8	+14.3°	+14.6°	+14.5° (15.4°)	+ 15.4°	8.1
Normal 1	-5.0°	-3.8°	-4.4°	-4.6 °	5.4	+0.2°	+0.3°	+0.3°	+1.2°	4.5
Normal 2	+2.5°	+4.0°	+3.3°	+4.1 °	10.3	-2.1°	+0.3°	-0.9°	-1.1°	10.8
Normal 3	-4.0°	-1.1°	-2.6°	-3.2 °	3.6	-4.3°	-5.3°	-4.8°	-5.2°	5.4
Normal 4	-5.5°	-4.8°	-5.2°	-5.4°	6.3	-1.1°	-1.6°	-1.4°	-0.7°	6.3
Normal 5	+1.3°	0.6°	+1.0°	2.1°	7.2	-5.8°	-8.2°	-7.0°	-5.5°	4.5
Normal 6	-4.1°	-3.2°	-3.7°	-2.8°	3.6	-2.5°	+0.3°	-1.1°	-1.8°	8.1
Normals, Mean	-2.5°	-1.4°	-1.9° (3.3°)	-1.6°	6.1	-2.6°	-2.4°	-2.5° (6.1°)	-1.8	6.6

Left/right= stimulus starting position in left/right hemispace, Left and Right= Mean across starting positions

References

Andersen, R. A., Snyder, L. H., Bradley, D. C., & Xing, J. (1997). Multimodal representation of space in the posterior parietal cortex and its use in planning movements. *Annual Review of Neuroscience, 20,* 303-330.

Barton, J. S., Behrmann, M., & Black, S. (1998). Ocular search during line bisection. The effects of hemi-neglect and hemianopia. *Brain, 121,* 1117-1131.

Battaglini, P. P., Galletti, C., & Fattori, P. (1997). Neuronal coding of visual space in the posterior parietal cortex. In P.Thier & H.-O. Karnath (Eds.), *Parietal Lobe Contributions to Orientation in 3D Space* (1 ed., pp. 539-553). Heidelberg: Springer.

Beis, J. M., Keller, C., Morin, N., Bartolomeo, P., Bernati, T., Chokron, S. et al. (2004). Right spatial neglect after left hemisphere stroke: qualitative and quantitative study. *Neurology, 63,* 1600-1605.

Engen, T. (1971). Psychophysics. I. Discrimination and detection. In J.W.Kling & L. Riggs (Eds.), *Woodworth & Schlossberg's experimental psychology* (pp. 11-86). London: Methuen & Co.

Ferber, S. & Karnath, H.-O. (1999). Parietal and occipital lobe contributions to perception of straight ahead orientation. *Journal of Neurology, Neurosurgery, and Psychiatry, 67,* 572-578.

Girotti, F., Casazza, M., Musicco, M., & Avanzini, G. (1983). Oculomotor idsorders in cortical lesions in man: the role of unilateral neglect. *Neuropsychologia, 21,* 543-553.

Ishiai, S., Sugishita, M., Mitani, K., & Ishizawa, M. (1992). Leftward search in left unilateral spatial neglect. *Journal of Neurology, Neurosurgery, and Psychiatry, 55,* 40-44.

Karnath, H.-O. (1997). Spatial orientation and the representation of space with parietal lobe lesions. *Philosophical Transactions of the Royal Society, London, B, B352,* 1411-1419.

Karnath, H.-O., Milner, A. D., & Vallar, G. (2002). *The cognitive and neural bases of spatial neglect*. Oxford: Oxford University Press.

Karnath, H.-O., Niemeier, M., & Dichgans, J. (1998). Space exploration in neglect. *Brain, 121,* 2357-2367.

Kerkhoff, G., Artinger, F., & Ziegler, W. (1999). Contrasting spatial hearing deficits in hemianopia and spatial neglect. *NeuroReport, 10,* 3555-3560.

Kerkhoff, G. & Marquardt, C. (1998). Standardized analysis of visual-spatial perception with after brain damage. *Neuropsychological Rehabilitation, 8,* 171-189.

Kerkhoff, G., Münβinger, U., Eberle-Strauss, G., & Stögerer, E. (1992). Rehabilitation of hemianopic alexia in patients with postgeniculate visual field disorders. *Neuropsychological Rehabilitation, 2,* 21-42.

Kerkhoff, G., Münβinger, U., & Meier, E. K. (1994). Neurovisual rehabilitation in cerebral blindness. *Archives of Neurology, 51,* 474-481.

Knudsen, E. I. & Brainard, M. S. (1995). Creating a unified representation of visual and auditory space in the brain. *Annual Review of Neuroscience, 18,* 19-43.

Lewald, J. & Ehrenstein, W. H. (1996). The effect of eye position on auditory lateralization. *Experimental Brain Research, 108,* 473-485.

Mazzoni, P., Bracewell, R. M., Barash, S., & Andersen, R. A. (1996). Spatially Tuned Auditory Responses in Area Lip of Macaques Performing Delayed Memory Saccades to Acoustic Targets. *Journal of Neurophysiology, 75,* 1233-1241.

Middlebrooks, J. C. & Green, D. M. (1991). Sound localization by human listeners. *Annual Review of Psychology, 42,* 135-159.

Pavani, F., Husain, M., Ladavas, E., & Driver, J. (2004). Auditory deficits in visuospatial neglect patients. *Cortex, 40,* 347-365.

Riddoch, M. J. & Humphreys, G. W. (1983). The effect of cueing on unilateral neglect. *Neuropsychologia, 21,* 589-599.

Robinson, D. L., McClurkin, J. W., & Kertzman, C. (1990). Orbital position and eye movement influences on visual responses in the pulvinar nuclei of the behaving macaque. *Experimental Brain Research, 82,* 235-246.

Sparks, D. L. (1988). Neural cartography: sensory and motor maps in the superior colliculus. *Brain Behaviour and Evolution, 31,* 49-56.

Stricanne, B., Andersen, R. A., & Mazzoni, P. (1996). Eye-centered, head-centered, and intermediate coding of remembered sound locations in area LIP. *Journal of the Neurophysiology, 76,* 2071-2076.

Vallar, G. (1997). Spatial frames of reference and somatosensory processing: a neuropsychological perspective. *Philosophical Transactions of the Royal Society, London, B, B 352,* 1401-1409.

Vallar, G., Guariglia, C., Nico, D., & Bisiach, E. (1995). Spatial hemineglect in back space. *Brain, 118,* 467-472.

Weintraub, S., Daffner, K. R., Ahern, G. L., Price, B. H., & Mesulum, M.-M. (1996). Right sided hemispatial neglect and bilateral cerebral lesions. *Journal of Neurology, Neurosurgery, and Psychiatry, 60,* 342-344.

Wenzel, E. M., Arruda, M., Kistler, D. J., & Wightman, F. L. (1993). Localization using nonindividualized head-related transfer functions. *The Journal of the Acoustical Society of America, 94,* 111-123.

Wightman, F. L. & Kistler, D. J. (1989a). Headphone simulation of free-field listening. II: Psychophysical validation. *The Journal of the Acoustical Society of America, 85,* 868-878.

Wightman, F. L. & Kistler, D. L. (1989b). Headphone simulation of free-field listening. I: Stimulus synthesis. *The Journal of the Acoustical Society of America, 85,* 858-867.