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Contrasting spatial hearing deficits in hemianopia and spatial neglect

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SPATIAL hearing deficits have been described in widely differing pathologies, including bilateral temporal or unilateral parietal lesions, hemispherectomy, spatial neglect and right-sided cortical lesions without neglect. However, the topography of spatial hearing deficits after cortical lesions is only poorly understood, unlike that of vision and touch. We investigated the auditory subjective straight ahead (SSA) with a new technique of binaural sound source simulation using broad-band single pulses which were filtered with head-related transfer functions and delivered with a 5° resolution over headphones in front space. Normal subjects showed quite accurate judgments of the SSA, with a small but significant shift to the left of centre (−1.7°) in the horizontal plane. Hemineglect without a scotoma, produced a large ipsilesional deviation of the auditory SSA (+22°), while two hemianopic subjects, both without neglect, showed the opposite deviation of their perceived auditory SSA towards their contralesional, blind hemifield (+10 *vs* −28°). Two control patients with unilateral lesions, both without neglect and without hemianopia, produced normal judgments of their auditory SSA (−3.0°, +3.8°). These results suggest at least two contrasting influences on directional spatial hearing after unilateral cortical lesions: hemianopia *vs* hemispatial neglect. The results are interpreted in favour of multisensory convergence of visual and auditory information in directional spatial hearing. *NeuroReport* 10:3555–3560 © 1999 Lippincott Williams & Wilkins.

Key words: Brain damage; Hearing; Hemianopia; Multisensory integration; Neglect; Subjective straight ahead (SSA)

Introduction

The localization of a sound source in space presents a challenge to the integrative capabilities of the nervous system. In contrast to vision, where a stimulus leaves an image and a position on the retina, and visual maps of space are found in many cortical and subcortical structures of the visual system, spatial hearing requires the computation of sound location by using interaural time and intensity differences, as well as spectral and pinna cues [1,2]. A variety of cerebral structures are involved in these processes [3]. Due to the limitations in spatial resolution within the auditory system and the much higher precision of visual-spatial resolution vision plays an important role in the calibration of spatial hearing [3], at least during development. Consequently, modifications of visual input, i.e. by prisms or eye patching, have significant behavioural effects on spatial hearing, and modify the underlying neural circuitry in the superior colliculus during development [4–6]. While it is generally believed that these multisensory interactions are most prominent during developmental phases after which such cross-modulatory influences are weaker [3], such influences have also been shown in adulthood in both animals [7] and human subjects [8].

Clinical studies of spatial hearing impairments in patients with acquired cerebral lesions have yielded rather contradictory results. Some studies show that unilateral right-sided cerebral lesions lead to greater impairments than left-sided lesions [9,10], and that patients with unilateral spatial neglect of the left hemispace after a right-hemispheric lesion show the greatest impairments [10–13]. In some studies an ipsilesional deviation of the judgment of the auditory subjective straight ahead (SSA) was found in front space [12] while another study concluded that right-hemisphere lesioned subjects with contralateral visual field defects showed the greatest ipsilesional

deviation of the SSA [14]. In a study by Pinek *et al.* [15], contralateral spatial hearing deficits in the horizontal plane were found in right parietal lesioned patients, whereas more widespread spatial localization deficits in the auditory modality were found in patients with left parietal lesions. Obviously, different factors may contribute to the contradictory results. One possible explanation for the divergence of results lies in the variety of methods used, another likely explanation is the widely differing pathology of patients with different syndromes often being grouped together (field defects, neglect, extinction). In the light of the above mentioned crossmodal interactions between vision and audition [3,16] and the cross-talk between both modalities found in spatial attention [17,18] it seems quite probable that different visual disorders arising as a result of a brain lesion might have significant effects on directional spatial hearing.

To this purpose, we recently developed new software for the analysis of spatial hearing by using binaural simulation [2]. This method allows for headphone-presentation of acoustic stimuli in numerous positions in virtual space with a resolution of 5°. The resolution is far better than any spatial resolution used so far with free-field auditory experiments in patients with brain lesions (10-30°, cf. [12,19]). Furthermore, this method allows nearly perfect control over the acoustic signal delivered to the subject's ear, without the necessity of a soundproof chamber and the problems of acoustic reflections from external sound sources.

To disentangle the potential contributions of a typical low-level visual disorder (hemianopia) and a high-level, supramodal spatial disorder (neglect) on directional spatial hearing, different patients with a selective disorder in one of these two categories as well as control patients without such a disorder, and normal subjects were evaluated. The present study reports the first results obtained with this new system dealing with the judgement of the auditory SSA in these different subject groups.

Materials and Methods

Subjects: Five patients (four female, one male, age 37–65 years) with unilateral hemispheric brain lesions (time post onset: 3–9 months), documented by CT/MRI scans were investigated. For comparison, 22 normal subjects were tested (15 female, seven male; mean age 48 years, range 42–73).

Visual perimetry and visual neglect tests: Three conventional neglect tests were performed: horizontal bisection of a 20×1 cm black line on a white sheet of paper; number cancellation (30 targets among 150 distractors, presented on a 29.7×21 cm sheet of white paper), and drawing of a clock face. Neglect was diagnosed when the truncation midline in bisection deviated more than 5 mm to the ipsilesional side, when more than one target was omitted on the left side in number cancellation, or when numerals were omitted or misplaced on the left side of the clock face test. Binocular visual fields were mapped perimetrically with a Tübingen perimeter in all patients (details see [20]; see Table 1). According to these criteria patients 1 and 2 had hemianopia, but no neglect, subject 3 had neglect, but completely intact visual fields, and subjects 4 and 5 had neither neglect nor hemianopia, but both had a unilateral brain lesion, as subjects 1–3 had. Thus, subjects 1–3 had contrasting deficits of hemianopia *vs* hemineglect, both in its pure form, while subjects 4 and 5 had neither hemianopia nor neglect, thus serving as patient control subjects.

Peripheral hearing tests: All subjects were screened with a Philips HP 8741/31 puretone audiometer for normal hearing functions. None of the patients or normal subjects had an unilateral hearing loss of > 10 dB in any of the frequency ranges tested (0.125, 0.25, 0.5, 0.75, 1, 1.5, 2, 3, 4.5, 8 and 10 kHz).

Auditory subjective straight ahead (SSA): In contrast to the frequently used external speakers we used a broad-band (white-noise), 3 s single pulse signal (sound pressure level, SPL: 75 dB, as measured by an audiometer). Signal pulses were passed through digital linear minimum phase filters (FIR-filter design) with directional dependent head-related transfer functions (HRTF, [21–23]) to simulate virtual sound locations in 5° resolution along the horizontal plane in front space. HRTF data used for binaural simulation stems from dummy head measurements (KEMAR dummy head, cf. [24]) which contain interaural and monaural auditory cues and are normalized with respect to an average across all directions (diffuse-field equalization, cf. [25]) to minimize the influence of the measurement system and ear channel response. This led to 37 sound source positions in the left and right hemispace, including the objective straight ahead position (0°). The starting positions of the stimuli were pseudorandomized across the 37 possible positions. Two trials were presented for each source position, adding to a total of 74 trials. Stimuli were delivered via an AKG K 240 headphone with a similar frequency response to that used in HRTF-measurements. The subjects sat in front of a PC monitor on which a central yellow fixation spot was presented. Head position was stabilized by use of a head and chin rest. Subjects were instructed to indicate as accu-

Table 1. Patient data

Patient	Age/sex	Etiology	Months since lesion	Lesion side and localization	Hemianopia field sparing (°)	Visual acuity (LE/RE)	Hemineglect	Clock face (L/R)	Line bisection deviation (mm)	Cancellation omissions (L/R)
1. Hemianopia	62/M	MCA	5	Right, T-P	Left 4	Near 1.0/1.0; Far 0.8/0.8	No	0/0	−10.5	1/0
2. Hemianopia	37/F	Aneurysm	5	Left, T-P	Right 3	Near 1.0/1.0; Far 1.0/1.0	No	0/0	+3.5	0/0
3. Hemineglect	40/F	MCA	6	Right, P	No	Near 0.8/0.8; Far 1.2/1.2	Yes, Left	1/0	+11.5	18/3
4. LBD, control	40/F	MCA	9	Left, BG,T	No	Near 1.0/1.0; Far 1.0/1.0	No	0/0	−1.0	0/0
5. RBD, control	65/F	MCA	6	Right, T-P	No	Near 0.6/0.8; Far 0.6/0.8	No	0/0	+2.5	0/0

Clockface: 0 = normal, 1 = omission of numerals on the left or right side. Line bisection: deviation from the true midline in mm (+ = to the right, − = to the left; cut-off = 5 mm). Number cancellation: omission of targets in left/right hemispace (cut-off = < 2 per hemifield).
MCA, middle cerebral artery infarction. The field sparing in the two hemianopic subjects is given for the horizontal meridian lying within the scotoma. Visual acuity (decimal) is given for the near (0.4 m) and far (6 m) viewing distance for the left eye (LE) and right eye (RE) measured on high-contrast visual acuity charts.
L/R, left/right; F/M, female/male; F/P/T/BG, frontal, parietal, temporal, basal ganglia.

rately as possible whether a presented stimulus came directly from the front (0°) or in which direction it had to be modified until it came from this subjective straight ahead position (SSA).The nature of the experiment was explained together with 12 practice trials until all subjects were clear about the purpose of the task. After half of the trials a break of 5 min was given to control for fatigue. No time constraints were imposed on the subjects during the measurements.

Results

Figure 1A–C displays the complete frequency distribution of the residual angles in the 74 trials when the subject finally indicated that the stimulus coincided with his/her subjective auditory SSA.

Normal subjects: As a group the normal subjects showed a small (mean −1.9°), but significant shift of their perceived SSA to the left of centre (*t*-test, two-tailed $t = -10.64$, $p < 0.0001$, significant from the 0° midline position). Seventeen of the 22 subjects showed a shift of their SSA which was significantly different from 0; of these, 13 deviated significantly to the left, while only four showed a similar, but numerically smaller shift to the right of the true midline ($p < 0.05$ in all comparisons). The maximal range of the perceived auditory SSA in our normal subjects was −7.6° to the left, and +3.3° to the right of the true midline (0°). For statistical purposes we took the mean deviation of the normal subjects (−1.9°) as a reference against which the results of the five brain-lesioned patients were compared.

Patients: t-tests showed that the two hemianopic patients (subjects 1, 2) differed significantly from the mean reference value of the normal subjects ($t = -19.6$, $p < 0.0001$ for subject 1; $t = 7.13$, $p < 0.0001$ for subject 2). Likewise, subject no. 3 with left-sided spatial neglect differed significantly in her perceived SSA from the normal reference ($t = 17.59$, $p <$ s0.0001). In contrast, subjects 4 and 5, without neglect and with intact visual fields, did not differ significantly from the normal reference value ($t = -1.7$, $p > 0.05$ for subject 4; $t = 1.79$, $p > 0.05$ for subject 5).

Independent *t*-tests (two-tailed and corrected for the number of tests) between the five subjects confirmed that the neglect patient (no. 3) shifted her auditory SSA far more to the right side than any other subject tested (smallest $t = 4.58$, $p < 0.0001$). The two hemianopic subjects differed significantly in their SSA ($t = 16.15$, $p < 0.0001$), and both also differed significantly when compared with the relevant brain-damaged control subjects: subject 1 and

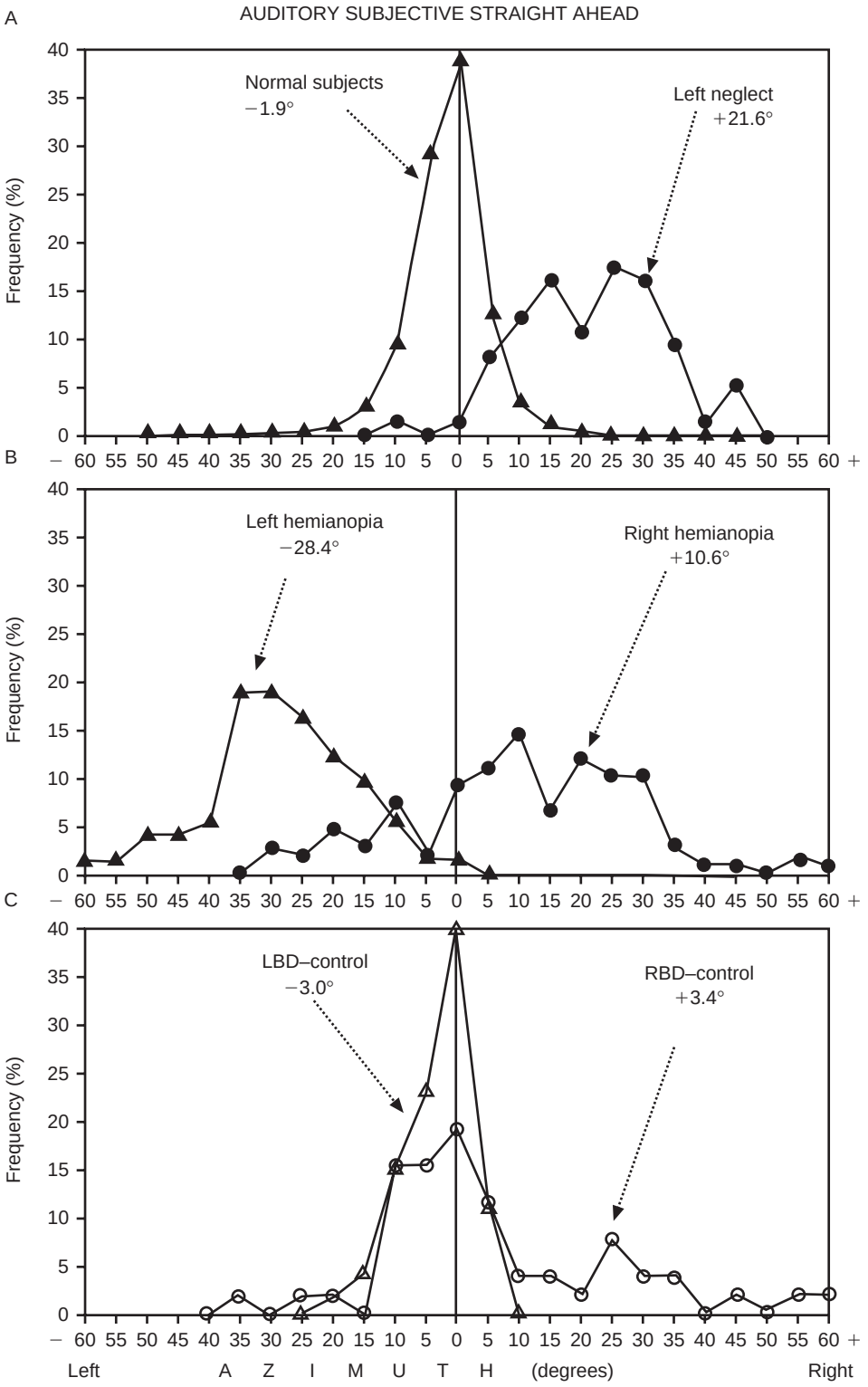

FIG. 1. Frequency distributions and mean values of 74 judgements of the auditory subjective straight ahead (SSA) in front space (in degrees of visual angle) in different subject groups. The x-axis gives the azimuth-position from −60° to the left up to +60° to the right of the objective midline (0°, vertical line in every plot). (**A**) Results from 22 normal subjects, and patient no. 3 with left-sided spatial hemineglect. Note the significant deviation of the auditory SSA in the neglect patient towards the ipsilesional (right) side, in contrast to the narrow frequency distribution of the normal subjects. (**B**) Contrasting, contralesional deviations of the perceived auditory SSA in two hemianopic subjects (subjects 1 and 2, Table 1), both without hemineglect. (**C**) Normal auditory SSA judgements in the LBD- and RBD-control patients (subjects 4 and 5, Table 1). In all figures minus denotes left-sided deviations from the true auditory midline position, and plus right-sided deviations.

5, both with right brain lesions, were significantly different ($t = 5.7$, $p < 0.0001$); subjects 2 and 4, both with left brain lesions, also differed significantly in their SSA ($t = -6.14$, $p < 0.0001$). The two brain-damaged control subjects scored slightly differently (subject 4 and 5; $t = 2.45$, $p < 0.05$), although they were not significantly different from the reference value of $-1.9°$ (see above).

Apart from the systematic shifts in the perceived auditory SSA outlined in Fig. 1, there are also more widespread reductions in the spatial sensitivity of the brain-lesioned patients which is indirectly expressed in their much broader frequency distributions in contrast to the steep and narrow distributions found in the healthy control subjects.

To summarize the findings: homonymous hemianopia and left hemineglect caused contrasting deviations in the perceived auditory SSA, while subjects with unilateral brain lesions, and neither hemianopia nor neglect, showed SSA judgments that lay within the range of normal subjects. The majority of the normal subjects showed a slight but statistically shift of their auditory SSA to the left of the true midline position.

Discussion

The present results provide for the first time evidence highlighting the role of vision (hemianopia) in spatial hearing. Ipsilesional deviation of the auditory SSA in leftsided spatial neglect has been reported previously [12,14]; however, many of the neglect patients reported in these two studies probably had contralateral visual field defects (100% in those patients with the greatest deficit [14]); or were not assessed perimetrically [12], so that the differential contributions of both factors may be difficult to disentangle. Obviously, in subsequent investigations it will be necessary to control for both factors appropriately.

Before discussing the results of the patients examined here a few words should be devoted to the performance of the normal subjects. They showed a significant though numerically small shift of their auditory SSA to the left of centre which is not explicable in terms of a starting position effect since this was controlled for by the randomization procedure during stimulus presentation (see methods). Since no manual response was required, motor factors can be excluded as a possible explanation. The slightly shifted auditory SSA in front space in normal subjects in our opinion probably reflects the activity of a neural spatial-attentional network in the parieto-temporal cortex which is stronger in the human right hemisphere. Evidence concerning this network is based on a wealth of anatomical, physiological, neuropsychological and imaging data [26,27]. A stronger right hemispheric spatial-attentional network might be responsible for a slight leftward shift of the auditory SSA in healthy subjects, and would predict larger deviations of the SSA in patients with damage to their right cerebral hemisphere rather than left hemispheric lesions.

How are the contrasting results of the patients to be explained? The ipsilesional deviation of the auditory SSA in neglect might be explicable in terms of an ipsilesionally translated or rotated egocentric reference frame [12], which is also found in the visual [14] and tactile modality [28]. Our results are consistent with this hypothesis and the relevant findings, thereby validating our new methods. While the effect of neglect on the auditory SSA has been expected, the opposite effect in nonneglecting, hemianopic patients is, at first glance, surprising.

Why should hemianopic patients have a contralesional deviation of their auditory SSA, hence a spatial hearing deficit? It is well known that these patients have a contralesional deviation of their visual SSA towards the scotoma [29,30], and that their ocular fixations during line bisection tasks are shifted towards their blind field [31], whereas neglect patients preferentially fixate within their ipsilesional hemispace [31]. This might suggest that eye position could have caused the shift in the auditory SSA in our two hemianopic subjects. Although we cannot completely rule out eccentric fixations, despite the instructions to all subjects to fixate straight ahead on the monitor, it is unlikely that eye position could account for the whole effect, since the magnitude of the eye-position effect on the auditory SSA is only about 5° with an eccentric gaze position of maximally 45° to the left or right [32]. Gaze deviations of this magnitude would have been detected in the present experiment. Hence, the observed perceptual deviation in our hemianopic patients is much larger than the maximal effect of an experimental gaze deviation in normal subjects. Finally, a chronic, eccentric fixation is an unlikely explanation since it inevitably causes severely reduced visual acuity of the eye(s) showing eccentric fixation, which was not present in our patients (see the acuity data in Table 1).

As an alternative explanation, the hemianopic field loss itself might produce an imbalance in cerebral structures which receive both visual and auditory input and deal with spatial orientation. As a result of the deviant visual SSA a discordance between the visual and auditory SSA would emerge. Since in most behavioural situations auditory-spatial localization is dominated by visual localization because of the higher spatial resolution in the visual system [3,33], the contralesional deviation of the auditory

SSA in hemianopic patients might represent the result of a behavioural adaptation in order to avoid discordances between the two modalities. In line with this cross-modal hypothesis, hemianopic patients were shown to have postural deficits [34]. Their centre of pressure, as measured by a force platform, was shifted contralesionally in contrast to the symmetrically balanced posture of normal subjects and patients with intact visual fields. Interestingly, patients with left-sided hemianopia showed the greatest deviation, which conforms to our finding of a much greater deviation of the left hemianopic patient (−28.4°) than of the right hemianopic patient (+10.5°). Obviously, a visual deficit acquired in adulthood influences spatial behaviour in non-visual modalities, i.e. audition and posture.

Cerebral areas with polysensory neurons, where such types of crossmodal integration could take place, have been identified in the superior colliculus [16], the anterior ectosylvian cortex of the cat [7] and in the superior temporal cortex of primates [35]. Furthermore, visual cortex lesions may cause reduced neuronal activity in subsequent cortical areas (V2, V3, V4) due to reduced afferent inflow [36], and may also do so in later cortical and subcortical areas receiving multisensory input.

Conclusion

The present study shows that homonymous hemianopia and hemispatial neglect lead to contrasting deviations in the subjectively judged auditory SSA. Thus, an acquired cortical visual disorder may lead to deficits in spatial hearing, just as the modulation of visual input during development strongly influences auditory-spatial behaviour. In extension of these developmental studies, the present results indicate that significant cross-modal interactions between vision and audition are likely in adult subjects with cortical lesions as well.

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