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Neuropsychologia, Vol. 19, No. 3, pp. 435–443, 1981.
Printed in Great Britain.

0028–3932/81/030435–09$02.00/0

AUDITORY SPATIAL DEFICITS IN THE PERSONAL AND EXTRAPERSONAL FRAMES OF REFERENCE DUE TO CORTICAL LESIONS*

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(*Received* 28 *November* 1980)

Abstract—Twenty-nine patients with unilateral cortical lesions were asked to localize simple auditory stimuli (the personal frame of reference) and to bisect the space between two auditory stimuli (the extra-personal frame of reference). Results indicate that the displacement error scores of the right posterior group were consistently greater than those of all other groups (the left posterior, right anterior, left anterior and normal control) in both frames of reference. Error analysis suggests that the right posterior effect reflects spatial dysfunction common to both hemispaces rather than the contralateral deficit characteristic of unilateral neglect.

A CONSIDERABLE body of evidence has accumulated showing that cerebral lesions differentially influence tasks designed to distinguish between the intrapersonal (e.g. left–right) and extrapersonal (e.g. east–west) aspects of space (in man [1], and in monkey [2, 3, 4]). All of these studies have utilized tasks which rely on vision and on somesthesis. The present study was undertaken in order to determine whether such impairments of spatial processing are limited to the visual and somatosensory modalities or whether some more general personal and extrapersonal frames of reference are disturbed by the lesions.

To this end a set of auditory localization tasks was devised. Acoustic signals are known to play a role in alerting some species of animals to danger arising in one or another locality. For example, owls have a highly advanced mechanism for auditory space perception [5].

There are some studies that have already investigated the possible effect of cortical lesions on the ability to localize sounds. SANCHEZ LONGO *et al.* [6] utilized a test for sound localization and concluded [7] that lesions in the temporal lobe (and no other part of the cortex) impair the ability to localize sounds. However, KLINGON and BONTECOU [8] failed to replicate this local temporal lobe effect, because patients with involvement of the frontal and parietal regions also showed "drastic displacements" of sound sources. But, in still another study, BARU and KARASEVA [9] cite the experiments of Blagoveshchenskaya in which the methods of SANCHEZ LONGO *et al.* [6] were used, and which showed that parieto-temporal (not primary auditory cortex [10]) lesions were primarily responsible for impairment of sound localization.

Studies investigating a family of symptoms described under the labels "unilateral neglect,"

*This paper was presented in part to the International Neuropsychological Society, February 1980, San Francisco, California, U.S.A.

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"extinction to bilateral simultaneous stimulation," "amorphosyntheses" and "hemi-inattention" (for review and excellent discussion see WEINSTEIN and FRIEDLAND [11]) had suggested possible differences between tasks employing personal and extra-personal reference frames. For instance, DIAMOND and BENDER [12] reported patients who perceived sounds as having originated in the hemispace ipsilateral to their lesion, when in fact the actual source was on the contralateral side (they referred to this as "alloacusis"). Heilman and his associates have also reported cases of similar displacement errors in patients who show severe hemi-inattention (see review article by HEILMAN and WATSON [13]). Thus, unilateral neglect can be conceived to be the underlying cause for sound dislocalization due to a gross disturbance of the personal frame of reference. A test of this hypothesis would entail the demonstration that: (1) errors were significantly greater in the hemifield contralateral to the lesion; and (2) the direction of these errors would show displacement towards the ipsilateral hemifield. Some indication for such tendencies was reported by KLINGON and BONTECOU [8] since they observed greater displacements of sound sources in the contralateral hemified. However, in their study, no distinction could be made between displacements due to an impaired personal vs an impaired extrapersonal frame of reference.

Such a distinction can be made if the displacement toward the ipsilateral hemifield (as in the unilateral neglect syndrome) is considered to be evidence for disturbance of the personal frame of reference. A test for disturbance of the extrapersonal frame of reference could then be devised which would elicit difficulties in perceiving the relationships among several sound sources themselves. Such a test was implemented by asking patients to bisect the space between sound sources.

METHOD

Subjects

The subject population comprised 29 patients with unilateral cortical lesions, primarily vascular and traumatic in nature, which were localized on the basis of surgical reports and various radiological techniques. The patients were divided into four groups according to hemisphere and locus of lesion on the anterior–posterior plane. Patients in the left anterior ($N=6$) and right anterior ($N=8$) groups presented lesions in the frontal, fronto-central or fronto-temporal regions. The patients in the left posterior ($N=8$) and the right posterior ($N=7$) groups presented lesions in the parietal, parieto-occipital or parieto-temporal regions. Neuropsychological diagnoses were available for all patients and served as selection criteria for evaluating the intellectual and linguistic abilities necessary for the comprehension of tests used in this experiment. The mean age of all patients was 36 years (S.D. = 12.6), and about one-third of the patients were female. Ten normals comprised the control group. No abnormality in pure tone thresholds was recorded for any of the subjects in any group and the sensitivity ranges between the two channels were in all instances equal.

Apparatus

Nine loudspeakers were arranged in a semicircle on a table in front of the subject. Each speaker was 75 cm from the center of the subject's forehead. The angular placement of the loudspeakers was 10, 30, 50, 70, 90, 110, 130, 150 and 170°. The subject's responses were scored in 5° increments. This measure of accuracy was chosen since humans appear to be able to localize sounds with an accuracy of approximately 5° [14]. An audio stimulator was constructed which allowed remoted initiation of a particular loudspeaker. The apparatus was adjusted to deliver a suprathreshold stimulus at 1,000 Hz for 1 sec.

Procedure

The subject sat facing the loudspeaker array. The experimenters made certain that no head movements occurred during the stimulus presentations. During the entire task the subject was blindfolded and was asked to use only the hand ipsilateral to his/her lesion.

Sound localization. This was the first task. In this task a stimulus was delivered through one of the nine loudspeakers. The subjects was asked to respond by pointing the ipsilateral index finger to the perceived location of

the sound source within the semicicle. Responses were recorded in terms of absolute magnitude of error (absolute error) and displacement toward the ipsilateral or contralateral side of the stimulus (directional error). One stimulus was presented over each of the nine loudspeakers in random order.

Auditory bisection. In this, the second task, two stimuli were sequentially presented through two loudspeakers and the subject was asked to point with the ipsilateral index finger to the perceived midpoint between the two stimuli. A total of 10 stimulus pairs were presented. The actual midpoints of the stimulus pairs were 50, 80, 90, 100 and 130°, with the speaker separation of 20 or 40°. Again, the absolute and directional errors were recorded.

In the auditory bisection task subjects were required to point to a position in space by relating two sound sources to one another. Thus, this task was considered to involve the extrapersonal frame of reference. On the other hand, in the sound localization task the subjects used no extrapersonal cues. Position was noted with reference to the subject's own body and was thus considered a test involving the personal frame of reference.

Finger placement. This task served to assess possible sensorimotor deficits which could confound auditory spatial performance on both the sound localization and auditory bisection tasks. The ipsilateral index finger was guided to a position within the previously described semicircle. The subject was then asked to withdraw the hand, to touch the chest and then place the finger on the original starting point.

RESULTS

Sound localization

The total absolute error was averaged across all subjects within each group (see Table 1). A one-way analysis of variance was significant, $F\ (4, 35) = 6.30$, $P < 0.001$. For all of the following post-hoc comparisons multiple t tests were performed. The first such analysis clearly indicated that absolute error of the right posterior group was significantly greater than that of any other group, $P < 0.01$. The left posterior group also demonstrated significantly greater absolute error than the control group, $P < 0.05$.

Table 1. Cumulative error scores on the sound localization task

Groups	Mean*	S.D.	*N*
Normals	15.10	3.93	10
Right anterior	26.75	16.02	8
Right posterior	50.33	19.16	7
Left anterior	29.40	18.88	6
Left posterior	28.80	10.19	8

*Represents the average over nine trials where 1.0 = 5°.

Total absolute error was re-evaluated for the ipsilateral and contralateral hemifields for each subject. A two-way analysis of variance was significant for the factor of groups, $F\ (3, 52) = 4.57$, $P < 0.007$; but neither the factor for hemifields nor the interactions were significant. Again, displacement error was significantly greater in the right posterior group.

The mean directional errors of left and right hemisphere patients are displayed as a function of angular position and compared with the performance of the normal control group in Figs 1 and 2, respectively. A two-way analysis of variance revealed no effect of subject group or hemifields.

Auditory bisection

Total absolute error was averaged across subjects within each group for all five midpoints (see Table 2). A two-way analysis of variance was performed and significance was obtained for the factor of groups, $F\ (4, 175) = 6.75$, $P < 0.001$, but not for the factor of position or the

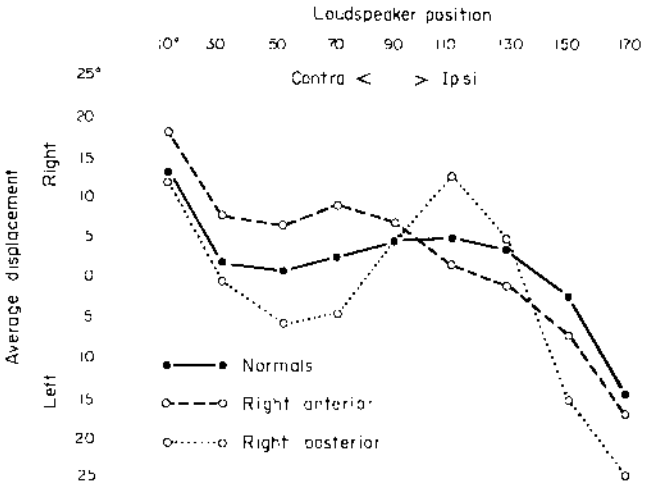

FIG. 1. Mean directional error scores in the sound localization task of patient groups with right hemispheric lesions.

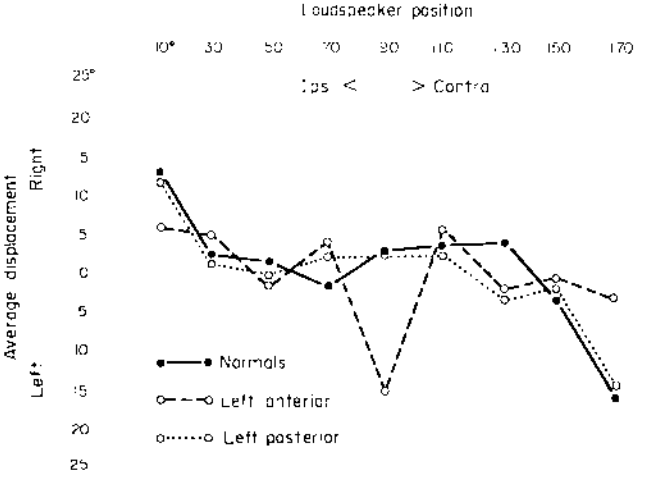

FIG. 2. Mean directional error scores in the sound localization task of patient groups with left hemispheric lesions.

interaction. The right posterior group demonstrated greater absolute error than the normal, $P<0.001$, the right anterior, $P<0.01$, and the left posterior groups, $P<0.05$.

In order to consider performance in the contralateral and ipsilateral hemifields the pooled data for the 50 and 80° midpoints on one side were compared to the pooled data for the 100 and 130° midpoints on the other side. A two-way analysis of variance again demonstrated the effect of groups, $F(3, 48)=3.07$, $P<0.04$. Neither the factor of hemifield nor the interaction was significant.

The mean directional error for left and right hemisphere patients is displayed as a function of angular position of the midpoint and compared to the performance of the control group in Figs 3 and 4, respectively. Directional errors were analyzed for groups and hemifields by means of a two-way analysis of variance. No significant effect was demonstrated.

Table 2. Cumulative error scores on auditory bisection according to midpoints*

Groups		50°	80°	90°	100°	130°
Normals	Mean	2.30	2.60	2.40	1.80	2.90
	S.D.	2.11	2.00	1.95	1.90	2.69
Right anterior	Mean	2.13	2.38	2.88	3.38	2.50
	S.D.	2.30	1.51	1.64	3.02	2.20
Right posterior	Mean	4.71	5.86	4.43	4.86	6.00
	S.D.	1.70	4.88	2.44	3.93	3.65
Left anterior	Mean	3.50	3.67	5.50	4.33	3.00
	S.D.	3.51	3.61	3.27	3.08	3.90
Left posterior	Mean	3.50	1.50	2.50	3.38	3.88
	S.D.	2.07	0.93	2.33	2.50	3.72

*Note: 1.0 = 5°.

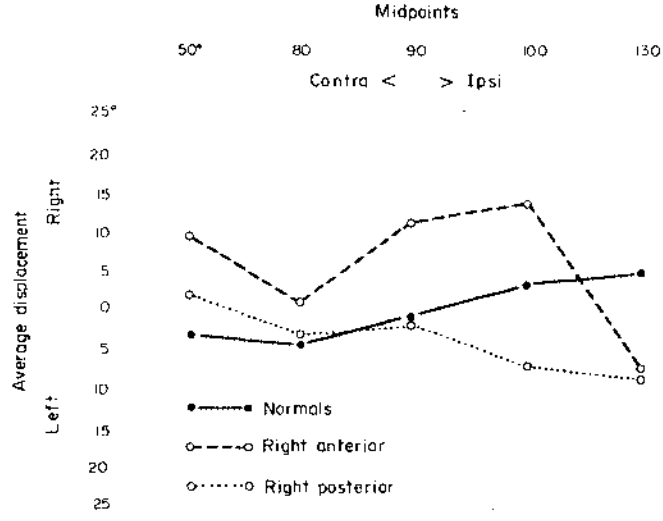

FIG. 3. Mean directional error scores in the auditory bisection task of patient groups with right hemispheric lesions.

Correlation between finger placement and sound localization tasks.

In none of the five groups was there a significant correlation between performance on the finger placement and the sound localization tasks. This was also the case when separate correlations for the ipsilateral and contralateral fields were computed. In general, performance on the finger placement task was more accurate than that of sound localization task. There was a tendency for most subjects to localize the most peripheral sound sources more toward the center of auditory (see Figs 1 and 2). This phenomenon was not observed in the finger placement task.

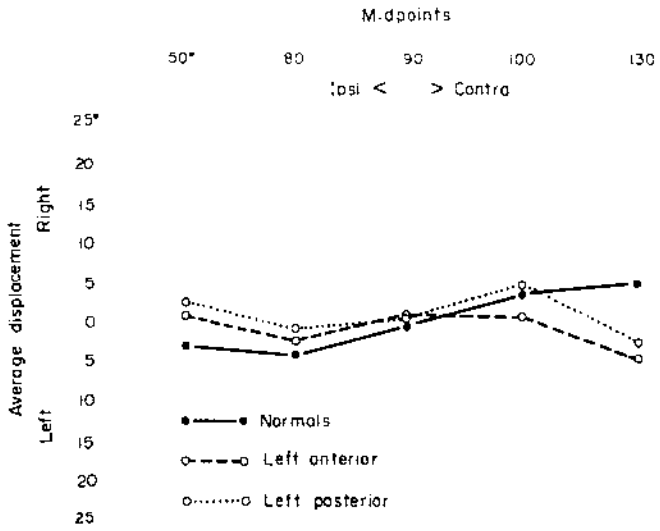

FIG. 4. Mean directional error scores in the auditory bisection task of patient groups with left hemispheric lesions.

DISCUSSION

In comparison to the control group, all patient groups performed at a lower level of accuracy in free field sound placements. However, the right posterior group was clearly singled out as having by far the greatest difficulty in tasks involving both the personal and the extrapersonal frame of reference. Sensory motor impairments were ruled out as having a major effect on this outcome because the sound displacement errors did not correlate with the performance on the finger placement task. Further, as noted in the methods section, auditory sensory deficits were ruled out as a possible underlying cause of the deficits. There is thus no doubt that the patients' sound placement disabilities were neither the direct result of auditory sensory deficits nor sensorimotor impairments.

How can the significant deficit of the patients with right posterior lesions be explained? Surely the most attractive angle from which to interpret this result is to link auditory spatial deficits with spatial impairments in general. Right posterior lesions are classically associated with spatial deficits, and this is, of course, well documented with tasks using sense modalities other than audition. Sound displacements are, therefore, interpreted as being primarily a spatial deficit. That is, patients with right posterior lesions lack the ability of mapping auditory sources in their spatial context. Based on our results, this conclusion seems to be almost too obvious, but in view of the controversial findings of SANCHEZ LONGO and FORSTER [7], KLINGON and BONTECOU [8] and BLAGOVESHCHENSKAYA [9] it is a clear-cut and parsimonious stand to take.

Our data do not dissociate personal from extrapersonal impairments. The right posterior group yielded the lowest accuracy levels in both tasks. This finding is consonant with that of BRODY and PRIBRAM [4] who found that parietal lesions in monkeys impaired tasks designed to test abilities in the personal and extrapersonal frames of reference. In that study, as in the current one, there is no evidence for any special involvement of the anterior frontal cortex in delineating the personal frame of reference.

Recently, HERSH [15] reported similar results on spatial analysis in the tactile modality. In his study, blindfolded patients (many of whom served as subjects in the present study) scanned a stimulus array, in this case using the preferred hand. Significant impairments in the extrapersonal frame of reference were demonstrated by the right posterior group only. Furthermore, the performance of both the left and right anterior groups in the personal and extrapersonal conditions was not found to be significantly worse than that of any other lesion group. Further studies are under way to analyze more complex forms of extrapersonal spatial analysis in which the exact location of a particular sound source is secondary and the relationship between an entire sequence outlining a two-dimensional acoustical pattern is primary (described in normals by RUFF and PERRET [16] and in patients with unilateral cortical lesions by RUFF [17]).

In the context of unilateral hemispheric lesions and their effects upon the ipsilateral and contralateral hemifields the following alternatives have been offered in the literature. SANCHEZ LONGO and FORSTER [7] considered sound localization to be a function of the temporal lobe and reported that in most instances the displacements were of greater magnitude in the contralateral hemispace. This work was discussed in detail by KLINGON and BONTECOU [8], who concluded that sound localization represents not primarily a temporal lobe but a hemispheric function. They agreed, however, that the unilateral lesions affected the auditory placements on the contralateral side, and that the cerebral hemispheres are therefore connected with the opposite auditory hemisphere. They viewed this as the outcome of the elementary sensory organization of the hemispheres. Although the findings of these studies and ours agree that right cerebral lesions result in auditory spatial deficits, our data stand in disagreement on two accounts. First, significantly greater sound displacements occurred not as a result of both right and left hemispheric lesions, but only in the patient group with *right* posterior lesions. Second, there were no contralateral effects, because the average error scores were of approximately equal magnitude in both hemispaces.

A recently published study by ALTMAN, BALONOV, and DEGLIN [18] shows some agreement with our results. These subjects were tested immediately after electroshock seizures in a free field localization task, and only right-sided shocks yielded significant impairments. Furthermore, displacement of sound sources occurred primarily in the contralateral hemispace and were often referred to the ipsilateral hemispace, an effect similar to "alloacusis" described by DIAMOND and BENDER [12]. The ALTMAN *et al.* study is, then in agreement with the observations of both SANCHEZ LONGO and FORSTER [7] and KLINGON and BONTECOU [8], but not with our findings. However, the absence of contralateral effects in a tactile spatial study was reported by HERSH [15]. As in the present study error analysis revealed that neither greater displacement in the contralateral hemispace, nor displacement toward or into the ipsilateral hemispace was associated with the significant right posterior impairment. These results are in complete agreement with our own.

Our finding of a lack of hemispatial differences appears independent of unilateral neglect: Three of our patients manifested signs of auditory unilateral extinction according to the clinical method of bilateral simultaneous stimulation, and all three patients yielded neither a disproportionate error rate between the hemispaces nor a greater absolute error score in comparison to their group members. A good possibility exists therefore that the task we used to test the personal frame of reference may be inadequate to that aim and that, in fact, displacement errors in that task also reflect an impairment of the extrapersonal frame.

Sound displacement errors can be based on (1) spatial deficits, (2) unilateral neglect symptoms and (3) a combination of the two; or (4) none of the above. We interpret our data

as indicating primarily a spatial deficit; that is, the right posterior group yields a severe impairment in tasks involving both the personal and extrapersonal frames of reference. This explanation also accounts for the fact that there were no differences between the performances in the hemispaces. In those studies [7, 8] where hemispatial differences were found, there may well have been an overlap of patients with spatial deficits and symptoms of neglect. Especially in cases involving mislocalization to the opposite auditory space (alloacusis), one suspects symptoms which are related to underlying deficits in orientation and attention, but not in spatial frames of reference. Auditory extinction which is based on bilateral simultaneous stimulation falls clearly in the category of "neglect" and, just as in the case of alloacusis, it should not be considered a spatial disorder. It is important in this regard to note that symptoms of neglect have been observed after lesions in both the left and right hemispheres [19], whereas spatial deficits occur primarily after right posterior lesions.

Acknowledgements—R. M. RUFF received support for the project From The Swiss National Science Foundation, University of Zürich. The authors gratefully acknowledge Dr. MARY BRYANT ACKER of Santa Clara Valley Medical Center and Dr. WILLIAM LYNCH of the Menlo Park Veterans Administration Hospital for their assistance. The work was supported in part by Career Research Grant No. MH15214-17 to K. H. PRIBRAM.

REFERENCES

1. SEMMES, J., WEINSTEIN, S., GHENT, L. and TEUBER, H. L. Correlates of impaired orientation in personal and extrapersonal space. *Brain* **86**, 747–772, 1963.
2. POHL, W. Dissociation of spatial discrimination deficits following frontal and parietal lesions in monkeys. *J. comp. physiol. Psychol.* **82**, 227–239, 1973.
3. UNGERLEIDER, L. G. and BRODY, B. A. Extrapersonal spatial orientation: The role of posterior parietal, anterior frontal, and inferotemporal cortex. *Expl. Neurol.* **56**, 265–280, 1977.
4. BRODY, B. A. and PRIBRAM, K. H. The role of frontal and parietal cortex in cognitive processing: Tests of spatial and sequence functions. *Brain* **101**, 607–633, 1978.
5. KNUDSEN, E. and KONISHI, M. A neural map of auditory space in the owl. *Science* **200**, 795–797, 1978.
6. SANCHEZ LONGO, L. P., FORSTER, F. M. and AUTH, T. L. A clinical test for sound localization and its application. *Neurology* **7**, 655–663, 1957.
7. SANCHEZ LONGO, L. P. and FORSTER, F. M. Clinical significance of impairment of sound localization. *Neurology* **8**, 119–125, 1958.
8. KLINGON, G. H. and BONTECOU, D. C. Localization in auditory space. *Neurology* **16**, 879–886, 1966.
9. BARU, A. and KARASEVA, T. *The Brain and Learning*. Consultants Bureau, New York, 1972.
10. HEFFNER, H. and MASTERTON, R. Contribution of the auditory cortex to sound localization in the monkey. *J. Neurophysiol* **38**, 1340–1358, 1975.
11. WEINSTEIN, E. A. and FRIEDLAND, R. P. (Editors), *Advances in Neurology*, Vol. 18, Raven Press, New York, 1977.
12. DIAMOND, S. P. and BENDER, M. B. On auditory extinction and alloacusis. *Trans. Am. neurol. Ass.* **90**, 154–157, 1965.
13. HEILMAN, K. M. and WATSON, R. T. The neglect syndrome—a unilateral defect of the orienting response. In *Lateralization in the Nervous System*, S. HARNARD, R. W. DOTY, L. GOLDSTEIN, J. JAYNES and G. KRAUTHAMER (Editors), pp. 285–302. Academic Press, San Francisco, 1977.
14. KEIDEL, W. Richtungshören und Entfernungshören. In *Psysiologie des Gehörs*, W. KEIDEL (Editor), pp. 381–291, Thieme, Stuttgart, 1975.
15. HERSH, N. A. Memory for spatial relations following brain injury. Presented at the 8th Annual Meeting of the International Neuropsychological Society, 2 February, 1980, San Francisco, California, U.S.A.
16. RUFF, R. M. and PERRET, E. Auditory spatial pattern perception aided by visual choices. *Psych. Res.* **38**, 369–377, 1976.
17. RUFF, R. M. *Empirische Analysen der auditiv-räumlichen Musterwahrnehmung: Fähigkeiten hirngesunder und fokal hirngeschädigter Personen*. Juris, Zürich, 1978.
18. ALTMAN, J. A., BALONOV, L. J. and DEGLIN, V. L. Effects of unilateral disorder of the brain hemisphere function in man on directional hearing. *Neuropsychologia* **17**, 295–301, 1979.
19. HEILMAN, K. M. and VALENSTEIN, E. Auditory neglect in man. *Archs Neurol.* **26**, 32–35, 1972.

Résumé :

On a demandé à 29 malades avec lésions corticales unilatérales de localiser des stimulus auditifs simples (cadre personnel de référence) et de séparer l'espace entre deux stimulus auditifs (cadre extra-personnel de référence). Les scores d'erreurs de déplacement du groupe postérieur droit était plus élevés, et de façon cohérente, que ceux de tous les autres groupes (postérieur gauche, antérieur droit, antérieur gauche et contrôles) selon les deux cadres de références. L'analyse des erreurs suggère que l'effet postérieur droit traduit une dysfonction spatiale commune aux deux hémi-espaces plutôt qu'un déficit contro-latéral caractéristique de la négligence unilatérale.

Zusammenfassung

29 Patienten mit einseitigen kortikalen Läsionen wurden aufgefordert, einfache akustische Stimuli zu lokalisieren (persönliche Referenz) und den Raum zwischen zwei akustischen Stimuli zu halbieren (extrapersonale Referenz). Die Ergebnisse zeigen, daß Seitwärtsverlagerungen bei der Gruppe mit rechtsseitig rückwärtiger Hirnschädigung konsistent größer waren als bei allen anderen Gruppen (links rückwärtig, rechts vorne, links vorne und normale Kontrollpersonen) in beiden Bedingungen. Die Fehleranalyse legte es nahe, daß der Effekt einer rechtsseitig rückwärtigen Hirnläsion eine räumliche Funktionsstörung anzeigt, die beiden Raumhälften gemeinsam ist und nicht das kontralaterale Defizit, das für einseitige Vernachlässigung typisch ist.