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Spatial and temporal auditory processing deficits following right hemisphere infarction
A psychophysical study

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Summary
Higher auditory function in a patient was investigated following a right hemisphere infarction between the middle and posterior cerebral artery territories involving the insula. The patient complained of lack of musical appreciation and a battery of tests confirmed a dissociated receptive musical deficit in the presence of normal appreciation of environmental sounds and speech. The ability to detect continuous changes in sound frequency in the form of sinusoidal frequency modulation was preserved. There was, however, a deficit in the analysis of rapid temporal sequences of notes which could underlie his musical deficit. This case provides further evidence for the existence of amusia as a distinct form of auditory agnosia, but does not support the hypothesis that bilateral lesions are required to produce such a deficit. Unexpectedly, the patient was also found to have a deficit in the perception of apparent sound-source movement. We suggest that this deficit is analogous to the visual phenomenon of akinetopsia, and is in accord with PET work suggesting involvement of areas outside primary auditory cortex in sound movement perception. A possible common deficit in auditory temporal and spatial 'scene analysis' is discussed.

Keywords: amusia; right hemisphere; stroke; auditory psychophysics

Abbreviations: FM = frequency modulation; IAM = interaural amplitude modulation; IPM = interaural phase modulation

Introduction
The term 'auditory agnosia' was originally introduced by Freud (1891) for a deficit in perception of certain complex sounds in the absence of deafness. Early descriptions focused on the speech domain (Lichtheim, 1885) but later work has focused on whether dissociated deficits in appreciation of environmental sounds and music constitute distinct agnosias (Spreen *et al*., 1965; Peretz *et al*., 1994). Auditory agnosia is rare, and the low incidence has been attributed to an 'almost constant' association with bilateral cortical lesions (Peretz *et al*., 1994). We describe here a case of dissociated loss of musical perceptual ability following a unilateral right hemisphere lesion, which we have characterized psychophysically as a deficit in rapid auditory sequencing.

Apart from investigating the deficit in the temporal analysis of sound, we have also carried out psychophysical assessment of spatial sound analysis and found a striking deficit in the perception of acoustic properties used as cues for sound-movement analysis. This deficit has been reported as a striking deficit in its own right (Griffiths *et al*., 1996).

Case report
H.V. and age-matched controls all gave informed consent to participate in this study, which was approved by the Ethics Committee of Newcastle University. H.V. was assessed at the age of 75 years, 1 year after a watershed infarction between the right middle and posterior cerebral artery territories. He had presented with left-sided arm and leg weakness and a left homonomous hemianopia without depression of his conscious level. He was an in-patient for a period of 2 weeks,

during which time his left-sided weakness resolved. He was admitted again 3 months after the first admission after an episode of collapse and obtundation. He was found to have left visual and tactile hemi-inattention, and was also documented to be in atrial fibrillation.

During the second admission the patient complained of difficulties with the comprehension of music which he had first noticed after discharge following the initial event. He had a lifelong interest in music, having been a chorister as a boy, though with no formal training in reading or playing music. After his voice broke he continued to sing frequently in amateur light opera and shows. He had always taken pleasure in listening to music, and particularly enjoyed popular classical piano pieces. H.V. fulfils the criteria for Grison's (Grison, 1972) third level of musical culture. Following the first admission, he noticed that he could not recognize some tunes that had previously been familiar to him, such as theme tunes to television programmes he knew well. In some cases he was able to use particular clues in the tune to help him recognize it. The most effective cues were slowly changing notes, such as the long sustained brass note at the onset of the theme to the UK television programme 'Coronation Street'. Additionally, he described a difficulty recognizing piano music with which he had previously been familiar. A particular feature was that music no longer brought him any enjoyment, and actually sounded unpleasant, like 'an out of tune child's dulcima'. Listening to stereo sound no longer produced any improvement in sound quality and he was unable to distinguish stereo from mono music on his music system. He also felt that his ability to sing had been impaired. H.V. had reported no difficulty with recognizing lyrics or speech or environmental sounds. In particular, he had not noticed any difficulty with appreciation of spatial qualities of environmental sounds, though he has led a very sheltered lifestyle after the initial event. The deficit had changed little between discharge after the first admission and his assessment.

Neurological assessment 1 year after his event revealed left visual inattention and slightly brisker left limb reflexes without any weakness. He is right-handed for writing and scores 11 out of 12 correct on an Annett hand preference questionaire (Annett, 1970).

Lesion localization (Fig. 1)

Figure 1 shows MRI scans performed 4 months and 12 months after the initial event. The early scan shows diffuse mild atrophy with a region of altered T_2 signal in the right hemisphere, consistent with an infarction between the right middle and posterior cerebral artery territories. The region of altered signal extends forward along the bank of the right insula. The scan also shows several small discrete areas of altered signal in the white matter of both hemispheres. The late scan shows regional atrophy affecting the temporal lobe and altered signal in the right insula.

EEG recording showed the presence of right-sided temporal slow wave activity.

Psychological assessment (Table 1)

Premorbid Global IQ was estimated to be 122 using the National Adult Reading Test. Assessment using the revised Wechsler Adult Intelligence Scale gave a Full Scale IQ of 117, with no significant discrepancy between performance and verbal subscales. H.V. showed significant impairment in the block design and digit symbol subtests of the performance scale. The Visual Object and Space Perception Battery confirmed the presence of visiospatial deficits with failure in the dot counting and cube analysis subtests. The Western Aphasia Battery revealed no abnormality of speech perception, but a right hemisphere language battery showed scores slightly below the mean for non brain-damaged subjects but above the mean for right brain-damaged subjects.

Agnosia assessment (Table 2)

Tune recognition

Twenty-four melodies were sung by a female singer in the form 'la, la, la' using tunes that the patient and his wife knew by title. The patient was given up to two lines of the song. The melodies included simple nursery rhymes such as 'Three Blind Mice', popular songs such as 'Summertime', and well-known hymns such as 'Jerusalem'. For each tune he was scored with 0 (failed to identify), 1 (incorrect but close) or 2 (correct). The patient scored 24 out of 48 for this task.

Lyric recognition

Single-line lyrics from 10 popular tunes, again selected on the basis of those his wife said he knew well, were read out as prose and the patient asked to identify the tune by name. H.V. scored 20 out of 20 using the same scoring as tune recognition.

Environmental sound recognition

Twenty exerpts from a BBC sound effect CD (BBC CD 792) were played and the subject asked to identify the sound. Common sounds with which the patient would have been familiar were selected from the CD. These included the sounds of animals such as dogs and cows, mechanical noises such as trains and aeroplanes, and other environmental noises such as footsteps and church bells. H.V. scored 36 out of 40 compared with a mean of 39 out of 40 in age-matched controls .

Prosody

The nonsense sentence 'fi gait schong gil gosser' was said by a male speaker in a variety of manners with the patient

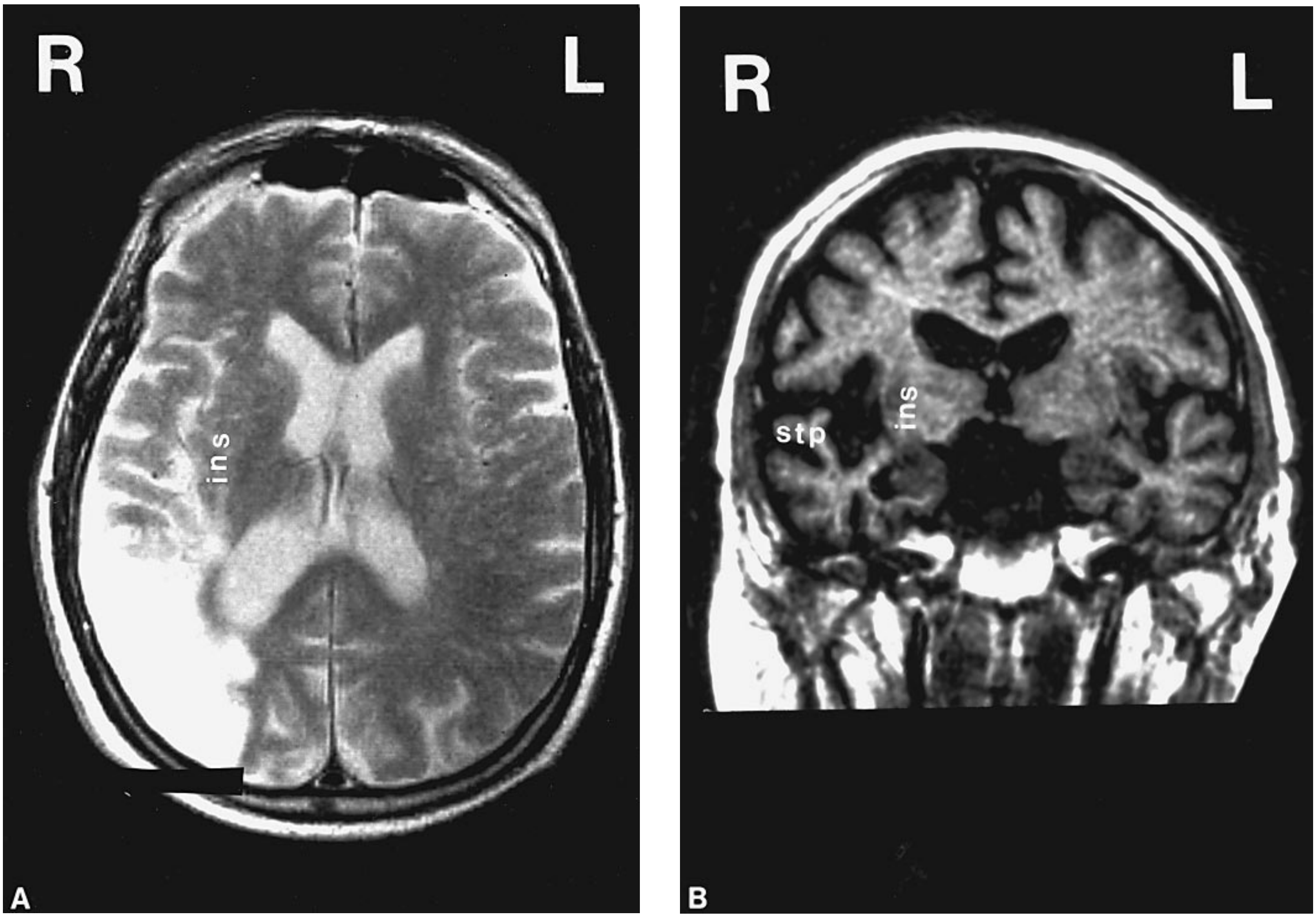

Fig. 1 MRI scans of patient H.V. carried out 4 months (**A**) and 12 months (**B**) after event. **A** is a T_2-weighted axial section showing an infarction between the right middle and posterior cerebral artery territories involving the temporal and parietal cortices and **B** is a coronal inversion recovery image showing mild right temporal lobe atrophy and involvement of the right insula in the lesion

sitting with his back to the speaker. A forced-choice response in the form of either sad, happy, angry or frightened was required. The patient made no errors.

Singing

H.V. was required to sing several popular tunes to command on being given the title alone. He did this tunefully and in key, with added vibrato. He felt, however, that his singing was not in tune. He was able to hold a sustained note with constant pitch.

Psychophysical assessment: temporal processing (Table 3A)

The assessment above defined a specific deficit in the recognition of music distinct from environmental sounds or speech. There was no expressive component in the form of an objective singing deficit and we sought to further characterize the deficit in terms of an underlying sensory or cognitive basis.

Pure tone audiogram

This showed a threshold within 20 dB of standard control data up to 4 kHz, worsening above this frequency The loss is normal for his age and would not explain the selective deficit in music perception.

Frequency modulation detection (Fig. 2)

Melody detection involves the detection and analysis of frequency changes. We considered whether a perceptual deficit in the temporal analysis of frequency and amplitude changes could account for the deficit in musical perception. The first task was, therefore, the detection of continuous frequency changes in sound in the form of frequency modulation (FM). There is evidence that deficits in the analysis of FM in sound may contribute to receptive forms of specific language impairment in children. Stefanatos and co-workers (1989) were unable to record steady-state evoked potentials to FM sound in these children. Music contains a range of frequency changes with rates that overlap with those in speech and vary with the type of music. H.V. was tested

Table 1 *Psychological assessment*

Test	Score
National Adult Reading Test (premorbid global IQ estimate)	122
WAIS-R global IQ	117
WAIS-R performance IQ	117
Picture completion	13
Picture arrangement	8
Block design	6
Object assembly	9
Digit symbol	4
WAIS-R verbal IQ	116
Information	12
Digit span	11
Vocabulary	14
Arithmetic	8
Comprehension	11
Similarities	11
VOSP	
Object perception	
Screening	20/20 P
Incomplete letters	16/20 P
Silhouettes	23/30 P
Object decision	18/20 P
Progressive silhouettes	13/20 P
Space perception	
Dot counting	3/10 F
Position discrimination	19/20 P
Number location	8/10 P
Cube analysis	5/10 F
Western Aphasia Battery Aphasia Quotient*	80/80
Spontaneous speech	20/20
Comprehension	10/10
Repetition	10/10
Naming	10/10
Right Hemisphere Language Battery	
Metaphor comprehension (picture)	8/10
Metaphor comprehension (written)	8/10
Inferences from paragraphs	8/12
Humour (written)	10/10
Semantic test	19/20
Production Emphatical Lexical Stress	10/10

*© 1982 The Psychological Corporation, Harcourt Brace Jovanovich, Inc. WAIS = Wechsler Adult Intelligence Scale; VOSP = Visual Object and Space Perception Battery (© 1991 E. K. Warrington and M. James). WAIS total scores and subscores are age-corrected with 10 representing a normal subscore. VOSP subscores are scored as pass (P) or fail (F). Right hemisphere language battery was administered by Professor R. Lesser.

with sinusoidally frequency modulated sound at low (1 Hz and 2 Hz) and high (40 Hz) modulation rates. The lower modulation rates would occur in orchestral music whilst the higher modulation rate would correspond to those occurring in certain speech sounds such as some consonant–vowel transitions. Figure 2A shows the psychophysical function for detection of 2-Hz FM for H.V. using a two-alternative forced-choice technique. The subject was required to identify in which of two intervals a 500-Hz tone was sinusoidally modulated compared with a reference interval in which the tone was unmodulated. Figure 2A shows the percentage of correct responses as a function of modulation depth at a modulation rate of 2 Hz. H.V. could perform the psychophysical task and achieved a threshold modulation index of 2.40 compared with a mean value of 1.24 (95% confidence interval 0.80–1.68) in age-matched controls. These modulation indices are equivalent to frequency changes of $\pm$4.8 Hz for H.V. and $\pm$2.48 Hz for the controls. These changes are well below a semitone. He was also able to detect FM at 40 Hz and, like normal controls, his threshold modulation index was higher than at 2 Hz.

Table 2 *Description of musical deficit*

Task	Score
Tune recognition	24/42
Lyric recognition	20/20
Environmental sound recognition	36/40 (mean control score 38/40)
Prosody	No errors
Singing	No objective deficit

Control subjects for the environmental sound recognition task were five male neurological patients with no hearing or cognitive deficit (mean age 65 years).

Although the patient's thresholds were higher than in normal controls, he was able to carry out the psychophysical tasks adequately. Few detailed auditory psychophysical studies have been carried out on patients with lesions, and the preservation of FM analysis encouraged us to look for dissociated deficits which might underlie the musical perceptual abnormality.

Tone sequence discrimination (Fig. 3)

Having demonstrated preserved detection of continuous frequency changes, we considered whether there might be a problem with the analysis of discrete tone sequences. We developed a two-alternative forced-choice version of the Seashore test (Seashore, 1919) using three tone sequences. Two pairs of three tones were presented. For one pair, the two tone sequences were identical, while in the other pair the second tone differed in frequency between the two sequences. The frequency difference was varied randomly between trials. The order of the two pairs was randomized and the patient was asked to say which interval contained the pair that was different. The percent correct discrimination was plotted as a function of the frequency change in the second note in Fig. 3. The rate at which the tones were presented was varied. A rapid sequence was chosen to be comparable with the piano sequences with which the patient had particular difficulty historically. Identification of the frequency change in the rapid sequence is a process likely to occur during early local processing of melodic pattern.

Table 3 *Psychophysical assessment*

Psychophysical task	Threshold	Control/normal value
(A) Temporal tasks		
FM 1 Hz	10.1	
FM 2 Hz	2.40	1.24 (0.80–0.68)
FM 40 Hz	0.56	
Slow tone sequence discrimination	23.1 Hz	9.6 Hz
Rapid tone sequence discrimination	Unable to achieve threshold	1.9 Hz
(B) Spatial tasks		
Right phase limen	82°	5°
Left phase limen	Unable to achieve threshold	5°
Right amplitude limen	5.9 dB	1 dB
Left amplitude limen	6.8 dB	1 dB
Sinusoidal IPM 1 Hz	11.7	
Sinusoidal IPM 2 Hz	3.0	0.31 (0.17–0.46)
Ramp IPM (180° linear phase shift to right in 800 ms)	Unable to achieve threshold	
Sinusoidal IAM discrimination 1 Hz	Unable to achieve threshold	0.075

FM = frequency modulation; IPM = interaural phase modulation; IAM = interaural amplitude modulation. Thresholds all assessed by Weibull analysis of 2AFC psychometric functions and expressed for sinusoidally modulated stimuli as the (dimensionless) modulation index. Control values for 2-Hz FM and IPM are expressed as mean of threshold for six naive controls (mean age 60 years, 3M 3F, three normal and three with peripheral neurological disorder) with the 95% confidence interval. Normal values for phase and amplitude limens based on (Blauert, 1983). Tone sequence thresholds correspond to the frequency change in the second note of a three-tone sequence at threshold (*see* text). Carrier frequency for all tests using modulated sound 500 Hz. Sensation level 60 dB.

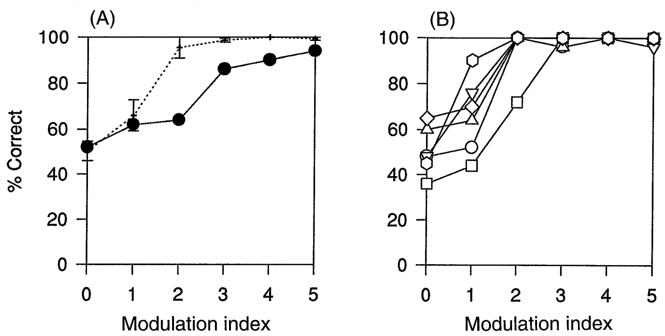

Fig. 2 Detection of sinusoidal FM as a function of modulation depth expressed as modulation index for (**A**) subject H.V. (closed symbols) and (**B**) six naive controls of mean age 60 years (open symbols). The mean and standard error of the normal data is also plotted on the graph for H.V. using a dotted line. Detection expressed as percent correct with two-alternative forced-choice testing with points representing the mean of at least 50 trials (H.V.) or 25 trials (controls). Sound presented binaurally over headphones at sensation level of 60 dB. Modulation rate 2 Hz and carrier frequency 500 Hz.

Figure 3 shows that H.V. was able to discriminate a change in the frequency of the second note when the rate at which the tones were presented was slow. This demonstrates that he can discriminate different tone frequencies in the sequence. The frequency change that he could detect in the slow tone sequence was approximately double that of the normal control, though still well below a semitone and compatable with appreciation of much western music. In contrast to the control subject, he performed at chance level for the rapid transitions.

Psychophysical assessment; spatial processing (Table 3B)

The sequencing test above confirmed a deficit in temporal processing. We went on to explore whether deficits also existed in auditory spatial processing.

Auditory lateralization

Fixed lateralization was tested using amplitude and phase cues for sounds presented over headphones. H.V. could reliably indicate the side of a monaural stimulus, and reported a fused sound image for binaural stimuli. His threshold difference limen for interaural amplitude differences was 5.9 dB at 500 Hz for an apparent sound displacement to the right, and 6.8 dB to the left, which is a level at which trained normal listeners, whose thresholds are ~1 dB, report approximately half of the maximum possible lateral displacement (Blauert, 1983). The phase-difference limen was 82° at 500 Hz for apparent sound displacement to the right, below the value producing maximum lateral displacement in normal listeners (Blauert, 1983). A phase-difference limen could not be reliably demonstrated for apparent displacement to the left. These tests confirm the presence of a fixed amplitude and phase lateralization deficit

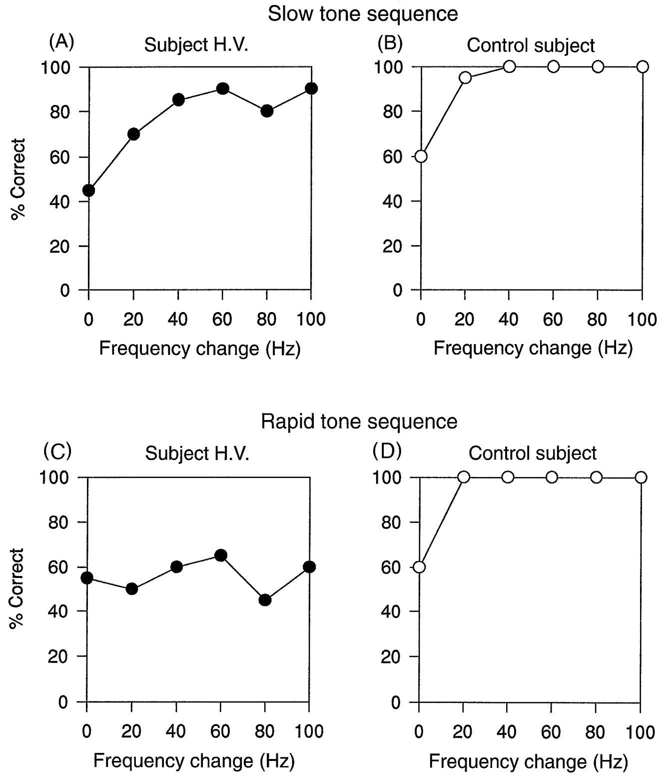

Fig. 3 Discrimination of tone sequence for H.V. (closed symbols) and a stimulus-naïve control subject (open symbols) plotted as a function of the difference in the frequency of the second tones in one of two pairs of three tone sequences. Discrimination represents the percentage correct identification of which pair of three tone sequences contained a different second note. In the slow tone sequence discrimination task (Fig. 2A and B) three notes each of duration 200 ms were presented over an interval of 650 ms. In the rapid tone sequence task (Fig. 2C and D) three notes of duration 85 ms were presented over 260 ms. The three frequencies before alteration of the second were 500, 700 and 400 Hz. Each point represents the mean of 20 trials.

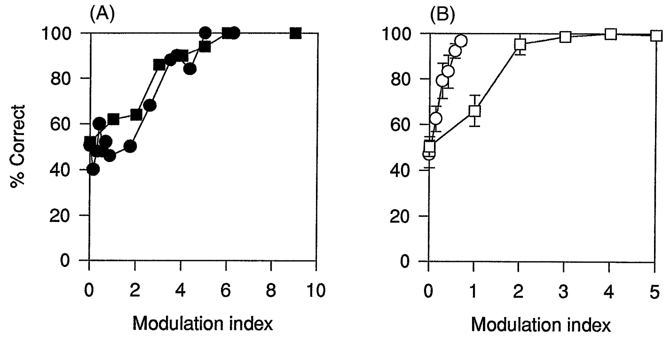

Fig. 4 (**A**) Detection of IPM for subject H.V. (closed circles) compared with the detection of the equivalent FM (closed squares). (**B**) IPM detection (open circles) and equivalent FM detection (open squares) for control subjects. H.V. failed to show the lower threshold for IPM detection compared with FM detection shown by the controls and perceived both stimuli as pitch changes due to the FM. Each point represents the mean of 50 trials for H.V. and 25 trials for the normal controls. Modulation rate 2 Hz, carrier frequency 500 Hz and sensation level 60 dB.

that was most marked for apparent sound displacement to the left.

Apparent sound-movement tasks

Apart from fixed lateralization, we analysed the detection of changes in sound phase and amplitude between the ears which would be produced by the movement of sounds in space. Such changes are important cues for the detection of sound movement, though movement of environmental sound in space also produces changes at either ear alone which may be important in the detection of sound movement (Strybel *et al.*, 1989). The detection of changing differences in both phase and amplitude between the ears was investigated in H.V. using stimuli presented over headphones.

Sinusoidal interaural phase modulation (IPM) was used in which the phase at one ear was advanced as the phase in the other was delayed at a low modulation rate of 2 Hz. At the carrier frequency of 500 Hz, these phase changes are equivalent to those used to detect a sound moving in an arc in front of the head, and have been used in previous studies to investigate IPM detection in normals (Green *et al.*, 1976, 1995). Strikingly, H.V. was completely unable to detect this stimulus as a sound movement at any modulation depth. If the modulation depth was increased sufficiently H.V. was able to detect the modulation; he detected the stimulus as a pitch change without any percept of sound movement. His threshold for detection of IPM (modulation index of 3.04) was similar to his threshold for detecting FM (modulation index of 2.40) (Fig. 4A). In contrast, normal subjects are more sensitive to the IPM compared with the FM, by a mean factor of 4.7 (95% confidence interval for six control subjects was 2.8–6.8 times) (Fig. 4B). The thresholds for H.V. and the normal controls correspond to maximum interaural phase disparities of 348° and 36°, respectively. The deficit was also present at lower modulation rates (1.0 Hz and 0.5 Hz), and H.V. was again unable to distinguish the IPM from the FM. The deficit in IPM detection at 2 Hz was still present when a 60° mean phase difference was used to move the sound into the right and left auditory fields. This was done in order to see if the deficit in sound movement still occurred when the sound was 'centred' in his better auditory hemifield.

Sound movement detection was also assessed using sinusoidal interaural amplitude modulation (IAM) similar to the IPM. In this stimulus, the amplitude was increased at one ear at the same time as it was decreased at the other. Interaural amplitude changes of this sort are also produced by sound movement in an arc in front of the head. Unlike the case for IPM, the IAM threshold for normal listeners is the same as the threshold for a control condition where the amplitude changes are matched at the two ears, binaural amplitude modulation (AM). However, normal listeners perceive sound movement above threshold with the IAM but not the AM task (Fig. 5B). In contrast, H.V. was unable to discriminate IAM from AM even at a modulation index of

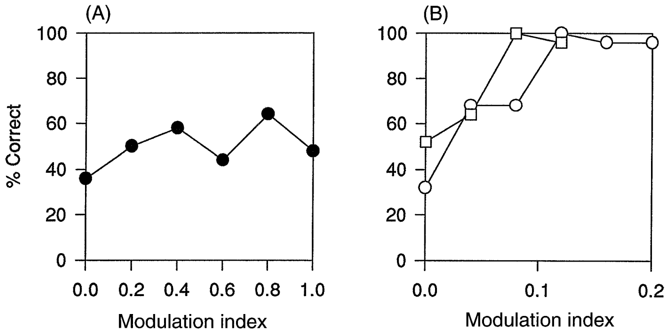

Fig. 5 Discrimination of IAM from binaural AM for (**A**) subject H.V. (closed circles) and (**B**) control subjects (open circles). A two-alternative forced-choice task was used in which the subject had to distinguish which of two intervals produced a percept of lateralized movement. Normal controls perceive the IAM as lateralized movement above a threshold value which is similar to their thresholds for IAM and AM detection using a pure tone comparison condition. H.V. failed to detect the movement cue even at a modulation index of 1.0, corresponding to movement of the apparent sound source between monaural presentation at either ear. Each point represents the mean of 50 trials for H.V. and 25 trials for the two controls. Modulation rate 2 Hz, carrier frequency 500 Hz and sensation level 60 dB.

1.0, corresponding to the extreme case of movement between presentation at either ear alone. This was also the case at the lower modulation rates of 1.0 Hz and 0.5 Hz.

Ramp stimuli simulating a sound source moving in one direction along an arc around the head were also used, in which interaural phase and amplitude differences were varied. H.V. was unable to perceive movement from large swings in the phase of a 500 Hz tone (180° over 800 ms), or from similar large amplitude swings, stimuli that produce a strong sensation of movement in normal controls. These ramp swings were from the midline to the right side.

Discussion

In this study a dissociated deficit has been described in the perception of music without any deficit in environmental sound perception or classical language deficit. This provides support for the hypothesis that distinct forms of non-verbal auditory agnosia exist (Peretz *et al.*, 1994). This case demonstrates several differences from the previously carefully reported cases of Peretz with dissociated musical deficits. First, although the patient complained of a deficit in musical perception, his objective performance in tune recognition was not as impaired as in the previous cases. Secondly, the deficit is more clearly dissociated than the previous cases, both of whom exhibited clear speech disturbances at one point (though these resolved) and one of whom demonstrated significant expressive musical deficit for singing. Thirdly, we have demonstrated an associated deficit in the analysis of spatial sound in the form of a deficit in the detection of sound properties used to detect sound movement. This is a striking observation in its own right. These deficits have been demonstrated after a single neurological episode affecting one hemisphere, unlike the previous cases, both of which occurred after sequential right then left hemisphere events.

Psychophysical nature of the underlying temporal auditory deficit

In this study we have addressed the question of whether a failure to analyse acoustic features might underlie the musical deficit. Previous studies have successfully used a music-based approach to define deficits and subdivide amusia, but we feel that it is important in any such case to look for a general deficit in auditory temporal processing. The three-tone sequences, that the patient had difficulty analysing cannot be reasonably defined as melody. However, melody recognition depends on more complex variations of pitch with time, which we would also expect to be impaired. The deficit in the detection of changes in tone frequency over short periods of time might be expected to produce deficits in 'local' pitch information processing which may correspond to a gestalt process in music. Right hemisphere processing, however, has been previously linked to analysis of 'global' features (Peretz, 1990). The tone sequence task contained a perceptual component, but also an auditory working memory component by virtue of the sequence-comparison task used, and it is possible that the deficit reflected a memory, as well as a perceptual impairment. However, the deterioration in performance with decreasing interstimulus interval would not be predicted by simple memory deficit models.

The presence of a deficit in low-level sequencing raises the question of why the deficit is specific to music. The deficit in the discrimination of rapid tone sequences occured at a presentation rate that also occurs in speech and environmental sounds. The acoustic structure of speech, however, is very different to the tone sequences used here. Speech does contain abrupt changes such as voice onsets and plosives, but also contains continuous changes in frequency and amplitude, for example diphthongs. Previous work suggests that deficits in the analysis of continuous frequency change produce deficits in speech comprehension (Stefanatos *et al.*, 1989; Tallal *et al.*, 1993). In H.V., the detection of continuous frequency change was preserved. We suggest, then, that a deficit in auditory-temporal processing can exist which produces dissociated deficits in the analysis of speech, environmental sounds and music by virtue of their different acoustic structure. A selective deficit in the recognition of music, speech or environmental sounds does not, therefore, necessarily indicate the absence of an acoustic deficit. Cases of such selective deficits do not support the existence of distinct musical and speech modes of perception, at the acoustic level (for discussion of a possible specific speech mode of analysis, *see* Liberman *et al.*, 1967; Schouten, 1980). It is possible that similar deficits to that demonstrated here are not uncommon, but are not manifest due to the patient's acoustic environment; this patient became symptomatic largely because of his interest in piano music.

Studies of tone sequence discrimination in a population of temporal lobectomy patients (not selected for musical deficit) support the concept of a general involvement of the right hemisphere in auditory sequencing (Milner, 1962).

Psychophysical nature of the spatial auditory deficit

It is perhaps surprising that previous studies of amusia have not looked at spatial sound analysis, in view of the association of amusia with superior temporal lobe damage that can produce both auditory sequencing deficits (Diamond and Neff, 1957; Dewson *et al*., 1970; Cowey and Weiskrantz, 1976; Colombo *et al*., 1990) and auditory spatial deficits (Neff *et al*., 1956; Jenkins and Merzenich, 1984; Altman and Kalmykova, 1986) in animals. In this study a deficit in the lateralization of fixed sounds has been demonstrated as in previous studies of human right hemisphere lesions (Bisiach *et al*., 1984; Pinek and Brouchon, 1992). More strikingly, the subject was unable to perceive IPM as sound movement, which has not been previously demonstrated (Green *et al*., 1995). A deficit in IPM could be produced by an impairment in the encoding of interaural time differences, for example at the brainstem (Griffiths *et al*., 1996), but the additional presence of a complete deficit in detecting IAM as sound movement suggests this to be a central deficit. This deficit is analogous to the specific visual motion deficit (Zihl *et al*., 1983; Rizzo *et al*., 1995) which has been given the name akinetopsia (Zeki, 1993). The patient was asymptomatic from the point of view of the auditory motion deficit, which may be due to the use of other spatial cues to detect movement such as vision and pinna effects, and due to his sheltered auditory environment after the stroke.

A possible unifying mechanism for the temporal and spatial deficits might involve a sequencing deficit in the temporal and spatial domains, or a combined memory deficit for acoustic feature or place. The former may be involved in auditory 'scene analysis' (Bregman, 1993). However, previous studies of auditory agnosia have not looked at spatial sound analysis; it will be of considerable interest to see if the temporal and spatial deficits dissociate in other cases.

Anatomical correlates; temporal sequencing

Electrical stimulation of the human cortex (Penfield and Perot, 1963) suggested that complex auditory analysis occurs in the superior temporal lobe outside the human primary auditory area, A1, located in Heschels gyrus. Detailed animal neurophysiology has demonstrated different response properties of neurones in A1 and adjacent auditory association cortex (Merzenich and Brugge, 1973; Brugge and Reale, 1985). Animal studies have also demonstrated that lesions of the superior temporal cortex can produce deficits in the analysis of tone sequences in the cat (Diamond and Neff, 1957) and monkey (Dewson *et al*., 1970; Cowey and Weiskrantz, 1976). These have been attributed to deficits in temporal pattern coding, though auditory memory is affected by similar lesions (Colombo *et al*., 1990). Such deficits can be produced by lesions on either side in the monkey, but are more marked for bilateral lesions (Dewson *et al*., 1970). The animal work should only be extrapolated to man with caution, and studies on temporal lobectomy patients suggest a particular temporal processing deficit for right-sided lesions (Milner, 1962; Shankweiler, 1966; Zatorre and Halpern, 1993). Consistent with this, PET has been used recently to demonstrate the involvement of right superior temporal cortex in the perceptual analysis of melodies (Zatorre *et al*., 1994). H.V. has a lesion involving the supero-posterior temporal lobe on the right which is consistent with these previous studies.

The perceptual deficits we have defined may be sufficient to explain the musical perceptual deficit, without recourse to explanations based on specific cognitive mechanisms for music. The presence of a deficit in tone sequencing following a right-hemisphere lesion is consistent with animal and human lesion studies. Earlier debate about the cerebral location of musical analysis based on lesion studies may have been partly hindered by the study of subjects with varying degrees of musical competence and training (for discussion, *see* Peretz, 1990), but also by the inclusion of subjects with deficits at different levels in the music comprehension pathway. This emphasizes the importance of adequate psychophysical definition of processing deficits.

Anatomical correlates; auditory movement analysis

Like the psychophysics of auditory movement analysis, the physiological basis of central auditory movement analysis is also imperfectly understood. Animal neurophysiology has demonstrated neurons in the primary auditory cortex, A1, which respond preferentially to sound which moves or simulates sound movement in space (Ahissar *et al*., 1992; Stumpf *et al*., 1992) and lesions including A1 can impair auditory movement discrimination (Altman and Kalmykova, 1986). We are not aware of any recording work in cortical areas other than A1, but a PET study on normal human subjects has suggested the involvement of areas outside of A1 on the right during analysis of sound containing changing interaural phase (Griffiths *et al*., 1994). One area activated was the right insula, which is involved in the lesion here. The analysis of sound movement in the insula could occur either directly, via brainstem and medial geniculate projections which have been demonstrated by tracer studies (Mesulam and Mufson, 1985), or via cortico-cortical projections from A1. This is an analogous scheme to the organization of V5 (e.g. ffytche *et al*., 1995) though the multi-modal nature of both parts of the insula would make it rather different in character from V5. A region adjacent to right posterior cingulate was also activated in the PET study, and work on behaving monkeys has suggested a role for posterior cingulate in spatial analysis, in the visual domain (Vogt *et al*., 1992; Olson *et al*., 1993). The lesion also involves the right parietal cortex, a region involved in the analysis of visual and auditory space (Andersen, 1995), and in which lesions in humans can give rise to a deficit in fixed spatial analysis (Pinek and Brouchon, 1992).

We will not address the question here of whether a lesion of a common area involved in temporal and spatial analysis could underlie the deficit. The question of a common psychophysical mechanism needs to be addressed first, and this patient has a large lesion involving several candidate areas. This case does suggest, however, that the deficits observed are due to lesions in areas outside of the primary auditory cortex, which is only affected by mild regional atrophy.

Conclusion

Using a psychophysical approach we have demonstrated a causative deficit in auditory sequencing for a patient with a dissociated receptive musical deficit, and an associated deficit in sound movement detection. These psychophysical deficits are consistent with predicted effects of the right hemisphere lesion expected from animal and human lesion studies of tone sequencing, and functional imaging studies on sound movement detection. We do not feel a specific higher musical processing deficit is needed to explain the problem, though we do not deny that this may exist in other cases. The case demonstrates that a right unilateral lesion can produce a dissociated amusia, and the site of the lesion supports the suggestion that human analysis of higher sound properties involved in auditory temporal and spatial pattern detection occurs outside the primary auditory cortex. We stress the importance of basic psychophysical assessment for auditory processing deficits, and suggest spatial analysis in future cases of amusia might help shed light on common mechanisms.

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