

Central auditory processing disorders

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Central auditory processing is essential for the perception of speech, environmental sounds and music, and may be deranged in two ways. Lesions of the ascending auditory pathway or cortex can produce deficits. Abnormal activity of the central auditory system is becoming increasingly recognized in disorders such as tinnitus. Recent work has investigated sound processing by the unconscious brain; such investigations may provide a 'window' into residual brain function and prognosis.

Curr Opin Neurol 15:31–33. © 2002 Lippincott Williams & Wilkins.

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Current Opinion in Neurology 2002, 15:31–33

Abbreviations

EEG	electroencephalogram
MEG	magnetoencephalogram
fMRI	functional magnetic resonance imaging
MMN	mismatch negativity response
PET	positron emission tomography

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1350-7540

Introduction

Central auditory processing is the processing of complex sounds after the initial transduction of sound energy into neural activity in the cochlea. Essentially, the process might be characterized as the representation of auditory patterns in frequency or time that are used to identify and localize sound objects. The work discussed in this paper concentrates on such pattern processing before the patterns acquire meaning (semantic processing). Central auditory processing of spectral and temporal patterns first occurs in the cochlear nuclei, whereas the processing of binaural cues for spatial analysis first occurs as early as the superior olives. On the other hand, processing mechanisms for higher-order patterns in sound occur well beyond the primary auditory cortex in medial Heschl's gyrus in the superior temporal plane. Such widely distributed processing mechanisms can be affected by a number of brain processes.

Disruption of central auditory processing may lead to deficits in the perception of speech, environmental sounds or music, in the absence of deafness (auditory agnosia). Acquired agnosia as a result of central lesions is well established [1], but recent work suggests the existence of a developmental form of agnosia. Apart from deficits in auditory processing, recent work has shed light on 'positive' central auditory phenomena in which central auditory mechanisms are abnormally active. Other studies have assessed central auditory processing during states of altered consciousness using the electroencephalogram (EEG) and functional imaging. This raises the exciting possibility that the processing of complex sound may provide a 'window' into the brain function of the unconscious, which is of possible prognostic significance.

Deficits in central auditory processing as a result of brain disorder

The assessment of auditory agnosia caused by central brain lesions can be carried out at a number of levels. Perceptual forms of agnosia are often but not invariably associated with bilateral lesions of the superior temporal lobe. Psycho-acoustic assessment to demonstrate deficits in the processing of sound patterns is at an early stage, but a new battery designed for neurological patients allows the systematic assessment of temporal processing, including amplitude and frequency modulation [2]. This approach complements the assessment of sound pattern at the level of speech, environmental sounds and music. In the case of music, the systematic assessment of agnosia using stimuli appropriate for naïve subjects was

pioneered by Peretz *et al.* [3]. A particularly striking case of agnosia identified by Peretz (I.R.) has been found to have deficits at the level of patterned sound [4] and at the level of music [5]. Interestingly, I.R. is still able to detect the emotion in music despite an almost total loss of musical recognition [5,6].

The term 'deaf hearing' has been suggested for a phenomenon described in a patient with bilateral destruction of the auditory cortices [7]. The patient acted as if he was deaf but could detect the onset and offset of sounds with attentional effort. This phenomenon is similar to blindsight, in that the recognition of a sensory feature is still possible after destruction of the primary cortex, but different in that the patient reported was aware of his performance in the sensory test. This case highlights the severe auditory attentional deficits that can occur as a result of bilateral lesions of the auditory cortices. Functional imaging demonstrated activation caused by sound in the middle temporal gyri and cerebellum outside the normal area of activation caused by sound stimuli.

A developmental disorder of musical perception has just been systematically described for the first time [8]. Subjects were reported with lifelong abnormal musical perception without a history of neurological event. Two-alternative forced-choice testing showed striking deficits in musical perception. It will be of considerable interest to see how common this disorder is in the population, at what level the deficit lies in these individuals and what brain correlates can be demonstrated. In the converse situation, in which individuals have good musical skills, interesting brain correlates have been described, such as structural asymmetry in the planum temporale associated with absolute pitch [9].

'Positive' disorders of central auditory processing

Tinnitus is a disorder that may be associated with abnormal activity in the ascending auditory system or auditory cortex. Using positron emission tomography (PET), Lockwood and colleagues [10*,11] studied patients with tinnitus evoked by facial or eye movements, a condition that allows individuals to 'switch' the tinnitus on and off to allow a demonstration of activity associated with the percept. Gaze-evoked tinnitus was originally thought to be rare, even among patients with eighth nerve section for acoustic neuroma, but has turned out to be more common in this group than was previously thought. The mechanism is likely to involve ephaptic transmission in the brainstem. Unilateral activation of the auditory cortex or auditory pons without auditory input was demonstrated in these patients. This pattern would not be seen with actual auditory input even to one ear, because of the

incomplete decussation of the auditory pathway. Lockwood and colleagues [10*,11] argued that central tinnitus associated with abnormal activity of the auditory cortex or pons might be likened to the phenomenon of 'alien limb' in amputees. A recent functional magnetic resonance imaging (fMRI) study [12*] examined the basis for tinnitus in more typical tinnitus patients who had not undergone cerebello-pontine angle surgery. The use of individuals who experienced lateralized tinnitus in the absence of hearing loss simplified interpretation. Indirect inference about abnormal activity in the inferior colliculus was made on the basis of less increase in activity with sound stimulation. This effect might be caused either by masking of abnormal central activity by external sound or saturation effects when the effect of central activity and external stimulation is combined. In either case, the results support abnormal activity in the central pathway in this more common form of tinnitus.

Another clinical study using PET [13] suggested that the condition of musical hallucinations can also be caused by abnormal central auditory activity. This disorder may occur in individuals who are in middle to later life with moderate to profound hearing loss. More rarely, the condition can also occur as a result of central lesions, epilepsy or psychosis. In the common form, individuals typically experience melodies that were previously familiar, and it has been argued on the basis of the phenomenology that the condition is caused by amplification of a normal mechanism for musical perception and imagery. In support of this, functional imaging of areas in which activation increased with the severity of the hallucination demonstrated a similar network to that shown in normal hearing individuals actually listening to sound sequences. This bilateral network includes the planum temporale and frontal operculum.

Central auditory processing during states of altered consciousness

An interesting recent development in the investigation of central auditory processing has been the measurement of brain responses to acoustic stimuli in individuals with altered consciousness. In the physiological case of sleep, Portas *et al.* [14*] carried out a combined EEG and fMRI study, which showed that the thalamus, auditory cortex and caudate are activated by sound during non-rapid eye movement sleep in a similar manner to the activations during wakefulness. Sounds in the form of pure tones and the subjects' own names were used, and a secondary analysis seeking areas showing greater differences in activity between the name and pure tone during sleep identified the left amygdala and prefrontal cortex. This may be the brain basis for the selective awakening of individuals by

sounds with affective significance (such as their own name or their baby's cry).

In the case of pathological states, evidence suggests that processing in the pathway up to and including the auditory cortex can occur during coma and the vegetative state. In coma caused by a variety of causes, EEG-evoked potential studies suggested that the early brainstem responses to click are often preserved, but that their absence correlates with poor survival [15–18]. Recent studies have looked at the processing of more complex sound patterns in the form of oddball trains (a random mixture of rare 'oddball' sounds with a different pitch or duration to more common sounds). Comparison of the EEG responses to oddballs and reference stimuli showed a mismatch negativity response (MMN) with a latency of approximately 130 ms; this response is likely to arise from the non-primary auditory cortex [19]. Studies of patients in comas [20*,21*] showed that the presence of MMN can correlate with a good prognosis at the level of functional outcome. The responses are, however, rather fickle, and the absence of the MMN response is difficult to interpret.

A PET study of five patients in the vegetative state as a result of diffuse hypoxia [22*] showed activation in the primary auditory cortex in the region of Heschl's gyrus and in the planum temporale behind in response to click stimuli, despite decreases in resting metabolism. These activations are similar to normal control PET data from this experiment and MEG studies of the normal click response [23]. Less activation in response to clicks was observed in the posterior cortex in the temporoparietal junction in patients compared with controls, and an analysis of functional connectivity showed a functional disconnection between the posterior superior temporal lobe and the inferior parietal lobule, anterior cingulate and hippocampus. This suggests a deficit in connections beyond the auditory cortices in these patients. Auditory stimuli thus have the potential to probe the integrative function of the brain needed for normal conscious functioning, and a challenge for the future is to develop auditory stimuli and techniques that can probe this integrative function in routine clinical settings.

Conclusion

Recent work has further characterized acquired deficits in central auditory processing, and suggested a new form of developmental agnosia. Aberrant activity within the central auditory system is becoming increasingly recognized. The use of sound stimuli to probe the unconscious brain is a developing area, with the potential to define distributed brain mechanisms relevant to functional outcome from coma and the vegetative state.

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