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Electrophysiological and behavioural processing of complex acoustic cues

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HIGHLIGHTS

- Cortical auditory evoked responses are sensitive to the encoding complex acoustic cues important for pitch perception.
- Combined approach using behavioural and electrophysiological tests are useful to measure pitch processing in individuals with normal hearing and sensorineural hearing loss.
- Individuals with sensorineural hearing loss have reduced sensitivity to complex acoustic cues compared to controls.

ABSTRACT

Objectives: To examine behavioural and neural processing of pitch cues in adults with normal hearing (NH) and adults with sensorineural hearing loss (SNHL).
Methods: All participants completed a test of behavioural sensitivity to pitch cues using the TFS1 test (Moore and Sek, 2009a). Cortical potentials (N1, P2 and acoustic change complex) were recorded in response to frequency shifted (deltaF) tone complexes in an 'ABA' pattern.
Results: The SNHL group performed more poorly than the NH group for the TFS1 test. P2 was more reflective of pitch differences between the complexes than N1. The presence of acoustic change complex in response to the TFS transitions in the ABA stimulus varied with deltaF. Acoustic change complex amplitudes were reduced for the group with SNHL compared to controls.
Conclusion: Behavioural performance and cortical responses reflect pitch processing depending on the salience of pitch cues.
Significance: These data support the use of cortical potentials and behavioural sensitivity tests to measure processing of complex acoustic cues in people with hearing loss. This approach has potential for evaluation of benefit from auditory training and hearing instrument digital signal processing strategies.

1. Introduction

The impact of sensorineural hearing loss (SNHL) is particularly noticeable while listening to speech in noisy backgrounds (Festen and Plomp, 1990; Gordon-Salant, 1985). Even when amplification is provided, a persistent complaint of hearing aid users is difficulty understanding speech in noise (Kochkin, 2007). A listener's ability to extract cues for pitch perception is an important factor for successful communication in background noise. The main acoustic cues contributing to the streaming of signals in noise are the

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Abbreviations: CAEPs, cortical auditory evoked potentials; Cz, central zero; Fz, frontal zero; SNR, signal to noise ratio; ENV, envelope; TFS, temporal fine structure; NH, normal hearing; SNHL, sensorineural hearing loss; TEN, threshold equalising noise; ANOVA, analysis of variance.

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slowly varying temporal envelope (ENV) and the rapidly varying temporal fine structure (TFS) (Moore, 2014). While ENV cues are primarily important for speech perception in quiet, TFS cues are important for speech perception in noise, sound localisation, music perception, and pitch perception (Moore, 2008). Recent studies using psychophysical measures have shown that listeners with SNHL have reduced ability to benefit from TFS information while the perception of ENV information is well preserved (Hopkins et al., 2008; Lorenzi et al., 2006, 2009; Moore et al., 2006b). It is thought that this lack of TFS sensitivity might account for poor speech understanding in noise and music perception in individuals with SNHL. Although most studies report group differences in the ability to make use of TFS cues between people with normal hearing (NH) and those with SNHL, performance varies greatly within each group, despite similar audiometric configurations (Hopkins et al., 2008; Hopkins and Moore, 2010; Strelcyk and Dau, 2009).

The processing of pitch-related acoustic cues can be investigated using objective cortical auditory evoked potentials (CAEPs) that reflect differential neural encoding of stimulus acoustic cues. CAEPs elicited using brief stimuli (clicks, tone bursts) consist of three peaks (P1–N1–P2) that occur within 300 ms (ms) after stimulus onset (Martin et al., 2008). N1 is a transient response evoked by short-term envelope change (Onishi and Davis, 1968). P2 is sensitive to attention and stimulus parameters such as intensity and pitch (Crowley and Colrain, 2004), as well as musical experience (Seppänen et al., 2012). CAEPs elicited using complex long-duration stimuli with acoustic changes within the stimulus have multiple N1–P2 complexes evoked by the stimulus onset, the acoustic change, and the stimulus offset (Digeser et al., 2009; Martin et al., 2008; Ostroff et al., 1998; Sharma et al., 2000). Cortical responses encoding the change in an ongoing stimulus have been described as the acoustic change complex (Martin and Boothroyd, 1999). Acoustic change complexes have been recorded in response to both speech and non-speech sounds (Martin and Boothroyd, 1999; Ostroff et al., 1998), as well as to acoustic changes within a speech sound such as formant frequency transition within a vowel (Martin and Boothroyd, 2000). The acoustic change complex shows distinct neural patterns in response to changing speech syllables in adults using hearing aids and cochlear implants (Friesen and Tremblay, 2006; Tremblay et al., 2006). The acoustic change complex was used in the current study to show differential neural encoding of complex acoustic cues important for pitch processing. Establishing a link between electrophysiological and behavioural TFS measures may help future research determine optimal hearing aid settings for robust speech perception in noise. Moreover, it would be useful to determine pitch-related enhancements in cortical responses corresponding to specific stimulus acoustic cues.

Sensitivity to changes in pitch cues has been extensively studied using complex tones (Hopkins and Moore, 2007; Moore and Moore, 2003; Schouten et al., 1962). Complex tones resemble the sounds of vowels in normal speech and sounds produced by many musical instruments. Pitch extraction of a complex tone primarily depends on the harmonic resolvability and this in turn depends on the number in the harmonic sequence, N, rather than the absolute F0 (Houtsma and Smurzynski, 1990; Plack et al., 2005). Pitch discrimination is usually good when filtered complex tones contain only low-numbered harmonics, which may be resolved at the level of the cochlea, i.e. $N < 8$, due to access to both place (spectral) and TFS (temporal) cues. Complexes with only high-numbered harmonics (partially resolved), with N between 8 and 12 harmonics produce a weaker pitch percept which might be conveyed solely based on TFS information (Bernstein and Oxenham, 2003; Moore et al., 2006a). Hence, pitch perception depends on the salience of pitch cues. Most cochlear implants have only a small number of channels and thus TFS cues important for pitch perception are typically not successfully encoded by these instruments (Wilson and Dorman, 2008). On the other hand, although hearing aids restore audibility (ENV cues) and convey TFS cues, SNHL listeners cannot utilise TFS cues for pitch and music perception (Chasin and Russo, 2004). The current study aimed to increase understanding of behavioural pitch discrimination abilities in NH adults and adults with either mild or high frequency SNHL, using low- and high-numbered harmonic complex tones. Behavioural results were compared to the neural encoding of pitch cues measured using the acoustic change complex. This combined approach using behavioural and electrophysiological measures will help determine stimulus acoustic cues dominant for pitch processing at the level of cortex.

2. Materials and methods

2.1. Participants

Ten young adults with NH aged 21–36 years (mean: 29 years, SD 4.6) and 9 adults with either mild or high frequency SNHL aged 20–55 years (mean: 37 years, SD 11.8) were recruited. Although there is a considerable variation in the age of participants, age effects on CAEPs are commonly reported when results are compared between young adults and people aged 60+ (Harris et al., 2009; Kim et al., 2012; Tremblay et al., 2004). Picton et al. (1984) who studied CAEPs across a broad age range from 20 to 79 years found no age effects for P1, N1, and P2 latencies and amplitudes. All NH adults were right handed, English speakers, with normal Type A tympanograms with present acoustic reflexes. Audiometric thresholds of the listeners with SNHL are shown in Table 1. All participants in the SNHL group were right handed, English speakers and had air-bone gaps of less than 15 dB and normal tympanograms. Audiograms for the NH and SNHL participants are shown in Fig. 1. Written informed consent was obtained from all participants before testing. The study was approved by the University of Auckland Human Participants Ethics Committee.

2.2. Stimulus conditions

Processing of pitch differences were tested for two stimulus conditions with strong (N6) and weak pitch salience (N12). Stimuli consisted of bandpass filtered harmonic and frequency shifted (deltaF) complex tones. Pitch processing was separately investigated using both spectral excitation and TFS cues (N6 condition) and TFS cues alone (N12 condition). Here N is used to refer to the harmonic number corresponding to the centre of the bandpass filter through which all tones were passed. Spectrograms of the stimuli are shown in Fig. 2. Values of the fundamental frequency (F0) and number of components in the passbands were 200 Hz and 3 for the N6 stimulus condition and 100 Hz and 5 for the N12 stimulus condition, respectively. The filter centre frequency

Table 1
Audiometric thresholds measured for the right ear for each SNHL participant.

Listener	Frequency (kHz)					
	0.25	0.5	1	2	4	8
SNHL1	15	10	10	35	55	65
SNHL2	5	5	10	10	30	35
SNHL3	10	15	15	20	60	80
SNHL4	10	15	10	25	35	45
SNHL5	15	15	15	15	35	30
SNHL6	20	30	10	10	5	5
SNHL7	10	15	5	25	25	25
SNHL8	10	10	30	10	5	5
SNHL9	30	30	35	45	35	55