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Research paper

Human auditory steady-state responses to changes in interaural correlation

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Abstract

Steady-state responses were evoked by noise stimuli that alternated between two levels of interaural correlation ρ at a frequency f_m. With ρ alternating between +1 and 0, responses at f_m dropped steeply above 4 Hz, but persisted up to 64 Hz. Two time constants of 47 and 4.4 ms with delays of 198 and 36 ms, respectively, were obtained by fitting responses to a transfer function based on symmetric exponential windows. The longer time constant, possibly reflecting cortical integration, is consistent with perceptual binaural "sluggishness". The shorter time constant may reflect running cross-correlation in the high brainstem or primary auditory cortex. Responses at $2f_m$ peaked with an amplitude of 848 ± 479 nV ($f_m = 4$ Hz). Investigation of this robust response revealed that: (1) changes in ρ and lateralization evoked similar responses, suggesting a common neural origin, (2) response was most dependent on stimulus frequencies below 1000 Hz, but frequencies up to 4000 Hz also contributed, and (3) when ρ alternated between [0.2–1] and 0, response amplitude varied linearly with ρ, and the physiological response threshold was close to the average behavioral threshold ($\rho = 0.31$). This steady-state response may prove useful in the objective investigation of binaural hearing.

Keywords: Steady-state responses; Binaural hearing; Interaural correlation; Time constants; Binaural sluggishness; Auditory modeling

1. Introduction

The estimation of interaural correlation forms a basis for a variety of binaural perceptual phenomena, including lateralization, binaural detection, and the precedence effect (e.g. Akeroyd and Summerfield, 1999; Trahiotis et al., 2005). Recent psychophysical studies have proposed that the temporal responsiveness of the binaural system in calculating interaural correlation is constrained by subsequent temporal integration (Grantham and Wightman, 1978; Grantham, 1982; Akeroyd and Summerfield, 1999). The integrating process is generally considered "sluggish", with a time constant ranging from a few tens of milliseconds to a few hundred milliseconds.

The superior olivary complex (SOC) in the lower brainstem is the first stage where inputs from the two ears can be compared (e.g. Brand et al., 2002; Tollin and Yin, 2005). Beyond the SOC, sensitivity to static and dynamic interaural differences has been measured in centers that

Abbreviations: 2AFC, two alternative forced choice; AD, analog-to-digital; AVCN, anteroventral cochlear nucleus; BIC, binaural interaction component; BMLD, binaural masking level difference; BOLD, blood oxygen level-dependent (response); COR, correlation; CSD, circular standard deviation; dB HL, decibel hearing level; dB SPL, decibel sound pressure level; EEG, electroencephalogram; FFT, fast Fourier transform; FIR, finite impulse response; fMRI, functional magnetic resonance imaging; HSD, honestly significant difference; IC, inferior colliculus; ICCI, interaural correlation change interval; ITD, interaural time difference; LAT, lateralization; MASTER, multiple auditory steady-state response; MEG, magnetoencephalogram; MSO, medial superior olive; RMS, root-mean-square; SD, standard deviation; SEM, standard error of the mean; SNR, signal-to-noise ratio; SOC, superior olivary complex

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include the nucleus of the lateral lemniscus (Kuwada et al., 2006), the inferior colliculus (IC) (e.g. Rose et al., 1966; Spitzer and Semple, 1993; Spitzer and Semple, 1998), the primary auditory cortex (e.g. Sovijärvi and Hyvärinen, 1974), and specialized cortical areas outside the primary auditory cortex (Griffiths et al., 2000; Warren et al., 2002). The temporal integration responsible for binaural "sluggishness" likely occurs after the level of the IC, as single unit measurements in the IC in the cat can follow changes in interaural correlation at rates up to several hundred Hertz (Joris, 1996; discussed in Culling and Summerfield, 1998; Joris et al., 2006).

The estimation of interaural correlation relies on the precise timing of neural spikes. For example, to detect interaural time differences in low frequency pure tones, the neural circuits in the SOC depend on inputs from auditory nerve fibers that phase lock to the stimulus, and that are carried through a single relay stage in the cochlear nucleus that preserves spike timing (e.g. Joris et al., 1994). Any degradation in the timing of neural firing, such as might occur in disorders of central auditory processing or in the aging auditory system, should distort binaural processing in general, and the estimation of interaural correlation in particular. Older listeners show an increase in interaural time difference (ITD) thresholds, a decrease in binaural masking level differences (BMLD), and poorer performance in ITD-dependent sound localization tasks that is independent of age-related peripheral hearing loss (Strouse et al., 1998; Abel et al., 2000; Babkoff et al., 2002).

Given the essential role that estimating interaural correlation plays in binaural processing, it would be useful to devise tests that objectively measure this function. In this paper, we describe the steady-state responses to noise signals with interaural correlations that vary with a frequency of rectangular modulation f_m. Varying f_m allowed us to characterize a "frequency response" of the binaural system, from which temporal parameters can be derived and compared to those obtained from psychophysics. Varying the degree of interaural correlation allowed us to estimate a physiological response threshold for the detection of interaural correlation.

2. Materials and methods

2.1. Subjects

Thirty-seven subjects (23 females) participated in one or more of the experiments. The subjects ranged in age between 21 and 53 years. None of the subjects had a history of hearing difficulty, and all had thresholds of 15 dB HL or less at 500, 1000, 2000, and 4000 Hz in both ears. The subjects sat in a comfortable reclining chair in an Industrial Acoustics Company (IAC) sound-insulated room. During the physiological experiments, they watched a muted movie with subtitles, and were asked not to attend to the auditory stimuli. The research was approved by the Research Ethics and Scientific Review Committee at the Baycrest Centre.

2.2. Stimuli

Except for the lateralized signals in experiment 2, the stimuli were dichotic noise signals that alternated abruptly between two levels of interaural correlation (ρ) at a repetition frequency (f_m), starting with $\rho \neq 0$ at zero phase (Fig. 1). In every half-cycle, to achieve the required ρ, and to avoid sequential correlations between the half-cycles, different combinations of four independent uniformly distributed noise samples were assigned to the right and left channels. When $\rho = +1$, sample 1 was presented to both the right and left ears, and the stimulus was heard as focused in the midline. When $\rho = 0$, samples 2 and 3 were presented to the right and left ears respectively, and the stimulus was perceived as diffuse (Gabriel and Colburn, 1981; Akeroyd and Summerfield, 1999). When $\rho = -1$, sample 1 was presented to one ear and the inverse of sample 1 to the other ear. In that case, the stimulus could be perceived as coming from two compact sources near the two ears, or as a blurred source displaced laterally (Boehnke et al., 2002). To achieve $0 < \rho < 1$ during a half-cycle, we used the formulas described in Gabriel and Colburn (1981):

$$n_L(t) = n_1(t),$$
$$n_R(t) = \rho n_1(t) + (1-\rho^2)^{1/2} n_2(t), \tag{1}$$

where $n_1(t)$ and $n_2(t)$ are two independent noise samples (in our case samples 1 and 4). This way of constructing the stimuli would have caused the amplitude distributions in the two ears to have been different when $\rho < 1$ (uniform for n_L and trapezoidal for n_R). This situation could have been averted by using normally distributed rather than uniformly distributed noise. However, it was highly unlikely that the subject could have used this difference as a cue in-

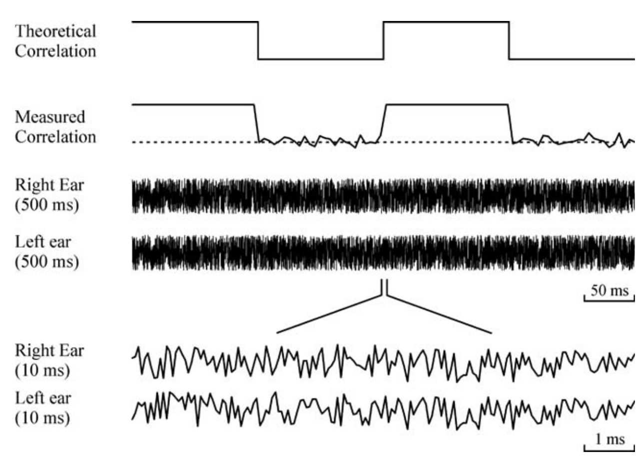

Fig. 1. Stimulus. The upper line shows two cycles of interaural correlation (ρ), which alternates between the two levels of 1 and 0 at rate of 4 Hz. The second line shows the correlation measured over 5 ms intervals. The third and fourth lines show the stimuli as presented to each ear. Note the lack of cycle-by-cycle amplitude variation. The lower two lines of the figure show a 10 ms epoch of the stimuli as it changes from the uncorrelated to the correlated section of the cycle. In the correlated section, identical stimuli occur in the two ears.