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Research paper

Electrophysiological and psychophysical asymmetries in sensitivity to interaural correlation gaps and implications for binaural integration time

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ABSTRACT

Brief deviations of interaural correlation (IAC) can provide valuable cues for detection, segregation and localization of acoustic signals. This study investigated the processing of such "binaural gaps" in continuously running noise (100–2000 Hz), in comparison to silent "monaural gaps", by measuring late auditory evoked potentials (LAEPs) and perceptual thresholds with novel, iteratively optimized stimuli. Mean perceptual binaural gap duration thresholds exhibited a major asymmetry: they were substantially shorter for uncorrelated gaps in correlated and anticorrelated reference noise (1.75 ms and 4.1 ms) than for correlated and anticorrelated gaps in uncorrelated reference noise (26.5 ms and 39.0 ms). The thresholds also showed a minor asymmetry: they were shorter in the positive than in the negative IAC range. The mean behavioral threshold for monaural gaps was 5.5 ms. For all five gap types, the amplitude of LAEP components N1 and P2 increased linearly with the logarithm of gap duration. While perceptual and electrophysiological thresholds matched for monaural gaps, LAEP thresholds were about twice as long as perceptual thresholds for uncorrelated gaps, but half as long for correlated and anticorrelated gaps. Nevertheless, LAEP thresholds showed the same asymmetries as perceptual thresholds. For gap durations below 30 ms, LAEPs were dominated by the processing of the leading edge of a gap. For longer gap durations, in contrast, both the leading and the lagging edge of a gap contributed to the evoked response. Formulae for the equivalent rectangular duration (ERD) of the binaural system's temporal window were derived for three common window shapes. The psychophysical ERD was 68 ms for diotic and about 40 ms for anti- and uncorrelated noise. After a nonlinear Z-transform of the stimulus IAC prior to temporal integration, ERDs were about 10 ms for reference correlations of ±1 and 80 ms for uncorrelated reference. Hence, a physiologically motivated peripheral nonlinearity changed the rank order of ERDs across experimental conditions in a plausible manner.

1. Introduction

The azimuthal position of a single sound source in silence is well described by the interaural time and level differences of the sound waves at the two ears (Rayleigh, 1907; Yost and Gourevitch, 1987). In most realistic situations, however, relevant signals are accompanied by sounds from concurrent sources, reverberation, or ambient noise, so that the resulting interaural disparities often yield conflicting or uncertain spatial cues in different frequency bands and time segments (Saberi et al., 1998; Faller and Merimaa, 2004; Nix and Hohmann, 2006, 2007). Nevertheless, the auditory system has the remarkable ability to exploit partially corrupted or temporally fluctuating spatial cues, either to localize a particular sound source or to effectively reduce the amount of masking produced by the interferers (Blauert, 1997; Bronkhorst, 2000; Faller and Merimaa, 2004; Beutelmann and Brand, 2006).

One statistical approach for assessing the relevance and reliability of auditory spatial cues in consecutive time segments is to calculate the normalized cross-correlation coefficient ρ between the two ear signals $L(t)$ and $R(t)$, i.e., their interaural correlation

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Abbreviations

AFC	alternative forced choice
ANOVA	analysis of variance
BOLD	blood oxygen level dependent
EEG	electroencephalogram
ERB	equivalent rectangular bandwidth
ERD	equivalent rectangular duration
fMRI	functional magnetic resonance imaging
IAC	interaural (cross) correlation
JND	just noticable difference
JNT	just noticable transition
LAEF	late auditory evoked field (MEG)
LAEP	late auditory evoked potential (EEG)
MEG	magnetoencephalogram
N1	negative deflection in the LAEP at about 100–130 ms after the stimulus
P2	positive deflection in the LAEP at about 200–230 ms after the stimulus
SEM	standard error of the mean
α	significance level in post hoc comparisons
p	probability of null hypothesis (ANOVA)
ρ_{ref}	interaural correlation of reference signal
ρ_{gap}	interaural correlation during a binaural gap
ρ-JND	just noticable IAC difference
ρ-JNT	just noticable IAC transition
t_{gap}	gap duration
θ_{gap}	shortest detectable gap duration (threshold)

(IAC):

$$\rho = \frac{\int \mathrm{L}(t)\,\mathrm{R}(t)\,\mathrm{d}t}{\sqrt{\int \mathrm{L}^2(t)\,dt}\sqrt{\int \mathrm{R}^2(t)\,\mathrm{d}t}}. \tag{1}$$

For an auditory target in front of the head, values of ρ other than $+1$ indicate the presence of concurrent sound sources away from midline, e.g., interfering speakers, reverberation or diffusely lateralized ambient noise. For an auditory target at a lateral position, the same applies after optimal equalization of interaural time differences.

A selection or weighting of spatial cues according to the outcome of a running cross-correlation process can improve the segregation of concurrent sounds or the accuracy of directional estimates not only in a technically robust manner but also in a perceptually plausible way (Stern et al., 1988; Kollmeier and Gilkey, 1990; Colburn, 1995; Stern and Trahiotis, 1995; Boehnke et al., 2002; Faller and Merimaa, 2004). Various psychophysical studies showed that human listeners are able to detect IAC variations lasting only 10 ms or less (Culling and Summerfield, 1995; Peissig and Kollmeier, 1997; Holube et al., 1998; Akeroyd and Summerfield, 1999; Boehnke et al., 2002; Braasch, 2002; Faller and Merimaa, 2004; Schimmel et al., 2008). However, it is not yet clear how the human brain processes such extremely brief segments in which the binaural information suddenly changes. The present study investigated the detectability of so-called "binaural gaps" in psychophysical and electroencephalographical (EEG) experiments with normal-hearing human listeners. The results of these experiments were used to test whether the assumptions and parameters of psychophysically motivated binaural detection models are compatible with physiological data.

1.1. *Audibility of IAC deviations: ρ-JNDs and the "binaural gap" paradigm*

The just noticeable difference (ρ-JND) between a reference correlation ρ_{ref} and some deviant IAC depends on both ρ_{ref} and on the direction of the IAC deviation: for broadband noise signals, typical ρ-JNDs range from 0.02 to 0.045 for $\rho_{\mathrm{ref}} = +1$, but are about 0.095 for $\rho_{\mathrm{ref}} = -1$. For $\rho_{\mathrm{ref}} = 0$, ρ-JNDs are markedly larger; typical values are 0.3-0.55 for IAC changes towards $+1$, and 0.46-0.67 for changes towards -1 (Pollack and Trittipoe, 1959; Gabriel and Colburn, 1981; Akeroyd and Summerfield, 1999; Boehnke et al., 2002; Lüddemann et al., 2009).

In addition to their ρ-JND measurements, Akeroyd and Summerfield (1999) investigated the detectability of brief IAC deviations in an ongoing signal by using Gaussian noise stimuli with an interaurally uncorrelated "binaural gap" in the middle, preceded and followed by reference segments with an IAC of $\rho_{\mathrm{ref}} = +1$. For 100-Hz wide noise stimuli centered around 500 Hz, they reported a mean binaural gap detection threshold ($\theta_{\mathrm{gap}}^{\mathrm{AFC}}$) of 14 ms. For a larger bandwidth of 100–500 Hz, the mean threshold was 5.3 ms.

For broadband noise (0–22,050 Hz), Boehnke et al. (2002) reported mean binaural gap detection thresholds of 2.40/7.60 ms for uncorrelated gaps in reference noise with $\rho_{\mathrm{ref}} = +1/-1$, and even lower thresholds for antiphasic gaps in diotic reference noise (1.48 ms). For interaurally correlated and antiphasic gaps in uncorrelated reference noise ($\rho_{\mathrm{ref}} = 0$), however, they found much larger thresholds of 21.0 and 42.9 ms, respectively.

1.2. *Asymmetries in psychophysical IAC sensitivity*

The above-mentioned psychophysical studies consistently show that the reference IAC and the IAC change direction have qualitatively similar effects on ρ-JNDs, on detection thresholds for stepwise IAC transitions in ongoing noise (ρ-JNT), and on binaural gap detection thresholds. Hence, the auditory system might use similar – if not identical – coding strategies and decision criteria for both the discrimination between temporally remote stimuli with static IAC and for the detection of step- and gap-like IAC deviations in an ongoing noise. Therefore, Lüddemann et al. (2009) proposed that IAC sensitivity can be generally characterized by two parameter range asymmetries:

1. The "major asymmetry" is a continuous increase of IAC sensitivity as $|\rho_{\mathrm{ref}}|$ increases from zero to one.
2. The "minor asymmetry" is a slightly greater IAC sensitivity in the positive than in the negative range of ρ; it has a smaller influence on IAC sensitivity than the "major asymmetry".

This concept of two asymmetries is also applicable to other aspects of binaural perception such as the slopes of psychometric functions and cumulative d' functions obtained from pairwise IAC comparisons (Culling et al., 2001, 2003; Lüddemann et al., 2010), or binaural masking release in tone detection experiments with various masker correlations (van der Heijden and Trahiotis, 1997; Breebaart and Kohlrausch, 2001).

1.3. *Asymmetries in neurophysiological IAC sensitivity*

Functional magnetic resonance imaging (fMRI) experiments by Budd et al. (2003) showed that the amplitudes of – and, more