Sensitivity to a break in interaural correlation is co-modulated by intensity level and interaural delay

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Abstract: This study investigated whether sound intensity affects listeners' sensitivity to a break in interaural correlation (BIC) embedded in wideband noise at different interaural delays. The results show that the detection duration threshold remained stable at the intensity between 60 and 70 dB SPL, but increased in accelerating fashion as the intensity decreased toward 40 dB SPL. Moreover, the threshold elevated linearly as the interaural delay increased from 0 to 4 ms, and the elevation slope became larger as the intensity decreased from 50 to 40 dB SPL. Thus, detecting the BIC is co-modulated by both intensity and interaural delay.

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1. Introduction

Human listeners are highly sensitive to a temporal break in interaural correlation (BIC, a change of interaural correlation from 1 to 0, then back to 1) (Akeroyd and Summerfield, 1999; Boehnke *et al.*, 2002; Huang *et al.*, 2009a; Huang *et al.*, 2009b; Li *et al.*, 2009). When a BIC occurs at the temporal middle of binaurally presented identical noises, introducing such a drop in interaural correlation does not alter the energy and spectrum but modifies the perceptual compactness/diffuseness, number, placement, and/or loudness of the noise object (Blauert and Lindermann, 1986; Hall *et al.*, 2005).

Previous studies have shown that the duration threshold for detecting a temporal (monaural) gap in noise is affected by the overall intensity level (e.g., Fitzgibbons, 1983; Plomp, 1964): The threshold increases in nonlinear fashion as the marker intensity becomes lower. However, whether the sensitivity to the BIC (binaural gap) is reduced by lowering the noise-marker intensity has not been reported in the literature. Detecting a BIC depends on both monaural coding of fine-structure signals and binaural calculation of the similarity of the fine-structure signals between the two ears. The coding of fine-structure signals is largely based on the ability of the auditory system to represent phase information of the low-frequency components of the stimulus waveform. It is known that the rate of auditory-nerve discharge fluctuates in synchrony with the sinusoidal changes in pressure (i.e., phase locking) produced by a low-frequency tone, and the waveform synchronization (measured with synchronization index) depends on both the frequency and overall intensity level of the tone (e.g., Fig. 3 in Johnson, 1980). Thus, it is worth examining the effect of the marker intensity on detection of the BIC. Moreover, when an interaural delay (up to 20 ms, which is much larger than the sound-propagation time between the two ears) is introduced, the BIC is still detectable (Huang *et al.*, 2009a; Huang *et al.*, 2009b; Li *et al.*, 2009) and the

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duration threshold for detecting the BIC increases monotonically as the interaural delay increases (Huang *et al.*, 2009b), suggesting that the auditory storage of the fine-structure signals coming from the leading ear declines quickly with increasing the interaural delay (Huang *et al.*, 2009a). Obviously, this auditory-storage decline reduces the interaural correlation between the auditory representation of the fine-structure signals of the BIC marker at the leading ear and that at the lagging ear, causing a decrease in the contrast between the BIC and the BIC markers. Thus, the detection of the BIC may be co-modulated by both the intensity level and the interaural delay. The present study investigated whether the noise-marker intensity affects listeners' sensitivity to the BIC embedded in the wideband noise markers, when the interaural delay is 0, 2, or 4 ms.

2. Methods

2.1 Participants

Six young university students (22–28 years old, mean age = 25 years, 4 females and 2 males) with normal hearing participated in this study. Their pure-tone thresholds were no more than 20 dB hearing level (HL) between 0.125 and 8 kHz (ANSI-S3.6, 2004) and the threshold difference between the two ears in each frequency was less than 15 dB HL. They gave their written informed consent to participate in the study and were paid a modest stipend for their participation.

2.2 Apparatus and stimuli

The participant was seated in a chair at the center of a sound-attenuated chamber (EMI Shielded Audiometric Examination Acoustic Suite). Gaussian wideband noises, 1000 ms in duration, including 30-ms rise-fall time, were synthesized using the "randn()" function in the MATLAB function library (the MathWorks Inc., Natick, MA) at the sampling rate of 48 kHz with 16-bit amplitude quantization. Stimuli were transferred using the Creative Sound Blaster PCI128 (Creative SB Audigy 2 ZS, Creative Technology Ltd, Singapore), and presented to participants by two headphones (HD 265 linear, SENNHEISER, Germany). The headphones have an ambient background sound level of 24 dB sound pressure level (SPL). The intensity of the noise stimulus was set at 40, 50, 60, or 70 dB SPL. Calibration of intensity was carried out with the Larson Davis Audiometer Calibration and Electroacoustic Testing System (AUDit and System 824, Larson Davis, Depew, NY). The right-ear noise always started simultaneously with or led the left-ear noise, and fresh noises were used for each trial.

2.3 Procedure

Duration thresholds for detecting the BIC in the temporal middle of the identical (correlated) noises were tracked at each of the combinations of interaural delay (0, 2, or 4 ms) and intensity (40, 50, 60, or 70 dB SPL) using an adaptive two-interval, two-alternative, forced-choice procedure. In one interval, identical 1000-ms noises were presented to the left and right ears. In the other interval, the left-ear 1000-ms noise was again identical to the right-ear noise, except that an independent noise segment was substituted at the temporal middle of the left-ear noise (this substituted noise segment was the BIC). In each trial, the BIC was randomly assigned to one of the two intervals. The participant's task was to identify which of the two intervals contained the BIC by pressing the left-button or the right-button on a response box. The BIC duration was manipulated by a three-down-one-up procedure: The duration was decreased after three consecutive correct identifications of the interval containing the BIC and increased after one incorrect identification. The initial step-size for changing the duration of BIC was 16 ms, and the step-size was altered by a factor of 0.5 with each reversal of direction until the minimum step-size of 1 ms was reached. Feedback was given visually after each trial via a LCD monitor in front of the participant. A test session of trials (i.e., a run) was terminated after ten reversals, and the duration threshold for a run was defined as the arithmetic mean BIC duration for the last six reversals. For each stimulus condition, the arithmetic mean of duration thresholds for three runs was used as the duration threshold.

3. Results

The following best-fitting psychometric function was used for describing the relationship between the BIC duration threshold and the sound level

$$y = y_0 + Ae^{Rx}, \tag{1}$$

where y is the duration threshold for detecting the BIC when the sound intensity level is x; y_0 was the baseline y value that is not determined by x; A is the whole dynamic range of the change of y determined by x; R is the coefficient determining the dynamic rate of the psychometric function; e is Euler's constant (which is 2.71 828).

All the participants were able to detect the BIC at each combined condition of the interaural delay and noise intensity. Figure 1(a) shows the group-mean duration threshold for detecting the BIC and the best-fitting psychometric function (curve) as a function of the noise intensity at each of the three interaural delays. A 4 (intensity) $\times$ 3 (interaural delay) two-way within-subject analysis of variance (ANOVA) showed that the interaction between the intensity and interaural delay on the duration threshold was significant [$F(6,30) = 9.561$, $p < 0.001$]. LSD *post hoc* analyses showed that the duration threshold stayed constant when the intensity decreased from 70 to 60 dB SPL ($p = 0.526$), but increased significantly when the intensity decreased both from 60 to 50 dB SPL and from 50 to 40 dB SPL (both $p < 0.01$). The best-fitting psychometric functions were equivalent across the three interaural delays except that the two constants ($y0$ and A) were determined by the interaural delay.

In addition, the duration threshold also increased significantly as the interaural delay increased from 0 to 2 ms ($p < 0.01$) and from 2 to 4 ms ($p < 0.05$) [Fig. 1(b)]. The best-fitting function indicates that the group-mean duration threshold was a linear function of the interaural delay at each of the four noise intensities. The slope of the linear psychometric function remained stable when the noise intensity was in the range

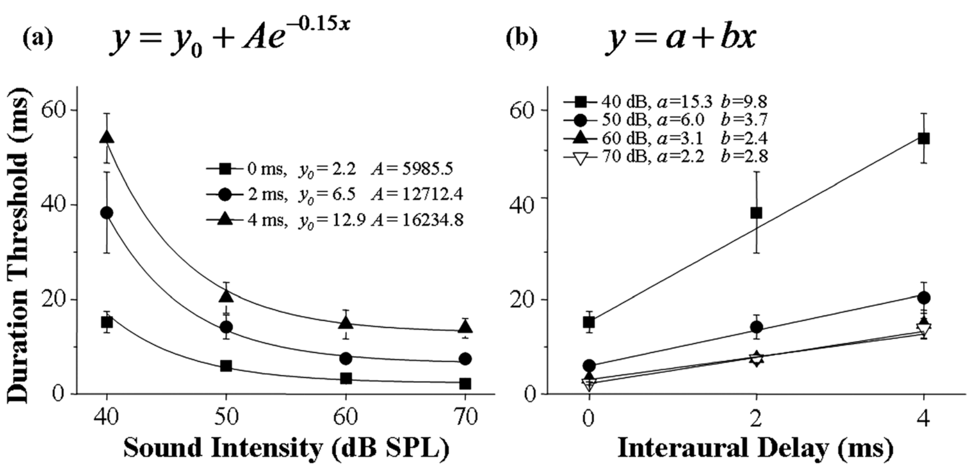

Fig. 1. (a) The group-mean duration threshold for detecting the BIC and the best-fitting psychometric function (curve) as a function of the noise intensity at each of the three interaural delays. (b) The group-mean duration threshold for detecting the BIC and the best-fitting psychometric function (curve) as a function of the interaural delay at each of the four noise intensities. In (a) and (b), error bars represent the standard error of the mean and the equation of the best-fitting psychometric function is presented on the top.

between 50 and 70 dB SPL, but became much larger when the intensity was 40 dB SPL. A one-way within-subject ANOVA showed that the effect of noise intensity on the slope was significant [$F(3,15) = 18.077$, $p < 0.001$]. LSD *post hoc* analyses showed that the slope of the linear function at 40 dB SPL was significantly larger than the slopes at the other three noise intensities (50, 60, 70 dB SPL, $p < 0.01$) and the slope differences between the three intensities over 40 dB SPL were not significant.

4. Discussion

The results of this study showed that the duration threshold for detecting the BIC in wideband noise was co-modulated by both the noise intensity and interaural delay. However, the modulation pattern of the intensity was different from that of the interaural delay. Specifically, the sensitivity to the BIC declined in accelerating fashion as the noise intensity drops from 60 toward 40 dB SPL. Also, the extreme values (i.e., the two constants $y0$ and A) of the best-fitting psychometric function were affected by changing the interaural delay in the range between 0 and 4 ms, but the dynamic feature of the intensity function was not altered (the coefficient of x was -0.15). On the other hand, the sensitivity to the BIC was modulated by the interaural delay in linear (but not accelerating) fashion when the interaural delay increased from 0 to 4 ms. However, it should be noted that the linear relation between the sensitivity to the BIC and the interaural delay may be broken when the interaural delay is larger. The slope of the best-fitting psychometric function remained stable when the intensity was 50 dB SPL or above, but became much larger when the intensity was lowered to 40 dB SPL.

The results of this study suggest that humans' sensitivity to the BIC (Akeroyd and Summerfield, 1999; Boehnke *et al.*, 2002; Huang *et al.*, 2009a; Huang *et al.*, 2009b; Li *et al.*, 2009) is not only interaural-delay dependent but also intensity dependent. Since both decreasing the intensity level (which worsens the synchrony in responses of auditory-nerve fibers to the tone stimulus; Johnson, 1980) and increasing the interaural delay (which destructs the temporal storage of acoustic signals coming from the leading ear; Huang *et al.*, 2009a) reduce the interaural correlation of the auditory representation of the BIC markers, the BIC-induced perceptual change (Blauert and Lindermann, 1986; Hall *et al.*, 2005) becomes weaker as the sound intensity is sufficiently low (i.e., 40 dB SPL or lower) and the interaural delay is elongated. It would also be of interest to know whether the intensity-determined sensitivity to the monaural gap (e.g., Fitzgibbons, 1983; Plomp, 1964) and that to the binaural gap (i.e., the BIC, the present study) share some similar mechanisms.

To date, no model is available in the literature for predicting the combined effect of sound level and interaural delay on the detection of the BIC. As indicated by Eq. (1), the BIC-duration threshold (y) is not only determined by the sound level (x) but also by the two parameters (y_0 and A), which in turn are determined by the interaural delay. Thus, the proposal of this equation by this study will encourage future empirical and modeling studies of BIC detection. Since the detection of the BIC is associated with both the ability to perceptually integrate the direct wave of the source with its highly correlated reflections and the ability to segregate this source from the other uncorrelated (masking) sources (Huang *et al.*, 2009a) in (simulated) noisy, reverberant environments, the declined sensitivity to the BIC as reported in older adults (Huang *et al.*, 2009b; Li *et al.*, 2009) may be associated with the reduced ability in the aged population to recognize speech in the adverse listening environments. Thus, it will be determined in the future whether the two parameters in Eq. (1) can be used for predicting the unmasking ability.

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