Detection of the break in interaural correlation is affected by interaural delay, aging, and center frequency

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This study investigated whether interaural integration is affected by introducing an interaural delay. In Experiment 1, both younger adults with normal hearing and older adults in the early stages of presbycusis were able to detect a transient break in interaural correlation (BIC) in the temporal middle of interaurally correlated wideband noises. However, their duration thresholds for detecting the BIC became larger with increasing interaural time difference (ITD) from 0 to 6 ms, and the threshold increase for older participants was larger than that for younger participants. In Experiment 2, to investigate whether the effect of changing ITD on the BIC detection is frequency-dependent, 1/3-octave narrowband noises with various center frequencies were used as stimuli. Results show that the duration threshold for detecting the BIC was higher for high-frequency noises than for low-frequency noises. Also, with increasing ITD from 0 to 4 ms, the threshold increase was larger for high-frequency noises than for low-frequency noises. The results suggest that there are age- and frequency-related temporal declines in maintaining fine-structure signals for interaural integration. These declines may affect the recognition of sound sources in reverberant environments.
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I. INTRODUCTION

In reverberant environments, listeners receive both the direct sound waves from sound sources and numerous reflections from various surfaces. To perceptually separate the target sound signal from irrelevant sound signals in such conditions, the auditory system needs to not only perceptually group direct sound waves emanating from the target source with reflections of the target source but also perceptually group direct sound waves emanating from an irrelevant source with reflections of the irrelevant source by both calculating correlations between sound waves and integrating highly correlated sound waves. In humans, the integration of the direct source wave with its reflections causes a perceptual consequence called fusion. That is, when the time interval between the sound and a delayed copy of the sound is sufficiently short, attributes of the lagging sound are perceptually captured by the leading sound (Li *et al.*, 2005), causing a single fused sound image that is perceived to be at or near the location of the leading sound. This phenomenon is generally named as the "precedence effect" or "the law of the first wavefront" (Freyman *et al.*, 1991; Litovsky and Shinn-Cunningham, 2001; Wallach *et al.*, 1949; Zurek, 1980; for a review see Litovsky *et al.*, 1999). The precedence effect plays a role in suppressing the perception of echoes and facilitating the recognition and localization of sources in reverberant environments. If the delay between the leading sound and the correlated lagging sound is sufficiently large, listeners will perceive a second sound image near the location of the lagging source. The minimum delay which allows a listener to distinctly perceive the lagging sound is called the echo threshold (e.g., Haas, 1951; Litovsky *et al.*, 1999; Rakerd *et al.*, 2000).

Processing the similarity and dissimilarity of sound waves arriving at the two ears is critical for the precedence effect and other binaural perceptual phenomena (Blauert and Divenyi, 1988; Litovsky *et al.*, 1999; Scharf, 1974; Shinn-Cunningham *et al.*, 1995; Trahiotis *et al.*, 2005; Yang and Grantham, 1997a, 1997b), and this interaural integration is important for auditory perception in noisy, reverberant environments (Bregman, 1990). Human listeners with normal hearing are very sensitive to small differences between a wideband noise delivered at one ear and its copy delivered at the other ear (Akeroyd and Summerfield, 1999; Boehnke *et al.*, 2002; Gabriel and Colburn, 1981; Goupell and Hartmann, 2006; Pollack and Trittipoe, 1959). Changing the interaural correlation[1] of wideband noises modifies the percept of the noises (Blauert and Lindemann, 1986; Hall *et al.*, 2005). For example, as reported by Blauert and Lindemann (1986), when the interaural correlation of wideband pink noises was 1, listeners perceived a single compact auditory event precisely localized in the middle of the head. When the interaural correlation was 0, listeners perceived two respective events, one at each ear. When the interaural correlation was 0.25, 0.50, or 0.75, listeners perceived one diffused event in the median plane, and two additional ones lateralized symmetrically with respect to the median plane. Thus, some perceptual dimensions of the sounds such as the compactness, number of images, and lateral position depend on the interaural correlation.

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The perceptual representation of interaurally correlated noises is also determined by the delay time between the two ears [interaural time difference (ITD)]. If identical steady-state wideband noises are presented at the two ears with the ITD of 0 ms, a single compact noise image is perceived at the middle point inside the head of a normal-hearing listener. When an ITD shorter than 1 ms, e.g., 0.5 ms, is introduced, the image is located between the middle of head and the leading ear. When the ITD is increased to 1 ms, the image is perceived at the leading ear. With a further increase in the ITD to a higher value within the range of the precedence effect, e.g., 4 ms, a single fused noise image is still located at the leading ear. Theoretically, when an ITD of several milliseconds is introduced, fine-structure information of the noise at the leading ear has to be maintained in the central auditory system for that period of time; otherwise, instead of one single fused image, multiple images would be perceived. Moreover, if there is a temporal decay of the central representation of fine-structure details of the noise, especially for that of high-frequency components, the binaural integration would decline with increasing ITD, even though the perceptual fusion is still maintained. Since processing fine-structure information is largely based on phase locking of neural firing and phase locking tends to breakdown as the frequency increases, it is of interest to know how the vulnerability of the interaural integration to ITD is frequency dependent.

Human listeners are also able to detect a transient break in correlation (BIC) between the two ears (i.e., a transient change of interaural correlation from 1 to 0 and to 1), and measuring the duration threshold for detecting this transient change in interaural correlation is a way of estimating the ability to temporally resolve fast changes in interaural configurations (Akeroyd and Summerfield, 1999; Boehnke *et al.*, 2002). Note that introducing a change in interaural correlation for wideband noises does not change the energy and spectrum in the signals, but it can change the loudness of the signals (Culling, 2007).

If there is a degeneration of the interaural integration of fine-structure details by introducing an ITD, a BIC should be less detectable (increase in the duration threshold for detecting the BIC). Thus, measuring the duration threshold for detecting the BIC at various ITDs provides a way of investigating whether the interaural integration of acoustic details is affected by an interaural delay. One of the purposes of this study was to investigate the effect of ITD on interaural integration of fine-structure acoustic details by examining whether the duration threshold for detecting the BIC embedded in either wideband or narrowband noises is affected by ITD.

The sensitivity to the interaural correlation appears to be frequency dependent (Akeroyd and Summerfield, 1999; Culling *et al.*, 2001; Mason *et al.*, 2005). For example, when the center frequency of the narrowband noise is 250 Hz and the bandwidth is 100 Hz, human listeners can detect the occurrence of the BIC with the mean duration threshold of 6.5 ms. When the center frequency becomes 1000 Hz and the bandwidth is still 100 Hz, the threshold increases to 35 ms (Akeroyd and Summerfield, 1999). However, it should be noted that because the bandwidth of the auditory filter varies roughly on a logarithmic scale with changing frequency (Glasberg and Moore, 1990), using a bandwidth that varies logarithmically is more appropriate for studying the center-frequency effect on interaural integration of fine-structure information of narrowband noises. Another purpose of this study was to examine whether the duration threshold for detecting the BIC embedded in narrowband noises is affected by the center frequency when the narrowband-noise bandwidth is fixed at 1/3 octaves across various center frequencies.

Recognizing acoustic signals (e.g., comprehending speech) is particularly difficult for older adults in noisy, reverberant environments (Nábělek and Robinson, 1982; Nábělek, 1988; Huang *et al.*, 2008b; Helfer, 1992; Helfer and Wilber, 1990). Since interaural integration is important for both the precedence effect (Blauert and Divenyi, 1988; Litovsky *et al.*, 1999; Scharf, 1974; Shinn-Cunningham *et al.*, 1995; Trahiotis *et al.*, 2005; Yang and Grantham, 1997a, 1997b) and auditory perception in noisy, reverberant environments (Bregman, 1990), it is possible that there is an age-related decline in interaural integration. However, previous studies have failed to find any age-related effects on a fusion-related localization task when the inter-click delay was in the range 0.7–8 ms for inducing the phenomenon of "the law of the first wavefront" (Cranford *et al.*, 1993), and on the echo threshold when stimuli was short-duration (4 ms) noises (Roberts and Lister, 2004), long-duration (from 250 to 350 ms) 1/4-octave-wide noise (with the center frequency of 1000, 2000, or 3000 Hz) (Lister and Roberts, 2005), or short-duration (about 2 ms) tone bursts (Schneider *et al.*, 1994). Nevertheless, two studies seem to have found some age-related effects. (1) Cranford *et al.* (1993) reported an age effect on the fusion-related localization task when the inter-click delay was no larger than 0.5 ms. However, it is still not clear whether this effect was caused by age-related hearing loss and/or binaural imbalance because the authors used the mean bilateral high-frequency pure tone averages across 1, 2, and 4 kHz as the criteria for assigning participants into the normal-hearing group or the hearing-loss group. It is still not clear whether group differences in the pattern of "error" occurred when the bilateral clicks started simultaneously or when the click on one side led the click on the other side. (2) Using 4 ms bursts of white noise as stimuli, Roberts *et al.* (2002) reported that listeners with hearing loss (mean age =68 years) had longer echo thresholds than listeners with normal hearing (mean age=29 years). However, their later studies (Roberts and Lister, 2004) have shown that there was no effect of aging or hearing loss on the echo threshold under dichotic or anechoic conditions. Specifically, under the reverberant condition, older adults with normal-hearing sensitivity (ONH) exhibited the highest thresholds, followed by those for younger adults with normal-hearing sensitivity (YNH) and older adults with impaired-hearing sensitivity (OIH). The mean echo thresholds for the ONH group were significantly higher than those of the OIH group, but the thresholds of the YNH group were not significantly different from those of the ONH group or the OIH group for the reverberant condition, showing no aging effects. Thus, there is a need to further investigate whether changes in interaural integration occur in people with the early stages of presbycusis.

This study investigated whether the duration threshold for detecting the BIC embedded in the temporal middle of interaurally correlated noises was influenced by increasing the ITD in younger adults with normal hearing and older adults in the early stages of presbycusis (Experiment 1). Moreover, this study also investigated whether the ITD-related modulation of the detection of the BIC in narrowband noises depends on the center frequency (Experiment 2). Instead of a linearly constant bandwidth as used by Akeroyd and Summerfield (1999), this study used the logarithmically-constant bandwidth of 1/3 octaves for the comparison across narrowband noises with various center frequencies.

II. EXPERIMENT 1

A. Methods

1. Participants

Ten younger university students (19–28 years old, mean age=23.0, six females) and eight older adults (65–74 years old, mean age=68.4, five females) participated in this study. None of the participants had any history of hearing disorders, and none used hearing aids. The participants gave their written informed consent to participate in the experiment and were paid a modest stipend for their participation.

The younger participants all had normal and symmetrical (no more than 15-dB difference between the two ears) and no more than 25-dB pure-tone hearing thresholds between 125 and 8000 Hz. In total, 43 older adults who self-reported to have normal hearing were examined for their hearing sensitivity, but only 8 of them passed the hearing test. These eight older participants had symmetrical (no more than 15-dB difference between the two ears) and no more than 25-dB pure-tone hearing thresholds between 125 and 500 Hz, and symmetrical and no more than 40-dB pure-tone hearing thresholds between 1000 and 4000 Hz. Although hearing thresholds at 8000 Hz were measured, they were not used for screening participants. Figure 1 presents average hearing levels for the two age groups as a function of the testing-tone frequency.

As Fig. 1 shows, the thresholds of older participants were generally higher than those of younger participants, and threshold differences between younger and older participants continued to increase with frequency. Although these older adults had clinically normal hearing, they were best characterized as being in the early stages of presbycusis.

2. Apparatus and stimuli

During a testing session, the participant was seated in a sound-attenuating chamber (EMI Shielded Audiometric Examination Acoustic Suite). Gaussian wideband noise signals (0–22.05 kHz) with the duration of 1000 ms (including 30-ms rise-fall times) were synthesized using the "randn()" function in the MATLAB function library at the sampling rate of 44.1 kHz with 16-bit amplitude quantization. The stimuli were transferred using the Creative Sound Blaster PCI128, passed through an AURICAL system, and presented to listeners by two headphones (Model HDA 200). Calibration of sound level was carried out with the Larson Davis Audiometer Calibration & Electroacoustic Testing System (AUDit and System 824, Larson Davis) with "A" weighting. Although a new random noise was generated for each trial, the sound level was fixed at 58 dB sound pressure level.

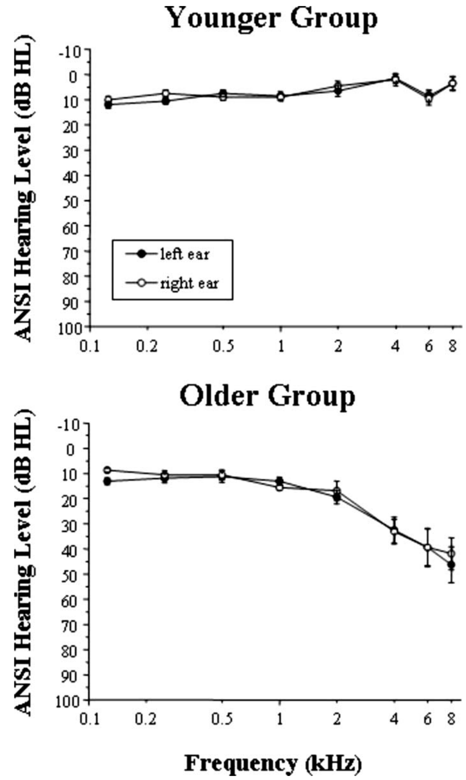

FIG. 1. Average hearing thresholds in the left ear (closed symbols) and the right ear (open symbols) for the younger-participant group (top panel) and those for the older-participant group (bottom panel) tested in Experiment 1. ANSI: American National Standards Institute (S3.6-1989). Error bars represent the standard errors of the mean.

3. Procedures

Two 1000-ms presentations of correlated noises were delivered over headphones. The right-headphone noise in one of the presentations was an exact copy of the left-headphone noise. The right-headphone noise in the other presentation was also identical to the left-headphone noise except for the substitution of a randomly selected independent noise fragment (i.e., BIC) introduced into the temporal middle of the correlated 1000-ms noises. The introduction of the BIC made the interaural correlation drop from 1 to a value near 0 (but not 0 because two randomly generated noises are not necessarily orthogonal) and then return to 1. For wideband noises used in this experiment, the interaural correlation for the BIC was not larger than 0.045. The duration of the BIC was systematically manipulated during the testing (see below).

In each trial, the inserted BIC had equal possibility to be randomly assigned to one of the two presentations. The delay between the two presentations (from the end of the first presentation to the onset of the second presentation) was 1000 ms. For each presentation, the noise presented on the left headphone started simultaneously with that presented on the right headphone or led the right-ear noise by 2, 4, or 6 ms. For each participant, the order of presenting the ITDs was randomized. A new noise was used for each trial. The participant's task was to identify which of the two presentations contained the transient change.

The participant initiated a trial with a particular ITD by typing a letter on the computer keyboard. The two-interval forced-choice procedure was used for measuring the BIC detection threshold. A three-down-one-up paradigm was used for systematically manipulating the BIC duration (Levitt, 1971). The starting BIC duration was set at 250 ms, which was a sufficiently large duration based on results of our pilot experiments. The BIC duration was decreased following three consecutive correct identifications of the presentation containing the BIC, and increased following one incorrect identification. The initial step size of changing the fragment duration was 50 ms, and then the step size was altered by a factor of 0.5 with each reversal of direction until the minimum step size of 0.5 ms was reached. Feedback was given visually after each trial. A test session was terminated following ten reversals in direction and the threshold for that session was defined as the average BIC duration for the last six reversals. Test sessions were repeated four times for each participant, and the average over the two lowest session thresholds defined the participant's threshold. To ensure that each participant understood the experimenter's instructions and became familiar with the procedure, a brief training session was used before the experiment.

B. Results

All the younger and older participants were able to detect the BIC when the BIC duration was sufficiently long at each of the ITDs (0, 2, 4, or 6 ms). Duration thresholds for younger and older individuals at the four ITDs are shown in the top panel of Fig. 2, and group-mean duration thresholds at the ITDs for younger and older participants are shown at the bottom panel of Fig. 2. Clearly, the duration threshold for detecting the BIC became larger with increasing ITD for each of the two age groups. Also, the thresholds were generally larger for older participants than for younger participants at all the ITDs.

A 4×2 two-way-mixed-subject analysis of variance (ANOVA) showed that the main effect of ITD was significant [$F(3,48)=17.55, p<0.001$], the main effect of age group was significant [$F(1,16)=6.40, p=0.022$], and the interaction between ITD and age group was significant [$F(3,48)=5.16, p=0.004$]. Further separate ANOVAs showed that when the ITD was 0 or 2 ms, the group effect was not significant ($p>0.05$ for both). However, when the ITD was increased to 4 or 6 ms, the group effect was significant [4 ms: $F(1,16)=4.49, p=0.050$; 6 ms: $F(1,16)=7.33, p=0.016$]. Separate ANOVAs also showed that the ITD effect was significant for both the younger group [$F(3,27)=5.93, p=0.003$] and the older group [$F(3,21)=10.23, p<0.001$]. These analyses indicate that changing the ITD significantly affects the detection of the BIC and older participants needed a larger BIC duration than younger participants to correctly detect the occurrence of the change in interaural correlation particularly when a sufficiently large ITD was introduced.

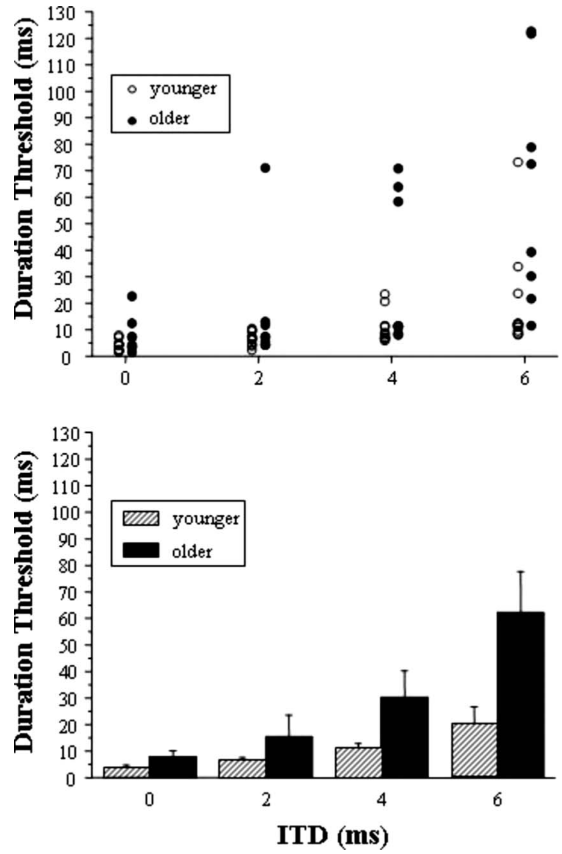

FIG. 2. Comparison of the duration threshold for detecting the BIC embedded in wideband noises between younger participants and older participants at each of the four ITDs (ITD=0, 2, 4, or 6 ms) in Experiment 1. The BIC was embedded in the 1000-ms interaurally correlated Gaussian noises. The top panel shows individuals' thresholds at each of the ITDs and the bottom panel shows group-mean thresholds at each of the ITDs. Error bars represent the standard errors of the mean.

C. Discussion

The stimulus design used in the present study was effectively the same as used in both the Akeroyd and Summerfield (1999) study and the study of Boehnke *et al.* (2002), that is, binaurally-presented noises underwent from correlated to uncorrelated and then to correlated, without introducing any substantial changes in energy and spectrum. In the present study, when no interaural delay was introduced (ITD=0 ms), the group-mean duration threshold for detecting the BIC was 4.0 ms for younger participants, which is larger than the mean threshold (2.3 ms) of the BIC measured in eight participants (20–35 years old) in the study of Boehnke *et al.* (2002) using a broadband noise (0–22 050 Hz) but smaller than the mean threshold of BIC (5.3 ms) measured in six participants (whose ages were not provided) in the Akeroyd and Summerfield (1999) study using band-pass noises (100–500 Hz). The present study also shows that although older participants needed larger durations (the group-mean threshold=7.8 ms) to detect the BIC than younger participants, the group difference was not statistically significant.

The detection of BIC depends on the central computation of the dynamic interaural correlation of noise fine structure. Both younger participants and older participants tested in the present study were able to detect the BIC even though an ITD of 6 ms was introduced, indicating that they could integrate fine-structure information of steady-state wideband noises at the two ears across an interaural delay at least 6 ms. These results are in agreement with previous studies showing that listeners with normal hearing are able to lateralize much larger ITDs than those experienced in free-field listening (e.g., Blodgett *et al.*, 1956; Mossop and Culling, 1998). However, the duration threshold for detecting the BIC increased as the ITD became larger, suggesting that the contrast between the central representation of the BIC and that of the rest of the noise (the temporal flanks of the BIC) decreases with increasing ITD. Moreover, when the ITD was increased to 4 or 6 ms, the group-mean duration threshold for older participants was significantly larger than that for younger participants. Thus there is an age-related decline in the ability to integrate fine-structure information of wideband noises presented at the two ears particularly when an interaural delay is introduced.

Since the perceived size of the noise image depends on the interaural correlation (Blauert and Lindemann, 1986; Goupell and Hartmann, 2006), detection of changes in correlation may be essentially detection of the size change of the auditory event. It is well known that detection of a small decrease in interaural correlation from a reference correlation continues to become worse as the reference correlation decreases (Boehnke *et al.*, 2002; Culling *et al.*, 2001; Gabriel and Colburn, 1981; Koehnke *et al.*, 1986; Pollack and Trittipoe, 1959). Thus it is much easier to detect the change from the perfectly correlated value (+1) to a slightly decorrelated value than from a slightly decorrelated value to a more decorrelated value. With increasing ITD, the central representation of fine structure of noise may be progressively diminished, and a compact, correlated image (when the correlation is 1) may be broadened, leading to reduced sensitivity to changes in the interaural correlation. Moreover, the reduction in the sensitivity to the correlation change is greater with increasing ITD in older participants than in younger participants.

Why does the compact image of interaurally correlated noise become broadened when the ITD increases? Stern *et al.* (1988) described a cross-frequency weighted-image model to explain perceptual-image lateralization of complex binaural stimuli based on theoretic operations on trajectories of the maxima of the frequency-dependent interaural cross-correlation function of the binaural stimuli. According to this model, listeners' subjective laterality of stimuli is determined by a weighted combination of the ITD centroids of the trajectories of the maxima following peripheral bandpass filtering and rectification. The frequency-independent "straightness" of the trajectory of maxima and the centrality of the trajectory of maxima are the two bandwidth-dependent weighting functions and they compete with each other for determining the consistent ITD. The straightness weighting function is to weigh heavily the trajectories that are straighter, which very likely represent a true ITD of a stimulus. The centrality weighting function is to emphasize the contribution of a greater number of trajectories with various values of internal delays. Thus an interesting question can be raised: If a trajectory with any magnitude is able to make its (weighted) contribution to the image laterality and the relative weight of a trajectory depends on its both straightness and centrality, does ITD also affect the stimulus compactness in addition to the stimulus laterality? Yost (1981) estimated the lateral position within the head for binaurally-presented tones with various frequencies and showed that although cross correlation or a coincidence network can account for the results at any one frequency, it cannot account for the results across frequencies. In other words, the image is not at the same position for a particular value of ITD at all frequencies. For tones with frequencies less than 1000 Hz, the lateral position corresponds more closely to the interaural phase difference than it does to the ITD. The model responses for expressing the image position within the head appear to be located at positions closer to midline as the tone frequency increases, and the range of the image distributions (which can be used to describe the degree of diffuseness) is also affected by the tone frequency. Thus introducing an ITD for interaurally correlated wideband noises may not only lateralize the auditory event (making the event move away from the midline and more toward one ear) but also weaken the compactness of the noise image, thereby reducing the sensitivity to a drop in interaural correlation (possibly due to compressed changes in event size). This view is supported by the Mossop and Culling (1998) study showing that with the increase in reference ITD, the just-noticeable differences between the reference-noise image and the testing-noise image in intracranial position became larger (the discrimination of laterality cues became poorer). This would provide an explanation for the elevated threshold for detecting the BIC in both younger and older listeners when the ITD became larger and the temporal flanks of BIC became more diffuse (i.e., the perception of laterality is fading).

Goupell and Hartmann (2006, 2007a, 2007b) showed that in the task of distinguishing between the slightly incoherent noises (coherence=0.992) and diotic noises (coherence=1.0), for narrowband noises, the incoherence was much more readily detectable in noises with larger fluctuations in interaural phase difference or in interaural level difference than in noises with smaller fluctuations. However, as the bandwidth increased, the incoherence became equally detectable in all the different noises, consistent with a model in which detection is predictable from interaural coherence alone. In their studies, when the coherence values were the same for noises with interaural phase fluctuations and interaural level fluctuations of difference size, incoherence was more easily detected for noises with large interaural fluctuations than for noise with smaller fluctuations. However, as the noise bandwidth increased, the distributions of interaural phase fluctuations and interaural level fluctuations across noises became narrower, and the value of noise coherence was sufficient to predict listeners' detection performance.

Since Gaussian wideband noises were used in Experiment 1 of this study, any potential age-related reduction in central representation of fluctuations in interaural phase difference and/or in interaural level difference might not contribute to the increase in threshold for detecting the BIC in the older group. Instead, the age-related threshold increase might be caused by declines in either monaural fine-structure processing (e.g., increase in filter bandwidth and reduction in phase-locking or synchrony) and/or binaural fine-structure processing (e.g., increase in "binaural sluggishness").

Some previous studies have shown that older normal-hearing listeners have smaller masking level differences (MLDs) than younger-adult listeners (Grose *et al.*, 1994; Olsen *et al.*, 1976; Pichora-Fuller and Schneider, 1991, 1992, 1998; Zurek and Durlach 1987; Strouse *et al.*, 1998). Since detection of interaural-correlation difference is closely associated with the MLD (Durlach and Pang, 1986; Bernstein and Trahiotis, 1992), the assumed age-related decline in processing fine-structure information would be associated with the age-related deficits of interaural integration. In the Pichora-Fuller and Schneider (1992) study, for example, the threshold of detecting a 500-Hz pure tone against band-limited white noise (0.1–5 kHz) for older participants differed significantly from that for younger participants only when the interaural delay of the noise masker was increased to a value between 0.5 and 5 ms. Results of the present study show that when the ITD was 0 or 2 ms, the mean threshold for detecting the BIC in older participants was not significantly larger than that in younger participants. However, when the ITD was increased to 4 or 6 ms, the mean threshold for detecting the BIC in older participants was significantly larger than that in younger participants. Thus the results of this study are generally in agreement with the Pichora-Fuller and Schneider (1992) report. The age-related decline in the ability to interaurally integrate correlated sounds when an interaural delay is introduced may be related to the difficulties experienced by older listeners in noisy, reverberant environments (Huang *et al.*, 2008b). However, it is not clear whether the age-related decline in the ability to integrate correlated sounds between the two ears is due to the age-related reduction or loss in monaural neural firing synchronization (monaural jitter) or the assumed age-related increase in binaural jitters. Pichora-Fuller and Schneider (1992) proposed that the age-related differences in binaural unmasking could be explained by the difference of change in temporal jitter as a function of internal interaural delay if the following two premises are satisfied: (1) temporal jitter in the binaural system does not vary as a function of internal interaural delay in old subjects, and (2) temporal jitter increases with internal interaural delay in young subjects. However, further evidence, especially physiological evidence, is still needed to clarify the issues of age-related temporal jitter.

III. EXPERIMENT 2

The results of Experiment 1 show that detection of the BIC embedded in wideband noises is affected by the ITD. As mentioned in Sec. I, the sensitivity to the interaural correlation is frequency dependent. Thus it is also important to know whether for narrowband noises the ITD effect on the interaural fine-structure integration is center-frequency dependent. In Experiment 2, we examined whether the sensitivity to the BIC in narrowband noises depends on the center frequency and, particularly, whether the center-frequency effect interacts with the ITD effect. Since fine-structure processing decreases with increasing frequency (due to degradation of phase locking), it was predicted that for narrowband noises, BIC detection would decrease with increasing center frequency (indeed, according to the "duplex" theory, BIC detection would become strikingly poor when the center frequency reaches 3000 Hz). In Experiment 2, the bandwidth was kept logarithmically-constant at 1/3 octaves across noises with various center frequencies.

A. Method

1. Participants

Twelve young university students (20–25 years, mean age = 22.7 years, eight females) with normal hearing participated in Experiment 2. They gave their written informed consent to participate in the experiment and were paid a modest stipend for their participation. The criteria for evaluating participants' hearing were the same as those used in Experiment 1.

2. Apparatus and materials

Similar to Experiment 1, the participant was tested in the EMI Shielded Audiometric Examination Acoustic Suite. To match the stimuli that were used in our recent neurophysiological studies of the effects of center frequency and ITD on humans' scalp event-related potentials to the BIC (Huang *et al.*, 2008a), the duration of Gaussian wideband noises was 2000 ms, including 30-ms rise-fall times, and the noises were synthesized using the randn() function in the MATLAB function library at the sampling rate of 48 kHz with 16-bit amplitude quantization.

In narrowband conditions, stimuli had a fixed logarithmically-constant bandwidth of 1/3 octaves and a center frequency of 200, 400, 800, 1600 or 3200 Hz. The stimuli were filtered with 512-point bandpass finite impulse response (FIR) filters. In wideband conditions, the stimuli were low-pass filtered at 10 kHz with a 512-order FIR filter. In order to avoid the spectral artifacts due to energy splatter outside the pass band, each stimulus was filtered after any uncorrelated fragment was introduced. The stimulus transduction, display, and calibration were the same as those used in Experiment 1.

Similar to Experiment 1, introducing a BIC in narrowband noises made the interaural correlation drop from 1 to a value close to 0 (but not 0 because the two randomly generated noises were not necessarily orthogonal) and then return to 1. However, the interaural correlation during the BIC for narrowband noises exhibited larger fluctuations than that for wideband noises. The maximum correlation for the BIC across narrowband noises used in this experiment varied with the center frequency (200 Hz: 0.255; 400 Hz: 0.200; 800 Hz: 0.150; 1600 Hz: 0.136; 3200 Hz: 0.116).

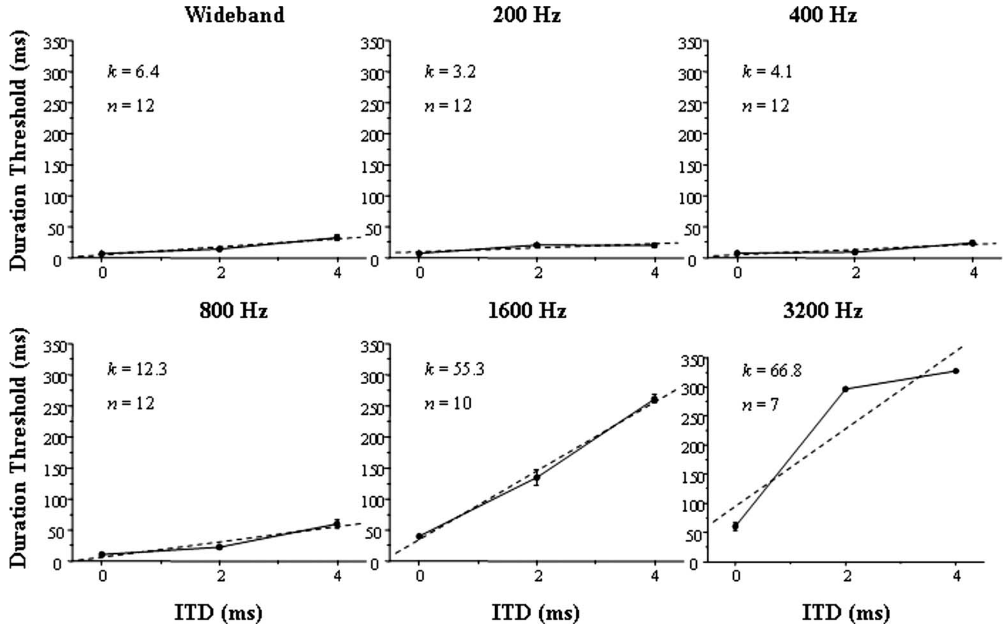

FIG. 3. The mean duration threshold across participants tested in Experiment 2 for detecting the BIC as a function of the ITD when the noise was wideband noise (top left panel) or narrowband noise with the center frequency of 200 Hz (top middle panel), 400 Hz (top right panel), 800 Hz (bottom left panel), 1600 Hz (bottom middle panel), or 3200 Hz (bottom right panel). The broken line in each panel is the (linear) best fitting of the duration threshold as a function of the ITD. *k* represents the slope of the best-fitting line. *n* represents the number of participants who could detect the BIC at all the ITDs under the particular noise-type condition. Error bars represent the standard errors of the mean

3. Procedures

The testing procedure and participants' task in Experiment 2 were the same as in Experiment 1. For each noise presentation, the noise at the left headphone either started simultaneously with that at the right headphone or led that at the right headphone by 2 or 4 ms. There were two within-subject factors: (i) noise type (wideband noise or narrowband noise with the center frequency of 200, 400, 800, 1600, or 3200 Hz) and (ii) ITD (0, 2, or 4 ms). The order of ITD was counterbalanced among 12 participants using the Latin-square design. Under each ITD condition, the order of noise type was in a random manner. A test session was terminated following ten reversals in direction, and the threshold for that session was defined as the average duration for the last six reversals. Test sessions were repeated three times for each participant, and the average over the three session thresholds defined the participant's threshold for the testing condition.

B. Results

When the BIC duration was sufficiently long, all the participants could detect the occurrence of the BIC around the temporal middle of the sustained noise under each of the noise-type conditions, except that two participants (Participant Nos. 1 and 8) could not detect the occurrence of the BIC embedded in the 3200-Hz narrowband noise even when the BIC duration was at the maximum value (330 ms) used in this experiment.

When the ITD was 2 ms, two participants (Participant Nos. 1 and 8) could not detect the BIC in the 1600-Hz narrowband noise and four participants (Participant Nos. 1, 7, 8, and 9) could not detect the BIC in the 3200-Hz narrowband noise. When the ITD was 4 ms, two participants (Participant Nos. 1 and 8) could not detect the BIC in the 1600-Hz narrowband noise and five participants (Participant Nos. 1, 2, 7, 8, and 9) could not detect the BIC in the 3200-Hz narrowband noise.

Figure 3 shows BIC duration thresholds for participants who could detect the BIC in a particular type of noise at all the ITDs. The broken line in each panel represents the linear best fitting of the duration threshold as a function of the ITD. The slope (k) of the best-fitting line is also indicated. Since some participants could not detect the BIC in high-frequency noises especially at long ITDs, the numbers of participants are not identical across panels.

For each noise type, the duration threshold was elevated with increasing ITD. For example, at the 400-Hz center frequency, as the ITD increased from 0 to 2 ms, the mean duration threshold increased from 7.6 to 9.2 ms. As the ITD increased to 4 ms, the threshold increased to 24.2 ms. At the 800-Hz center frequency, as the ITD increased from 0 to 2 ms, the mean duration threshold increased from 10.8 to 22.8 ms. As the ITD increased to 4 ms, the threshold increased to 60.0 ms. Obviously, the effect of the ITD on the duration threshold for narrowband noises was affected by the center frequency. Detection of the BIC in high-frequency narrowband noises was much more vulnerable to the change in the ITD than that in low-frequency noises. This important feature can be indicated by the slope of the best-fitting line in each panel. With the increase in the center frequency, the slope increased considerably. The largest effect occurred when the center frequency was 3200 Hz.

For the seven participants who could detect the BIC in each of the noise types at all the ITDs, a 3 (ITD) $\times$ 6 (noise type) within-subject ANOVA showed that the main effect of ITD, the main effect of noise type, and the interaction between the two factors were all significant ($p < 0.001$ for all).

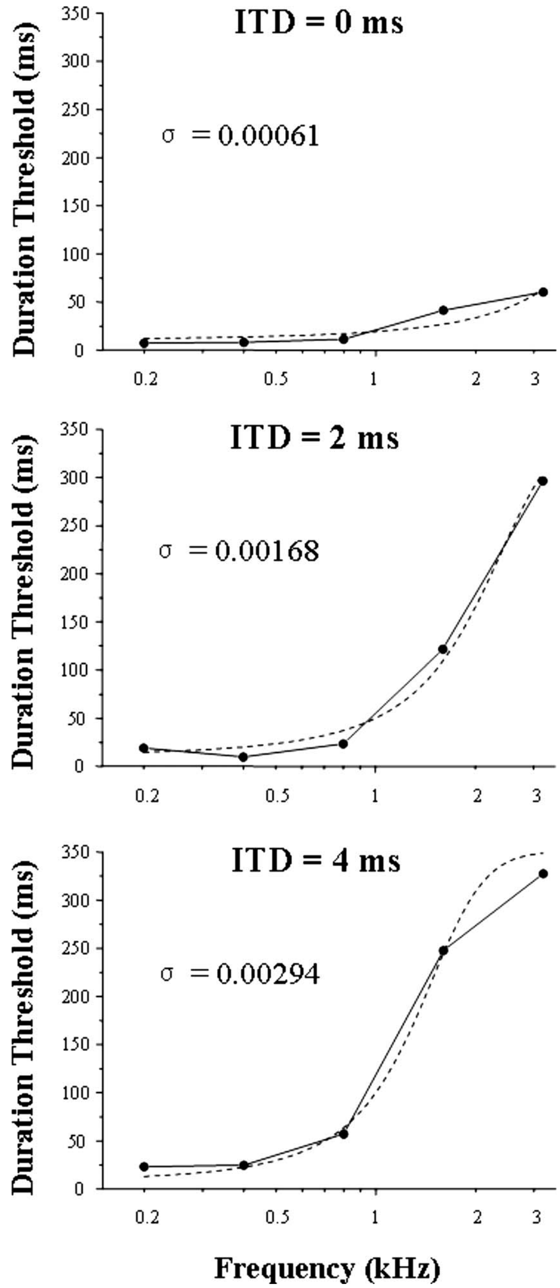

FIG. 4. The mean duration threshold across seven (young) participants tested in Experiment 2 for detecting the BIC in narrowband noises as a function of the center frequency when the ITD was 0 ms (top panel), 2 ms (middle panel), or 4 ms (bottom panel). The broken curve in each panel represents the logistic function for fitting the duration threshold as a function of the center frequency. σ is the slope parameter of the psychometric function.

Separate one-way within-subject ANOVAs showed that at each of the ITDs, the effect of noise type was significant ($p<0.001$ for all), confirming that detection of the BIC was noise-type dependent. Moreover, separate one-way within-subject ANOVAs showed that for each of the six noise types the effect of ITD was significant ($p<0.001$ for all).

To further estimate the interaction of ITD and center frequency on the BIC detection, Fig. 4 shows the BIC duration thresholds for narrowband noises as a function of the center frequency for the seven participants who could detect the BIC in each of the noise types at all the ITDs, when the ITD was 0 ms (top panel), 2 ms (middle panel), or 4 ms (bottom panel). As indicated in Fig. 4, with increasing ITD from 0 to 4 ms, the detection of BIC became more affected by the center frequency.

We used the following logistic function to fit the threshold data across center frequencies at each of the ITDs (the broken curve) using the Levenberg–Marquardt method (Wolfram, 1991):

$$y = \frac{350}{1 + e^{-\sigma(x-\mu)}},$$

where y is the threshold at the frequency x, μ is the frequency corresponding to 50% of the maximum y value on the psychometric function at an ITD condition, and σ determines the slope of the psychometric function. The σ value at each of the ITDs is indicated in Fig. 4. Clearly, with increasing ITD from 0 to 4 ms, the slope parameter σ became larger, indicating that the BIC detection threshold increased faster with the center frequency as the ITD increased. Note that the same function can also fit the data across ITD at each of the center frequencies.

C. Discussion

The results of Experiment 2 show that the duration threshold for detecting the BIC in narrowband noises with the fixed bandwidth (1/3 octaves) largely depended on the center frequency. With increasing center frequency from 200 to 3200 Hz, the duration threshold for detecting the BIC progressively increased. Thus the results support the view that detecting the dynamic changes in interaural correlation is easier for low-frequency narrowband noises than for high-frequency narrowband noises (Akeroyd and Summerfield, 1999). Although Bernstein and Trahiotis (1999) suggested that temporal processing for binaural detection must be accounted for differently for high-frequency and low-frequency stimuli, a gradual degradation of processing dynamic changes in interaural correlation may occur as the frequency changes from low to high. Moreover, since the duration threshold for detecting the BIC in the wideband noise was very close to that for low-frequency (200 or 400 Hz) narrowband noise, low-frequency components in wideband noises seem to make a majority of the contribution to the BIC detection. The results also support the view proposed by Akeroyd and Summerfield (1999) that high-frequency components in wideband noises would not interfere with the detection of the transient break in interaural correlation. The frequency dependency of the sensitivity to the dynamic change in interaural correlation may be associated with both the frequency dependency of the discrimination of interaural-correlation difference (Culling *et al.*, 2001) and the frequency dependency of the perceived auditory source width of interaurally correlated noise stimuli (Mason *et al.*, 2005). Since fine-structure ITDs of acoustic stimuli cannot be processed well when the frequency becomes higher than 1500 Hz, in Experiment 2 a sharp increase in the duration threshold occurred when the center frequency changed from 800 to 1600 Hz. Note that since the maximum value of the BIC used in Experiment 2 was 330 ms, the change in duration threshold when the center frequency changed from 1600 to 3200 Hz (see Figs. 3 and 4) might be underestimated due to a potential ceiling effect particularly when the ITD was 2 or 4 ms.

The center-frequency effect also interacts with the ITD effect on the detection of BIC. For each of the noise types used in this experiment, with the change in the ITD from 0 to 4 ms, the perceptual fusion of the noises presented to the two ears was not broken but the threshold of detecting the BIC increased. Particularly, the rate of the threshold elevation became monotonically larger as the center frequency of narrowband noise was increased (Fig. 4). These results suggest that the interaural integration of high-frequency acoustic components degenerates faster with increasing ITD than that of low-frequency components, supporting the reports that a great range of ITDs can be lateralized when low frequencies are present than when only high frequencies are available (Blodgett *et al.*, 1956; Mossop and Culling, 1998). Thus, center frequency cooperates with ITD in determining the interaural integration of correlated noises.

IV. SUMMARY

This study provides evidence that the interaural integration of correlated noises is affected by ITD, aging, and center frequency (the last for narrowband noises). Even when listeners do not experience a breakdown of the perceptual fusion of two correlated noises presented at the two ears with the increase in the ITD, there is a temporal degeneration of the interaural integration of fine-structure acoustic information. In younger listeners with normal hearing, this temporal degeneration of the interaural integration for narrowband noise is center-frequency dependent: high-frequency noises degenerate faster with increasing ITD than low-frequency noises. Moreover, there is an age-related decline in the ability to integrate binaural noises particularly when an ITD is introduced.

Processing the similarity and dissimilarity of sound waves arriving at the two ears contributes to binaural perceptual phenomena including the precedence effect (Blauert and Divenyi, 1988; Litovsky *et al.*, 1999; Scharf, 1974; Shinn-Cunningham *et al.*, 1995; Trahiotis *et al.*, 2005; Yang and Grantham, 1997a, 1997b). Since interaural integration is important for auditory perception in noisy, reverberant environments (Bregman, 1990), it will be necessary in the future to investigate the relationship between the age-related changes in interaural integration and age-related difficulties in recognizing sound sources (e.g., speech) in such adverse situations.

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[1]In this manuscript, we use the term "interaural correlation" following the definition by Grantham (1995): "The interaural correlation of a sound is the correlation between the sound waveform presented to the left ear and the sound waveform presented to the right ear after one waveform is shifted in time to maximize the correlation." We also notice that a related term, "coherence," has been used by some authors. For example, as proposed by Blauert (1982), "the degree of coherence k is defined as the maximum absolute value of the normalized cross-correlation function of two signals." According to our present knowledge, the term interaural correlation, but not the term "interaural coherence," has been used in a large number of (over 100) papers published in primary journals in the field. Particularly, to keep the consistency with the two previous studies that are most related to the present study (e.g., Akeroyd and Summerfield, 1999; Boehnke *et al.*, 2002), interaural correlation, instead of interaural coherence, is used in this manuscript.

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