

Aging Effects on Detection of Spectral Changes Induced by a Break in Sound Correlation

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Objectives: Previous studies have shown that both younger adults and older adults with clinically normal hearing are able to detect a break in correlation (BIC) between interaurally correlated sounds presented over headphones. This ability to detect a BIC improved when the correlated sounds were presented over left and right loudspeakers rather than over left and right headphones, suggesting that additional spectral cues provided by comb filtering (caused by interference between the two channels) facilitate detection of the BIC. However, older adults receive significantly less benefit than younger adults from a switch to loudspeaker presentation. It is hypothesized that this is a result of an age-related reduction in the sensitivity to the monaural spectral cues provided by comb filtering.

Design: Two experiments were conducted in this study. Correlated white noises with a BIC in the temporal middle were presented from two spatially separated loudspeakers (positioned at ± 45 -degree azimuth) and recorded at the right ear of a Knowles Electronic Manikin for Acoustic Research (KEMAR). In Experiment 1, the waveforms recorded at the KEMAR's right ear were presented to the participant's right ear over a headphone in 14 younger adults and 24 older adults with clinically normal hearing. In Experiment 2, 8 of the 14 younger participants participated. Under the monaurally cueing condition, the waveforms recorded at the KEMAR's right ear were presented to the participant's right ear as Experiment 1. Under the binaurally cueing condition, waveforms delivered from the left loudspeaker and those from the right loudspeaker were recorded at the KEMAR's left and right ear, respectively, thereby eliminating the spectral ripple cue, and were presented to the participant's left and right ears, respectively. For each of the two experiments, the break duration threshold for detecting the BIC was examined when the interloudspeaker interval (delay) (ILI) was 0, 1, 2, or 4 msec (left loudspeaker leading).

Results: In Experiment 1, both younger participants and older participants detected the BIC in the waveforms recorded by the right ear of KEMAR, but older participants had higher detection thresholds than younger participants when the ILI was 0, 2, or 4 msec without an effect of SPL shift between 59 and 71 dB. In Experiment 2, each of the eight younger participants was able to detect the occurrence of the BIC in either the monaurally cueing or binaural-cueing condition. In addition, the detection threshold under the monaurally cueing condition was substantially the same as that under the binaurally cueing condition at each of the four ILIs.

Conclusions: Younger adults and older adults with clinically normal hearing are able to detect the monaural spectral changes arising from comb filtering when a sudden drop in intersound correlation is introduced. However, younger adults are more sensitive than older adults are, at detecting the BIC. The findings suggest that older adults are less able than younger adults to detect a periodic ripple in the sound spectrum. This age-related ability reduction may contribute to older adults' difficulties in hearing under noisy, reverberant conditions.

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INTRODUCTION

In noisy reverberant environments, older listeners often find it difficult to understand speech (e.g., Nabelek & Robinson 1982; Gelfand et al. 1988; Helfer & Wilber 1990; Cheesman et al. 1995; Huang et al. 2008a). Older adults' speech comprehension difficulties in such situations may arise from their failure to perceptually isolate target speech from competing sounds, because they cannot easily associate the myriad sound reflections with the appropriate sound source (see Schneider et al. 2007). To parse the auditory scene (Bregman 1990) into its component sound sources, the auditory system needs to both integrate the direct wave from the target sound with its correlated reflections and segregate the target sound waves from sound waves generated by other sources. In other words, the auditory system has to be able to recognize whether one wave is highly correlated with another.

Human listeners with normal hearing are able to detect small differences in cross-correlation between a wideband noise delivered at one ear and its copy delivered at the other ear (e.g., Pollack & Trittipoe 1959; Gabriel & Colburn 1981; Akeroyd & Summerfield 1999; Boehnke et al. 2002; Goupell & Hartmann 2006). Modulation of the interaural correlation of wideband noises changes the percept of the noises (Blauert & Lindemann 1986; Hall et al. 2005). The ability to differentiate highly correlated sounds from uncorrelated sounds can be estimated by measuring the ability to detect a break in correlation (BIC) between the noises presented over left and right headphones (where a BIC refers to a change in interaural correlation from 1 to 0 and then a return to 1) (Akeroyd & Summerfield 1999; Boehnke et al. 2002; Huang et al. 2008b, 2009a,b; Li et al. 2009). Introducing a change in interaural correlation can change both the loudness (Culling 2007) and the diffuseness/compactness (Blauert & Lindemann 1986) of the noises. Our recent studies have shown that there are age-related declines in the ability to detect a BIC, particularly when an interaural time delay between correlated left- and right-ear sounds is introduced, suggesting that older adults are less able than younger adults to recognize when the sound in one ear is a delayed version of the sound in the other ear (Huang et al. 2009b; Li et al. 2009). Wang et al. (2011) have argued that a loss of neural synchrony with age (Starr et al. 1996; Miranda & Pichora-Fuller 2002; Cowper-Smith et al. 2010) is a contributing factor to older adults' reduced ability to recognize when a sound in one ear is a delayed version of the sound in the other. To detect a change in interaural correlation, the central nervous system has to compare the neural representation of the left- and right-ear signals. A loss of neural synchrony in the auditory nervous system would disrupt this comparison.

However, it is also possible that age-related losses in sensitivity to monaural spectral cues may also contribute to older

adults' reduced ability to detect a change in correlation when sounds are presented in a sound field. When the correlated sounds are presented over left and right loudspeakers rather than over left and right headphones, detection of the occurrence of the BIC becomes much easier for both younger and older adults (Li et al. 2009), suggesting that listeners are able to benefit from the comb filtering, which occurs when wavefronts from the left and right loudspeakers intersect (Bilsen 1966; Narins et al. 1979; de Cheveigné 1993). However, older adults receive significantly less benefit than younger adults do from this change in stimulus-presentation manner (Li et al. 2009).

When a broadband stimulus is delayed by τ sec and added back to itself, the resulting stimulus has a rippled power spectrum, in which power sinusoidally varies as a function of frequency, and the spacing between the peaks in the spectrum (measured in Hertz) is equal to the reciprocal of the delay ($1/\tau$). Modulating the spectrum this way gives rise to a perception that the noise has a pitch that is equal to approximately $1/\tau$ (see Yost et al. 1978; Hartmann 1997). It is interesting to note that the ability to resolve spectral ripple has been shown to be correlated with speech reception in noise in both cochlear implant users (Won et al. 2007) and normal listeners (Henry et al. 2005). Hence, age-related changes in this ability could contribute to the difficulties experienced by older adults in complex auditory environments.

In addition, the introduction of a novel independent noise will change the nature of the spectral ripple at an ear, thereby providing a monaural acoustic cue that a second sound source has appeared in the acoustic scene. To see how a sudden change in the periodicity of the spectrum of the sound impinging on a single ear can be used to detect the onset of a new sound or the offset of one that is just finished, consider the following simple acoustic scene. In this scene, there is a single sound-reflecting barrier in an otherwise anechoic environment, with the barrier situated perpendicular to the listener's right ear at a distance of 3 m and with a single band-limited (0–1 kHz) omnidirectional white noise sound source located to the listener's left. The wavefront arriving at the listener's right ear will travel a further 3 m before encountering the barrier, where it is reflected back toward the right ear. The time that it takes to make this additional 6 m journey will be approximately 6/343 sec (assuming that the speed of sound is 343 m/sec). Let $x(t)$ be the amplitude of the direct wave impinging on the right eardrum from the left-side sound source. The sum of the direct and reflected wave arriving at the right ear is given by $x(t) + x(t - 6/343)$ if we assume, for simplicity, that the sound is not attenuated with distance and the barrier is a perfect reflector. Under these conditions, the long-term spectrum of the right-ear sound (Fig. 1A) will be $2 + 2 \cos(2 \pi f 6/343)$ $\{0 < f < 1000\}$. Now, suppose that a second independent broadband (0–1 kHz) omnidirectional sound source is placed 2 m to the listener's right. It will take 2/343 sec for the direct wavefront to reach the right ear, and 4/343 sec for the reflection of that wavefront off of the barrier to reach the same ear. Let $y(t)$ specify the amplitude of the direct wavefront at the right ear from this second source. The sum of the direct and reflected waves from this source then becomes $y(t) + y(t - 2/343)$, and the spectrum of the sound from this source at the right ear (Fig. 1B) is given by $2 + 2 \cos(2 \pi f 2/343)$ $\{0 < f < 1000\}$. Finally, when both sound sources are on simultaneously, neglecting the effects of diffraction around the head, the spectrum of the sound arriving at the right ear from

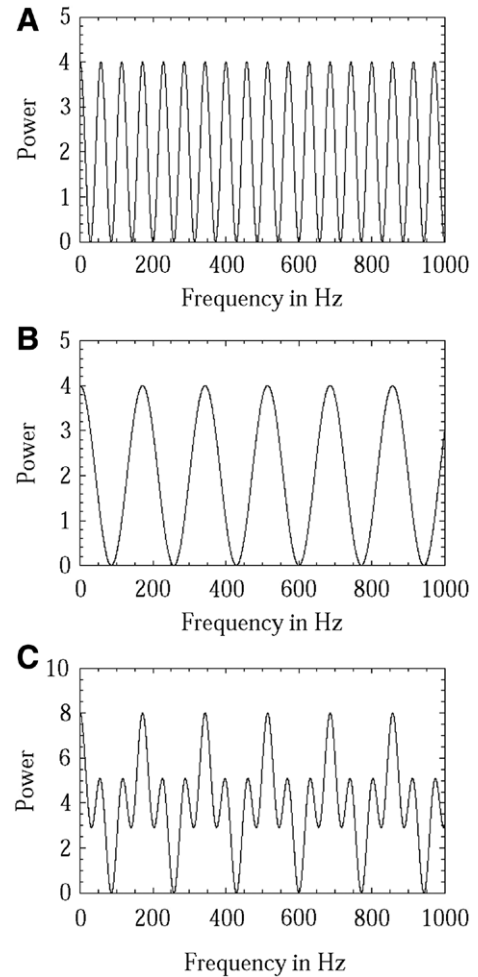


Fig. 1. A, Long-term spectrum for the sum of a 1 kHz band-limited white noise with a delayed version of itself, where the delay is 6/343 sec. B, Long-term spectrum for the sum of a 1 kHz band-limited white noise with a delayed version of itself, where the delay is 2/343 sec. C, Sum of signals in conditions (A) and (B).

both sources (Fig. 1C) becomes $4 + 2 \times \cos(2 \pi f 6/343) + 2 \times \cos(2 \pi f 2/343)$. Note that switching the right-side sound on and off changes the nature of spectral ripple from that shown in Figure 1A to that shown in Figure 1C. Hence, the appearance or disappearance of a broadband sound when another broadband sound is present will change the periodicity of the ripple pattern of the spectrum of the sound at an ear, thereby facilitating scene analysis.

Thus, an investigation of the effect of auditory aging on the ability to detect sudden changes in monaural spectral ripple may help explain how auditory aging affects a listener's ability to detect the onset or offset of new sound sources in the sound field.

We hypothesize that one of the reasons that older adults are less sensitive to BICs embedded in noises delivered when the noises are presented over spatially separated loudspeakers is an age-related loss in spectral resolution. To take advantage of the cues provided by comb filtering, the individual's auditory filter has to be sufficiently narrow to enable her/him to detect a regular pattern of peaks and troughs across the bank of filters. A broadening of the auditory filter width with age (see Patterson

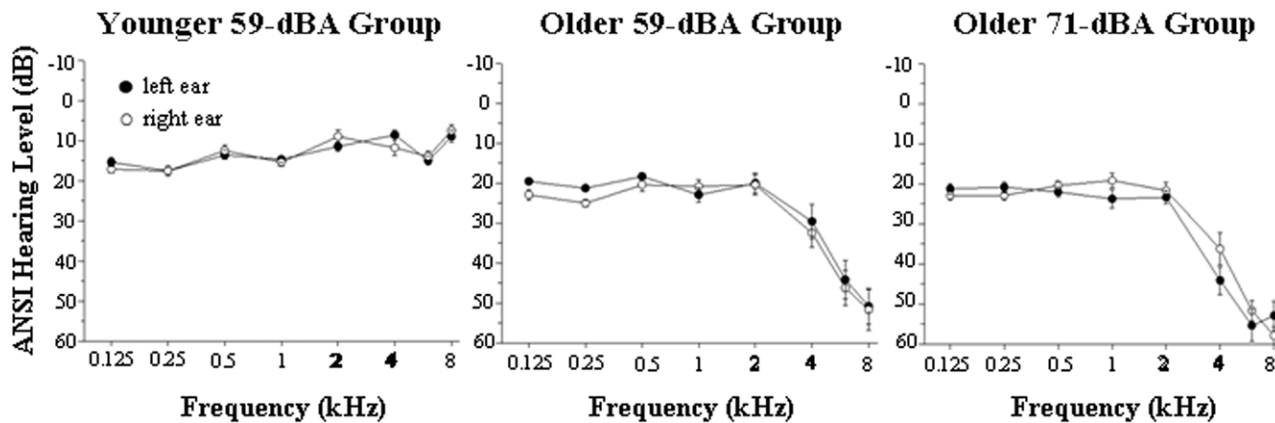


Fig. 2. Group-mean hearing thresholds in the left and right ears for the three participant groups in Experiment 1. ANSI = American National Standards Institute (S3.6-1989). The error bars indicate the SE of the threshold.

et al. 1982) would diminish this ability. Alternatively, an age-related loss in the ability to attend to or scan a bank of filters to detect pattern changes could also contribute to decrements in the ability to detect monaural spectral ripple.

In this study, we investigated how age influences a person's ability to detect a change in the monaural spectral ripple that accompanies a BIC when the two sounds are presented over loudspeakers. In Experiment 1, the sound arriving at the right ear of a Knowles Electronics Manikin for Acoustic Research (KEMAR) was recorded in an anechoic chamber when identical noises (except for a BIC in the temporal middle of the noise) were played over loudspeakers located 45 degrees to the left and right of the KEMAR with interloudspeaker intervals (ILIs, the onset delays between sounds delivered from the 2 loudspeakers) of 0, 1, 2, and 4 msec. These recorded waveforms were presented over a headphone to the right ear of younger and older adults, and the duration threshold for detecting the BIC was examined when the ILI was 0, 1, 2, or 4 msec.

In Experiment 2, the sound arriving at the left ear of the KEMAR was recorded when only the left loudspeaker was active, and the sound arriving at the right ear of the KEMAR was recorded when only the right loudspeaker was active. The left- and right-ear recorded sounds were then played over headphones to participants with ILIs of 0, 1, 2, or 4 msec. This headphone presentation preserved the interaural-timing differences provided by the left- and right-loudspeaker sounds while eliminating the crosstalk between them. Hence, Experiment 2 provided a way of evaluating the effects of ILIs without the additional monaural cues provided by comb filtering.

EXPERIMENT 1

Participants and Methods

Participants • Fourteen younger adult students studying at Peking University (20–26 years old; mean age = 22.4 years; 9 women and 5 men) and 24 older adults recruited from local communities near Peking University (60–70 years old; mean age = 64.5 years; 17 women and 7 men) participated in Experiment 1. All the participants had symmetrical hearing (≤ 15 dB difference between the 2 ears). Pure-tone hearing thresholds were no more than 25 dB HL between 125 and 8000 Hz for younger participants, no more than 25 dB HL between 125 and

500 Hz, and no more than 40 dB HL between 1000 and 4000 Hz for older participants. Although hearing thresholds at 8000 Hz were also measured in older participants, they were not used for screening purposes. Figure 2 presents group-mean hearing levels for the three participant groups as a function of frequency. Because the thresholds of older adults exceeded 25 dB HL at the higher frequencies, the older participants are best characterized as being in the early stages of presbycusis.

Apparatus and Stimuli • Experiments 1 and 2 were conducted in an anechoic room (560 × 400 × 193 cm; Beijing CA Acoustics Company Ltd., Beijing, China). Gaussian broadband noise bursts were generated using the MATLAB Function Library at a sampling rate of 48 kHz with a 16-bit amplitude quantization and low-pass filtered at 10 kHz with a 512-point low-pass finite impulse response filter. Noise bursts with a duration of 2000 msec (including 30 msec rise/fall times) were then created, transduced using the Creative Sound Blaster PCI128, and presented over two balanced loudspeakers (DA-BM6A, Dynaudio Acoustic, Denmark) in the frontal azimuthal plane at the left and right 45-degree positions with respect to the median plane. The loudspeaker height was approximately ear level for a seated listener with an average body height. The distance from each of the loudspeakers and the center of the participant's head was 2 m.

Two types of noises were presented over the two loudspeakers: one having no BIC and the other having a BIC in the temporal middle. For noises without the BIC, the right-loudspeaker noise was a copy of the left-loudspeaker noise. For noises with the BIC, the right-loudspeaker noise was also identical to the left-loudspeaker noise, except for the substitution of a transient BIC introduced into the temporal middle of the 2 sec noise by substituting an independent noise segment to the left source. The noise coming from the left loudspeaker led the noise coming from the right loudspeaker by 0, 1, 2, or 4 msec (i.e., ILI). The duration of the BIC varied between 1 and 300 msec, with a resolution of 1 msec.

A KEMAR was placed at the center of the anechoic room for recording noises delivered from the two loudspeakers at each of the ILIs (Fig. 3). Waveforms recorded at the right ear of the KEMAR were processed using the Creative Sound Blaster PCI128 and passed through a computer-operated Aurical audio diagnostic fitting system (Madsen, Copenhagen, Denmark) for controlling the SPL. Fresh noises were also generated for each trial.

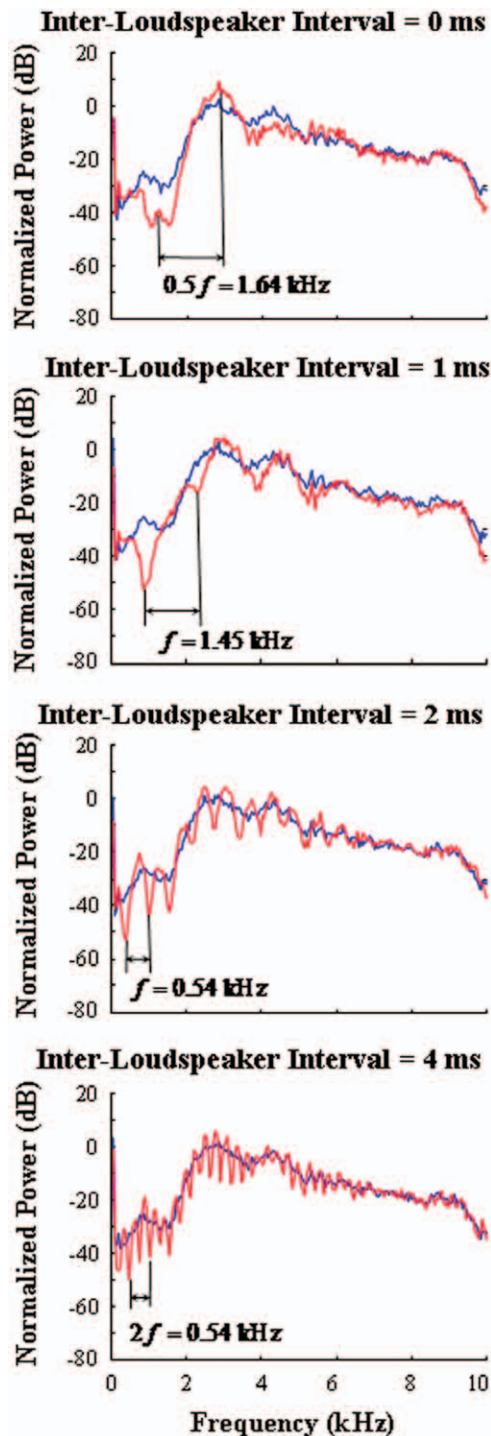


Fig. 3. Spectra of noise signals that were recorded at the right ear canal of a KEMAR placed at the center of the anechoic room. The white noises (duration = 2,000 msec; 0–10 kHz) were delivered from the two loudspeakers in the frontal azimuthal plane at the left and right 45-degree positions with respect to the median plane. They were either correlated (red curves) or independent (uncorrelated) (blue curves). The loudspeaker height was ear level for the KEMAR, and the distance from each of the loudspeakers and the center of the KEMAR was 200 cm. The interloudspeaker interval was 0, 1, 2, or 4 msec (the left channel was leading). The periodicities in the long-term power spectrum measured at the right ear of the KEMAR were 3.27, 1.45, 0.54, and 0.27 kHz for delays of 0, 1, 2, and 4 msec, respectively. KEMAR, Knowles Electronics Manikin for Acoustic Research.

In the KEMAR, the distance from one ear to the center of the head is 7.6 cm. The two loudspeakers were located 45 degrees to the left and right from the center of head, each at a distance of 2 m from the center of the head. Hence, simple trigonometry shows that the distance from the left speaker to the right ear is 2.0544 m and the distance from the right speaker to the right ear is 1.9470 m. Assuming that the speed of sound is 343 m/sec, it will take approximately $2.0544/343 = 0.005990$ sec for low frequencies of the sounds to reach the right ear from the left loudspeaker and $1.9470/343 = 0.005677$ sec for the sound from the right loudspeaker to reach the right ear. If there is no interloudspeaker delay, the left-ear sound will arrive at the right ear $0.005990 - 0.005677 = 0.000313$ sec after the right-loudspeaker sound has arrived at the right ear. Hence, the sinusoidal periodicity imposed on the summed waveforms from the left and right loudspeakers (in the absence of the KEMAR) should be approximately $1/0.000313 = 3,192$ Hz. If the left loudspeaker leads the right by 1 msec, the left loudspeaker sound will arrive at the right ear $0.001 - 0.000313 = 0.000687$ sec before the sound coming from the right loudspeaker. Hence, the periodicity in the long-term spectrum of the sum of the two signals at the location of the right ear should be approximately 1,456 Hz. Similar calculations indicate that, when the left loudspeaker leads the right loudspeaker by 2 and 4 msec, the periodicity in the sum of the left- and right-loudspeaker sounds should be 593 and 271 Hz, respectively.* Figure 3 shows that the periodicities in the long-term power spectrum measured at the right ear of the KEMAR closely correspond to these calculated periodicities (3.27, 1.45, 0.54, and 0.27 kHz for delays of 0, 1, 2, and 4 msec).

The recorded sound files were presented to the participant's right ear by a headphone (Model HDA 200, MADSEN, Denmark). Calibration of the sound level of the headphone was carried out with the Larson Davis Audiometer Calibration and Electroacoustic Testing System (AUDit and System 824; Larson Davis, Depew, NY) with "A" weighting. The SPL for 14 younger participants and 12 (9 females and 3 males; 60–70 yrs old; mean age = 64.7 yrs) out of the 24 older participants was fixed at 59 dB. To improve the audibility of high-frequency components of the noise stimuli in older participants, largely based on the threshold difference at 2 kHz between younger and older participants, the SPL for other 12 older participants (8 females and 4 males; 60–70 years old; mean age = 64.2 years) was fixed at 71 dBA, leading to the case that the SPL for this older adult group was 10 to 12 dB higher than that for the younger adult group.

Procedure • The participant initiated a trial by pressing a key on the computer keyboard. Two presentations of noises, recorded from the right ear of the KEMAR, were delivered to the participant's right ear. The BIC occurred with equal probability in the first or second presentation (one with the BIC and the other one without the BIC). The offset-to-onset time interval between the two presentations was 1000 msec. Within a trial, the two presentations had the same ILI. The participant's task was to identify which of the two presentations contained "a sudden change" in the temporal middle of the noise.

In a testing session, the starting BIC duration for younger participants was 50 msec at the 0 msec or 1msec ILI, 100 msec

* These periodicities will somewhat be modulated by the head-related transfer functions for the sounds coming from the left and right loudspeakers and, hence, may somewhat vary from these values, depending on the locations of peaks and troughs in these head-related transfer functions.

at the 2 msec ILI, and 300 msec at the 4 msec ILI. The starting BIC duration for older participants was 100 msec at the 0 msec ILI, 200 msec at the 1 msec ILI, and 300 msec at the 2 or 4 msec ILI.

The BIC duration was decreased after three consecutive correct identifications of the presentation containing the BIC and increased after one incorrect identification, using a three-down-one-up procedure (Levitt 1971). The initial step size for changing the BIC duration was 16 msec, and the step size was reduced by a factor of 0.5 with each reversal of direction until the minimum size of 1 msec was reached. Feedback to participants' responses was visually provided at each trial. A test session was terminated after 10 reversals in direction, and the threshold for that session was defined as the average duration for the last 6 reversals. Test sessions were repeated three times for younger participants, and the arithmetic average over the three session thresholds was defined as the younger participant's threshold. Test sessions were repeated four times for older participants, and the arithmetic average over the three

lowest session thresholds was defined as the older participant's threshold. Fresh noises were generated for each trial.

To ensure that each participant understood the experimenter's instructions and became familiar with the procedure, a brief training session preceded the experiment proper.

RESULTS

In Experiment 1, when the BIC duration was sufficiently long, all the younger and older participants could detect the occurrence of the BIC around the temporal middle of the noise at each of the four ILIs. Duration thresholds for younger individuals and those for the two groups of older individuals are shown in Figure 4A–C. These three panels indicate that there is a considerable overlap between younger and older adults. Group-mean duration thresholds at each of the four ILIs for younger participants and the two groups of older participants are shown in Figure 4D. For both younger and older participants, the duration threshold generally became larger as the ILI was increased.

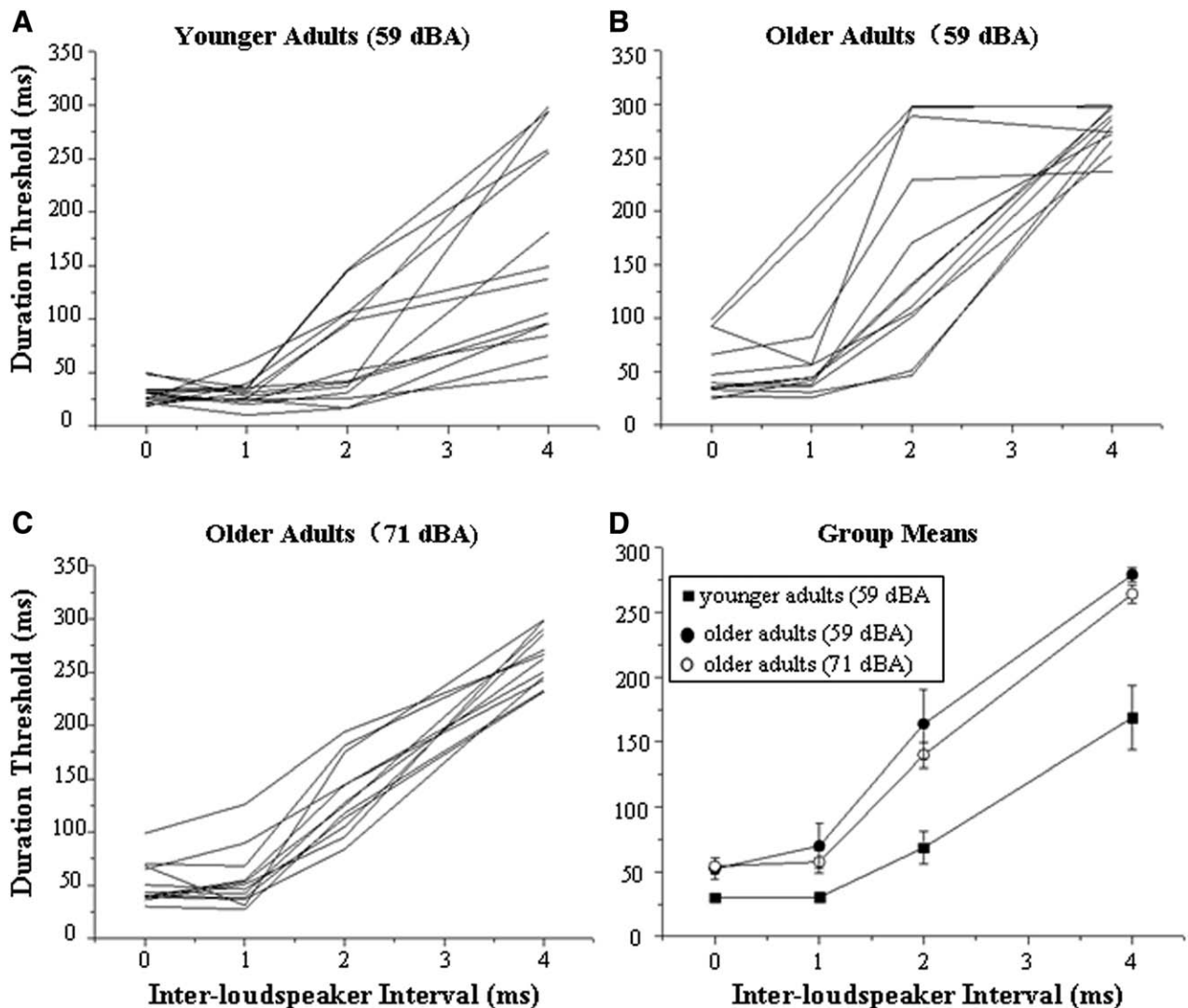


Fig. 4. Duration thresholds for using monaural spectral cues in Experiment 1 to detect the break in correlation embedded in correlated wideband noises delivered over two spatially separated loudspeakers in younger and older participants at each of the four interloudspeaker intervals (0, 1, 2, and 4 msec). Panel A, Younger individuals' thresholds when the SPL was 59 dBA. Panel B, Older individuals' thresholds when the SPL was 59 dBA. Panel C, Older individuals' thresholds when the SPL was 71 dBA. Panel D Group-mean threshold for the three groups of participants. Error bars in this and the next figure represent the SEM.

Also, the group-mean threshold was larger for older participants than for younger participants (Fig. 4D), and the group difference between the younger and older participants seemed to be ILI determined; in particular, the difference was larger when the ILI was 2 or 4 msec than when the ILI was 0 or 1 msec.

A 4 (ILI: 0 msec, 1 msec, 2 msec, 4 msec) by 3 (group: younger participant, older participant with an SPL of 59 dBA, older participant with an SPL of 71 dBA) two-way analysis of variance (ANOVA) shows that the main effect of ILI was significant ($F[3, 105] = 201.540; p < 0.001$), the main effect of group was significant ($F[2, 35] = 13.927; p < 0.001$), and the interaction between ILI and group was significant ($F[6, 105] = 4.675; p < 0.001$).

Separate between-subject ANOVAs were conducted for each of the ILIs. These ANOVAs showed that the group effect was significant at the ILIs of 0, 2, and 4 msec (0 msec: $F[2, 35] = 5.358, p = 0.009$; 2 msec: $F[2, 35] = 8.043, p = 0.010$; 4 msec: $F[2, 22] = 13.479, p < 0.001$) but not significant at the ILI of 1 msec ($F[2, 35] = 3.849; p = 0.031$). The significance level was adjusted to 0.05/4. Post hoc tests show that, at the ILI of 0, 2, or 4 msec, the group-mean duration threshold for detecting the BIC in the younger group was significantly shorter than that in each of the two older groups ($p < 0.05$ after Bonferroni adjustment). However, there was no significant difference in the threshold between the two older groups.

EXPERIMENT 2

The results of Experiment 1 indicate that both older and younger participants with clinically normal hearing were able to detect the BIC by using the monaural cues when the BIC duration was sufficiently long. Nevertheless, when the noise stimuli containing the BIC are presented by the two (left and right) loudspeakers, not only monaural but also binaural cues are available for listeners to detect the occurrence of the BIC. Experiment 2 of this study was to compare the BIC-duration threshold for monaural cues with that for binaural cues in some younger participants who participated in Experiment 1.

Participants and Methods

Participants • Eight younger adult students (19–24 years old; mean age = 22 years; 4 women and 4 men) who participated in Experiment 1 participated in Experiment 2.

Apparatus and Stimuli • The apparatus and stimuli used in Experiment 2 were the same as used in Experiment 1. However, in addition to the KEMAR right-ear recordings of sound waves simultaneously delivered from the two loudspeakers (for inducing monaural spectral cues), other KEMAR recordings were carried out for inducing binaural cues: sound waves delivered from the left loudspeaker were recorded only at the left ear, and those from the right loudspeaker were recorded only at the right ear. Then, the bilaterally recorded signals were presented to the participant’s left and right ears, with various ILIs (0, 1, 2, or 4 msec), using the headphones. The binaurally presented noise signals either contained or had no BIC. Thus, under the binaural-cueing condition, there was no crosstalk between the sound waves delivered from the two loudspeakers and, thus, no spectral ripple cue for detecting the BIC. Recorded waveforms were also transferred using the Creative Sound Blaster PCI128 and passed through an AURICAL system. Fresh noises were

also generated for each trial. The SPL at each of the participant’s ears was fixed at 59 dBA.

Procedure • The procedure used in Experiment 2 was the same as that used in Experiment 1.

RESULTS

In Experiment 2, when the BIC duration was sufficiently long, all the eight younger participants could detect the occurrence of the BIC around the temporal middle of the noise at each of the four ILIs under either the binaural- or the monaural-cueing condition. Individual- and group-mean duration thresholds at each of the four ILIs are shown in Figure 5. In general,

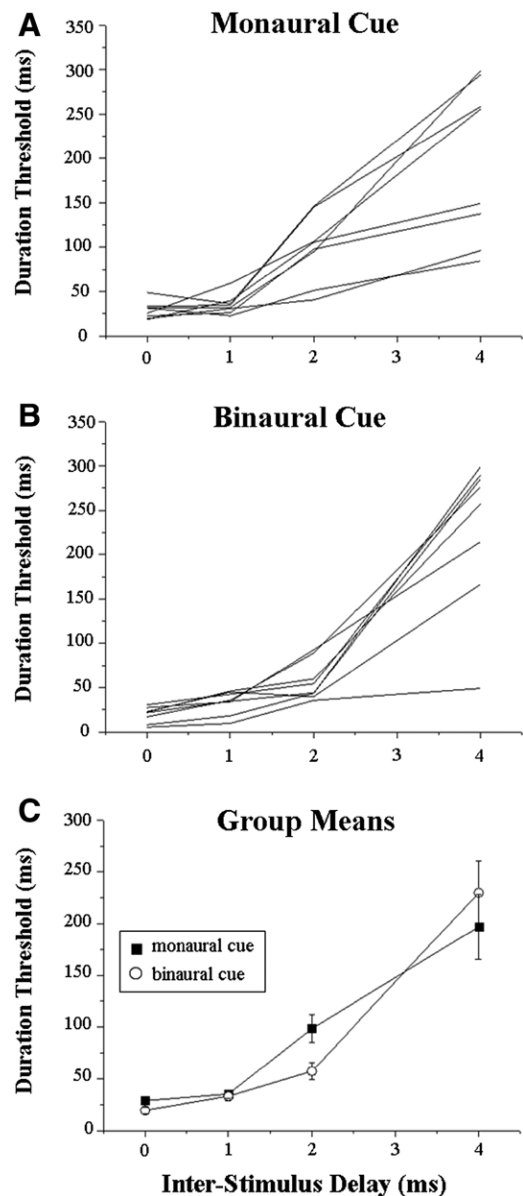


Fig. 5. Comparison of the duration thresholds for detecting a break in correlation between the monaural- and the binaural-cueing condition in eight younger participants at each of the four interloudspeaker intervals (0, 1, 2, and 4 msec). Panel A, Individual participants’ thresholds under the monaural-cueing condition. Panel B, Individual participants’ thresholds under the binaural-cueing condition. Panel C, Group-mean threshold at each of the two cueing conditions. Note that the data in Figure 5A are a subset of those in Figure 4A.

for each of the two cueing conditions, the duration threshold for detecting the BIC became larger with increasing the ILI.

A four (ILI) by two (presentation condition: binaural, monaural) two-way ANOVA shows that the main effect of ILI was significant ($F[3, 21] = 52.102; p < 0.001$), the main effect of cueing condition was not significant ($F[1, 7] = 0.172; p = 0.691$), and the interaction between two factors was marginally significant ($F[3, 21] = 2.134; p = 0.042$). Figure 5C indicates that the interaction is a result of the binaural cue being more effective at 2 msec (produced a shorter duration threshold), whereas the monaural ripple cue was more effective at 4 msec.

DISCUSSION

In this study, we used two spatially separated (left and right) loudspeakers to present correlated white noises with a BIC in the temporal middle to younger adults and older adults. In Experiment 1, the sound stimuli delivered from the two loudspeakers were recorded at the right ear canal of a KEMAR, and then, the recorded waveforms were presented to the participant's right ear using a headphone. Because frequency ripple is induced by the crosstalk between two correlated broadband noises delivered from the two spatially separated loudspeakers (comb filtering; Bilsen 1966; Yost et al. 1978; Narins et al. 1979; de Cheveigné 1993), the BIC eliminates the frequency ripples. Thus, a cue to the detection of a BIC is a change in the ripple frequency. In the natural environment, a change in monaural ripple frequency would accompany the introduction or cessation of an independent broadband source when other broadband sources are present and could facilitate auditory scene analysis. As shown in Figure 3, with the increase of the ILI from 0 to 1, 2, and 4 msec, the ripple period (along the frequency dimension) becomes shorter. Hence, the ability to benefit from this monaural cue will depend on the listener's ability to resolve periodic ripples in the sound spectrum.

The results of Experiment 1 show that, when the BIC duration was sufficiently long, both younger participants and older participants were able to use the monaural cues to detect the occurrence of the BIC at each of the ILI. Thus, this study provided substantial support to our speculation that both younger and older listeners benefit from monaural cues arising from interaction of correlated sound waves in detecting a sudden drop in intersource correlation (Li et al. 2009).

With increasing ILI, the duration threshold for detecting the BIC became larger for both age groups. It is important to note that older participants needed longer BIC durations than younger participants did to detect the BIC, particularly when the ILI increased to 2 or 4 msec. One possible reason for this result is that the reduced ability of older adults to detect BICs based on monaural spectral cues is related to the loss of frequency resolution, which typically accompanies presbycusis (Patterson et al. 1982), or to age-related high-frequency hearing loss (leading to loss of ripple information in the high-frequency region). To examine whether the duration threshold for detecting the BIC was related to audiometric thresholds, the pure-tone thresholds were assigned into two categories: low frequency (125, 250, 500, and 1000 Hz) and high frequency (2000, 4000, 6000, and 8000 Hz). Mean pure-tone thresholds across the two ears were then calculated for the low- and high-frequency pure-tone averages. For each of the three participant groups, the threshold for detecting the BIC at any ILIs was not significantly correlated

with either low- or high-frequency pure-tone average. In addition, the correlations were not significant across the individual participants. Although the lack of correlation suggests that age effects on monaural threshold may not be the main reason for causing the difference in detecting the BIC, the role of the age-related hearing loss should not be completely ruled out.

Another possible explanation for the age-related loss of sensitivity in detecting the monaural cues associated with a BIC is a diminution in the ability of older adults to notice that the fine structure in the monaural waveform at time t is similar to (correlated with) the waveform at time $t - \tau$, where τ is the delay (in milliseconds). When a ripple is introduced into the spectrum of a noise by adding a delayed version of the noise to itself, it gives rise to the perception that the noise has a pitch that is approximately equal to the reciprocal of the delay τ (Bilsen 1966; Yost 1978). One explanation of this result is that the pitch is based on the harmonic structure of the rippled spectrum. An alternative explanation for this result is that the listener's perception of pitch is based on the autocorrelation function, which exhibits a peak at a delay equal to τ (Yost 1978, 1996). This implies that the listener is responding to the similarity (correlation) between the fine structure of the sound at times t and $t - \tau$. Hence, a loss of phase locking (increased temporal jitter) in the auditory system would reduce the quality of the fine-structure information available to the listener, thereby making it more difficult to detect that the monaural acoustic pattern at time t is similar to that at time $t - \tau$. A number of studies have suggested that aging is associated with increased temporal jitter (e.g., Miranda & Pichora-Fuller 2002; Pichora-Fuller et al. 2007), which would reduce the ability of older adults to detect a BIC based on monaural cues if the detection of a BIC is based on autocorrelation rather than on spectral ripple. Of course, it is difficult to determine whether listeners are using cues based on the ripple in the spectrum or cues arising from the autocorrelation function, given that the autocorrelation function and the power spectrum constitute a Fourier pair (the power spectrum of a wave is the Fourier transform of its autocorrelation function). Hence, the determination of whether the age-related decline in the ability to detect the monaural cues in a BIC is because of a loss of fine-structure cues or because of declines in spectral sensitivity awaits further investigation.

In Experiment 2 of this study, the duration threshold for detecting the BIC under the binaurally cueing condition (with the ripple cue removed) was compared with that under the monaurally cueing condition. The results show that both kinds of cues are almost equally effective, with the only difference being that binaural cues are more effective than monaural cues at 2 msec.

In noisy (simulated) reverberant environments, listeners are able to use both binaural and monaural cues to detect a BIC. In binaural-listening conditions, the presence or absence of periodicity in the cross-correlation function between the signals in the two ears can be used to determine whether the two signals are correlated (Huang et al. 2009a). In addition, the monaural cues induced by comb filtering can also be used to determine whether the left- and right-ear signals are correlated. In other words, there are two sets of cues that can be used to determine whether two noises are correlated. To the extent that listeners are sensitive to both, we would expect to find lower duration thresholds when both cues are present than when only of them is present. The reduced ability of older adults to detect cross-ear correlations (Huang et al. 2009b; Li et al. 2009; Wang et al.

2011) and monaural frequency ripples (or the sudden appearance of a peak in the autocorrelation function) may contribute to age-related difficulties of understanding speech under adverse conditions (Nabelek & Robinson 1982; Gelfand et al. 1988; Helfer & Wilber 1990; Cheesman et al. 1995; Schneider et al. 2007; Huang et al. 2008a). In particular, age-related declines in the ability to detect changes in spectral ripple (or in the autocorrelation function) could make it more difficult for older adults to segregate a new sound source from the background when it is first introduced or to notice its departure when it ceases. In the future, it would be interesting to determine whether individual differences in speech recognition in noise in older adults are related to individual differences in sensitivity to spectral ripple, as has been shown for normal-hearing younger adults and those with cochlear implants (Henry et al. 2005; Won et al. 2007). If so, it might be possible to use a clinical measure of sensitivity to spectral ripple to identify older adults who are likely to perform poorly in noisy, reverberant environments.

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