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

Tianshu Qu,[1] Shuyang Cao,[1] Xun Chen,[1] Ying Huang,[1] Liang Li,[1] Xihong Wu,[1]
and Bruce A. Schneider [2]

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.

(Ear & Hearing 2013;34;280–287)

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

---

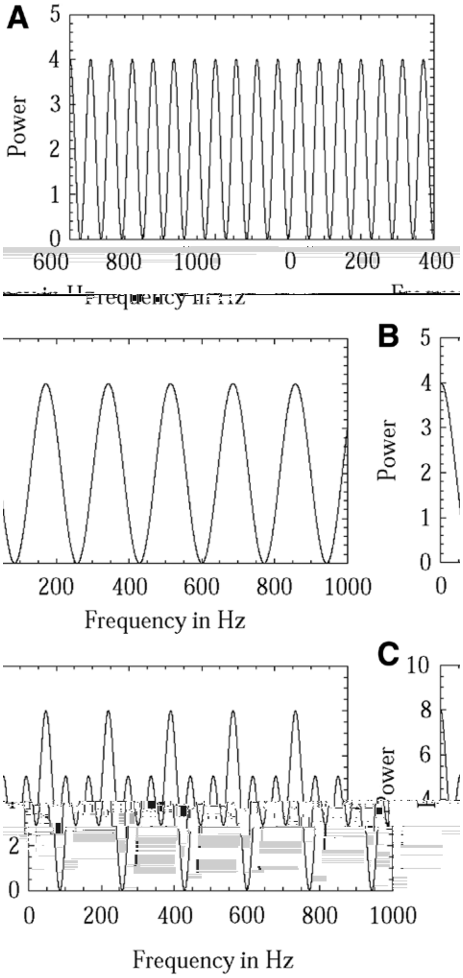
[1] Department of Machine Intelligence, Department of Psychology, Speech and Hearing Research Center, Key Laboratory on Machine Perception (Ministry of Education), Peking University, Beijing, China; and [2] Department of Psychology, University of Toronto Mississauga, Mississauga, Ontario, Canada.

0196/0202/13/343-0280/0 • Ear and Hearing • Copyright © 2013 by Lippincott Williams & Wilkins • Printed in the U.S.A

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 (l/τ). Modulating the spectrum this way gives rise to a perception that the noise has a pitch that is equal to approximately l/τ (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.

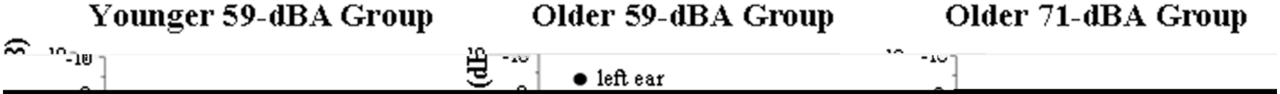
In addition, the introduction of a novel independent noise will change the nature of the spectral ripple at an ear, thereby providing a monaural acoustic cue that a second sound source has appeared in the acoustic scene. To see how a sudden change in the periodicity of the spectrum of the sound impinging 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 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.



1. [illegible]

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



[redacted]

[illegible]

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

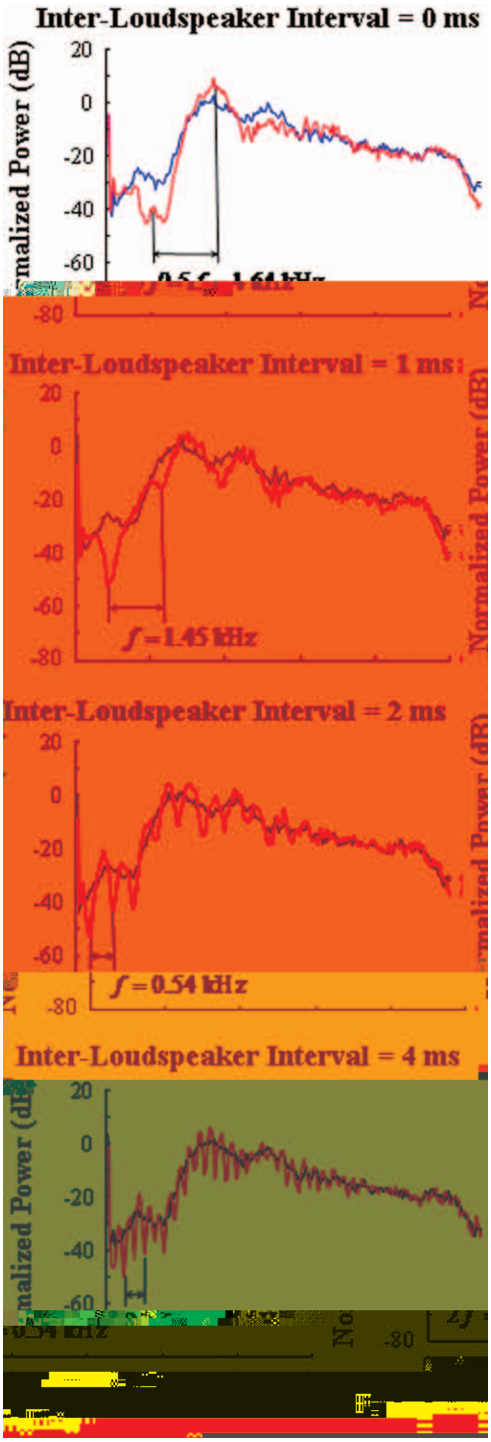
Participants and Methods

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 presbyacusis

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.



[illegible]

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 1 msec 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.

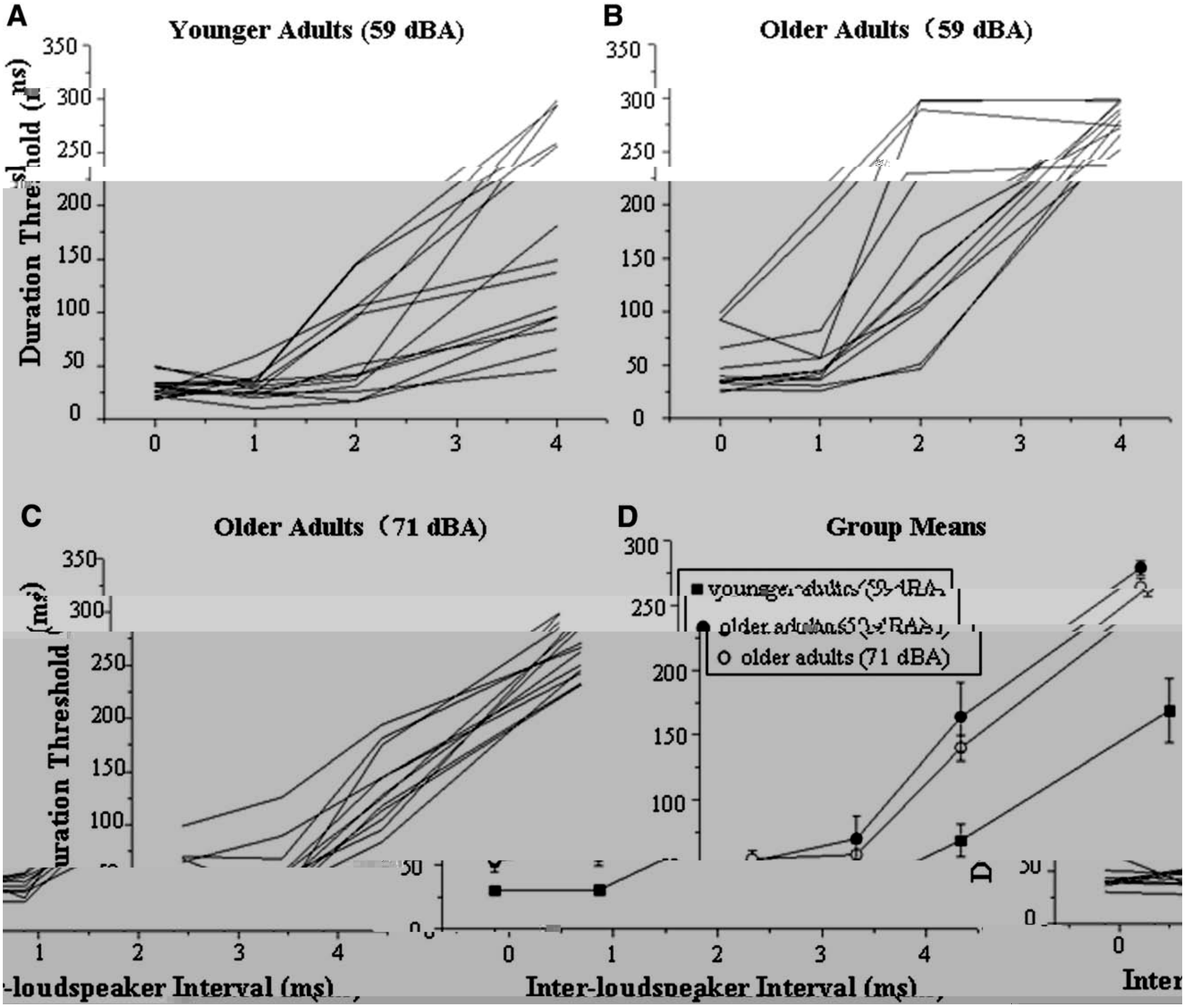
at the 2 msec ILI, and 300 msec at the 4 msec ILI. The starting BIC duration for older participants was 100 msec at the 0 msec ILI, 200 msec at the 1 msec ILI, and 300 msec at the 2 or 4 msec ILI.

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.



[illegible]

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

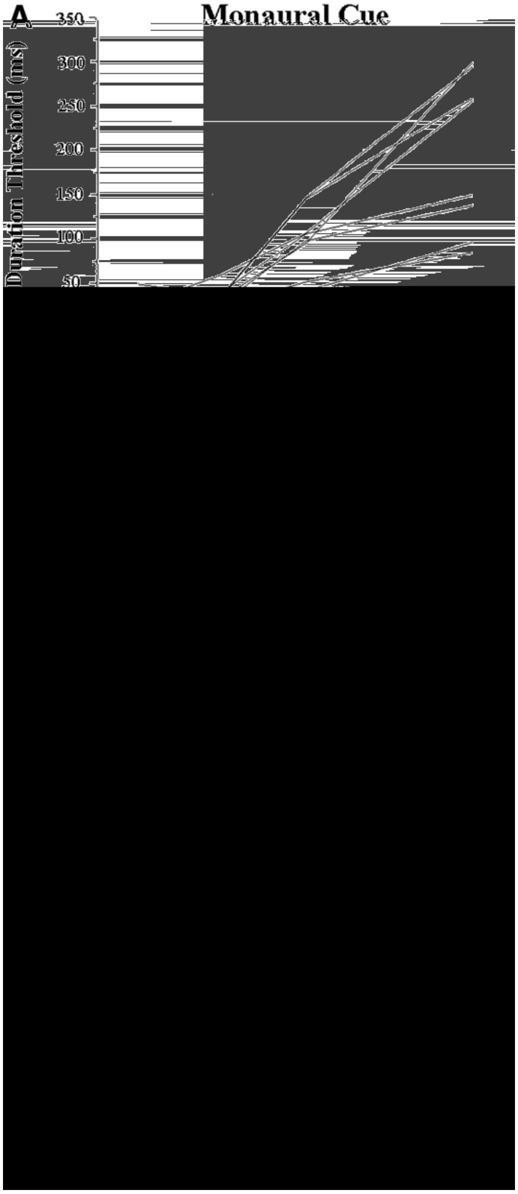
Participants • Eight younger adult students (19–24 years old; mean age = 22 years; 4 women and 4 men) who participated in Experiment 1 participated in Experiment 2.

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,



[illegible] (0, 1, 2, [illegible]). [illegible] 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 the 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 headp

@h e p e te p teal duql eft l (ted idsepa

rP s s
p ' a p

5

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.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (61175043; 31170985; 90920302; 60811140086), the “973” National Basic Research Program of China (2009CB320901; 2011CB707805), the international collaborative fund granted by the Ministry of Science and Technology of China (2010DFA31520), the Chinese Ministry of Education (20090001110050), the research program from Microsoft China, “985” grants from Peking University, the He Gao Ji grant (2011ZX01042-001-001), and the Natural Sciences and Engineering Research Council of Canada (RPIN 9712).

The authors declare no conflicts of interest.

Address for correspondence: Xihong Wu, Department of Machine Intelligence, Peking University, Beijing, China, 100871. E-mail: wxh@cis.pku.edu.cn

Received May 11, 2010; accepted July 11, 2012.

REFERENCES

Akeroyd, M. A., & Summerfield, A. Q. (1999). A binaural analog of gap detection. *J Acoust Soc Am*, *105*, 2807–2820.

Bilsen, F. A. (1966). Repetition pitch: Monaural interaction of a sound with the repetition of the same, but phase shifted sound. *Acustica*, *17*, 295–300.

Blauert, J., & Lindemann, W. (1986). Spatial mapping of intracranial auditory events for various degrees of interaural coherence. *J Acoust Soc Am*, *79*, 806–813.

Boehnke, S. E., Hall, S. E., Marquardt, T. (2002). Detection of static and dynamic changes in interaural correlation. *J Acoust Soc Am*, *112*, 1617–1626.

Bregman, A. S. (1990). *Auditory Scene Analysis: The Perceptual Organization of Sound*. Cambridge, UK: MIT Press.

Cheesman, M. F., Hepburn, D., Armitage, J. C., et al. (1995). Comparison of growth of masking functions and speech discrimination abilities in younger and older adults. *Audiology*, *34*, 321–333.

Cowper-Smith, C. D., Dingle, R. N., Guo, Y., et al. (2010). Synchronous auditory nerve activity in the carboplatin-chinchilla model of auditory neuropathy. *J Acoust Soc Am*, *128*, EL56–EL62.

Culling, J. F. (2007). Evidence specifically favoring the equalization-cancellation theory of binaural unmasking. *J Acoust Soc Am*, *122*, 2803–2813.

de Cheveigné A. (1993). Separation of concurrent harmonic sounds—Fundamental-frequency estimation and a time-domain cancellation model of auditory processing. *J Acoust Soc Am*, *93*, 3271–3290.

Gabriel, K. J., & Colburn, H. S. (1981). Interaural correlation discrimination: I. Bandwidth and level dependence. *J Acoust Soc Am*, *69*, 1394–1401.

Gelfand, S. A., Ross, L., Miller, S. (1988). Sentence reception in noise from one versus two sources: Effects of aging and hearing loss. *J Acoust Soc Am*, *83*, 248–256.

Goupell, M. J., & Hartmann, W. M. (2006). Interaural fluctuations and the detection of interaural incoherence: Bandwidth effects. *J Acoust Soc Am*, *119*, 3971–3986.

Hall, D. A., Barrett, D. J., Akeroyd, M. A., et al. (2005). Cortical representations of temporal structure in sound. *J Neurophysiol*, *94*, 3181–3191.

Hartmann, W. M. (1997). *Signals, Sound, and Sensation*. New York, NY: Springer.

Helfer, K. S., & Wilber, L. A. (1990). Hearing loss, aging, and speech perception in reverberation and noise. *J Speech Hear Res*, *33*, 149–155.

Henry, B. A., Turner, C. W., Behrens, A. (2005). Spectral peak resolution and speech recognition in quiet: Normal hearing, hearing impaired, and cochlear implant listeners. *J Acoust Soc Am*, *118*, 1111–1121.

Huang, Y., Huang, Q., Chen, X., et al. (2008a). Perceptual integration between target speech and target-speech reflection reduces masking for target-speech recognition in younger adults and older adults. *Hear Res*, *244*, 51–65.

Huang, Y., Huang, Q., Chen, X., et al. (2009a). Transient auditory storage of acoustic details is associated with release of speech from informational masking in reverberant conditions. *J Exp Psychol Hum Percept Perform*, *35*, 1618–1628.

Huang, Y., Kong, L., Fan, S., et al. (2008b). Both frequency and interaural delay affect event-related potential responses to binaural gap. *Neuroreport*, *19*, 1673–1678.

Huang, Y., Wu, X., Li, L. (2009b). Detection of the break in interaural correlation is affected by interaural delay, aging, and center frequency. *J Acoust Soc Am*, *126*, 300–309.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *J Acoust Soc Am*, *49*, Suppl 2:467.

Li, L., Huang, J., Wu, X., et al. (2009). The effects of aging and interaural delay on the detection of a break in the interaural correlation between two sounds. *Ear Hear*, *30*, 273–286.

Miranda, T. T., & Pichora-Fuller, M. K. (2002). Temporally jittered speech produces performance intensity, phonetically balanced rollover in young normal-hearing listeners. *J Am Acad Audiol*, *13*, 50–58.

Náběelek, A. K., & Robinson, P. K. (1982). Monaural and binaural speech perception in reverberation for listeners of various ages. *J Acoust Soc Am*, *71*, 1242–1248.

Narins, P. M., Evans, E. F., Pick, G. F., et al. (1979). A comb-filtered noise generator for use in auditory neurophysiological and psychophysical experiments. *IEEE Trans Biomed Eng*, *26*, 43–47.

Patterson, R. D., Nimmo-Smith, I., Weber, D. L., et al. (1982). The deterioration of hearing with age: Frequency selectivity, the critical ratio, the audiogram, and speech threshold. *J Acoust Soc Am*, *72*, 1788–1803.

Pichora-Fuller, M. K., Schneider, B. A., Macdonald, E., et al. (2007). Temporal jitter disrupts speech intelligibility: A simulation of auditory aging. *Hear Res*, *223*, 114–121.

Pollack, I., & Trittipoe, W. J. (1959). Binaural listening and interaural noise cross correlation. *J Acoust Soc Am*, *31*, 1250–1252.

Schneider, B. A., Li, L., Daneman, M. (2007). How competing speech interferes with speech comprehension in everyday listening situations. *J Am Acad Audiol*, *18*, 559–572.

Starr, A., Picton, T. W., Sininger, Y., et al. (1996). Auditory neuropathy. *Brain*,*119*(Pt 3), 741–753.

Wang, M., Wu, X., Li, L., et al. (2011). The effects of age and interaural delay on detecting a change in interaural correlation: The role of temporal jitter. *Hear Res*, *275*, 139–149.

Won, J. H., Drennan, W. R., Rubinstein, J. T. (2007). Spectral-ripple resolution correlates with speech reception in noise in cochlear implant users. *J Assoc Res Otolaryngol*, *8*, 384–392.

Yost, W. A. (1996). Pitch of iterated rippled noise. *J Acoust Soc Am*, *100*, 511–518.

Yost, W. A., Hill, R., Perez-Falcon, T. (1978). Pitch and pitch discrimination of broadband signals with rippled power spectra. *J Acoust Soc Am*, *63*, 1166–1175.