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# The effects of age and interaural delay on detecting a change in interaural correlation: The role of temporal jitter

Mengyuan Wang [a], Xihong Wu [a], Liang Li [a,**], Bruce A. Schneider [b,*]

[a] Department of Psychology, National Key Center on Machine Perception, Speech and Hearing Research Center, Peking University, Beijing 100871, China
[b] Department of Psychology, Centre for Research on Biological Communication Systems, University of Toronto Mississauga, Mississauga, ON, Canada L5L 1C6

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ABSTRACT

Duration thresholds for detecting a change in interaural correlation (from 0 to 1, or from 1 to 0) in the initial portion of a 1-second, broadband noise (0–10 kHz) were determined for younger and older adults in a two-interval, two-alternative forced choice paradigm as a function of the interaural delay between the noise bursts presented to each ear. When the interaural delay was 0 ms, older adults found it harder to detect a change in correlation from 0 to 1 than from 1 to 0. For younger adults, however, this pattern was reversed. For interaural delays greater than 0 ms, both younger adults and older adults found it easier to detect a change in interaural correlation from 0 to 1 for short interaural delays (1 ms) with the reverse being true for longer interaural delays (5 ms). It is shown that this pattern of results is expected if temporal jitter (loss of neural synchrony in the auditory system) increases with age and with interaural delay. The implications of these results for age-related changes in stream segregation are discussed.


## 1. Introduction

In order to process and comprehend what a target talker is saying when the listening situation is complex (e.g., when there are many people talking at the same time), listeners first have to locate and perceptually segregate the voice belonging to the target talker from the auditory background (Bregman, 1990). Otherwise, information carried by the non-target talkers may intrude into working memory (Daneman and Carpenter, 1980), and interfere with semantic and linguistic processing of the targeted information (Hasher and Zacks, 1988; Schneider et al., 2010). Several studies (e.g., Li et al., 2004; Li et al., 2009; Vongpaisal and Pichora-Fuller, 2007; Snyder and Alain, 2005; Huang et al., 2008; Humes et al., 2006) have indicated that age-related changes in hearing may make it more difficult for older adults to utilize the acoustic cues that allow listeners to segregate the target voice from competing sound sources, thereby making it more difficult for them to comprehend speech in difficult listening situations. This study compares the ability of younger and older adults to integrate and/or segregate two auditory streams based on the degree of interaural correlation between the two streams.

* Corresponding author. Tel.: +1 905 828 3963; fax: +1 905 569 4850.
** Corresponding author.
*E-mail addresses:* liangli@pku.edu.cn (L. Li), bruce.schneider@utoronto.ca (B.A. Schneider).

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### 1.1. Stream segregation based on interaural differences

Auditory stream segregation takes time to build up (Carlyon et al., 2001), and may be easier to achieve when the streams have non-simultaneous onsets. For example, Wagener and Brand (2005) have shown that it is easier to recognize words in noise when the onset of the noise precedes word onset. Presumably it takes longer when the background and target have simultaneous onsets because it takes time for the listener to segregate the word from the background noise. However, when the noise begins before the onset of the target word, by the time the target is presented, the listener may have had enough time to build up the perception of a noise stream, which, in turn, would facilitate its segregation from the target word. Heinrich et al. (2008) and Heinrich and Schneider (2010), in a serial-position memory experiment in a background of babble (12 people talking simultaneously), found that when babble onset preceded the presentation of words to be remembered, older adults remembered the same number of words as younger adults for words presented in the last two serial positions, but remembered fewer words than younger adults in those serial positions when babble was gated on with the words. They attributed this effect to the buildup of stream segregation being more sluggish in older than in younger adults (see also, Alain and McDonald, 2007; Alain et al., 1996). Hence, one possible reason why older adults find it particularly vexing when several people start to speak at the same time, is that the processes involved in stream segregation are more sluggish in older than in younger adults.

In natural listening situations, stream segregation is greatly facilitated by spatial separation. Because older adults are less sensitive than younger adults to interaural differences (see Eddins and Hall, 2010, for a recent review), one possibility is that older adults in everyday listening situations, where sound sources are usually spatially separated, are disadvantaged with respect to stream segregation, relative to younger adults. In the present study we looked for age-related changes in the time it takes to either 1) segregate auditory streams which could only be differentiated on the basis of interaural differences between left- and right-ear signals, and 2) integrate left- and right-ear signals when the signals to the two ears were correlated.

To investigate age-related changes in the ability to integrate auditory signals arriving at the two ears, in Experiment 1, we simulated, over earphones, an anechoic situation in which a loudspeaker is placed directly in front of the listener. If a complex sound is played over that loudspeaker, the signals arriving at the left- and right-ears of the listener will be highly correlated, and a normal-hearing adult will perceive a single compact sound source on the frontal plane. Because stream segregation takes time to build up (Carlyon et al., 2001), it would be interesting to determine how long the sound must be on in order for the left- and right-ear signals to be perceived as originating from the same source. To determine the duration that correlated signals to the two ears must be on before the left- and right-ear sounds are perceived as originating from a single centered source, we employed a two-interval, two-alternative, forced-choice paradigm in which the stimulus in one of the intervals (the standard stimulus) consisted of two independent sounds (bandlimited white noises of equivalent bandwidth and intensity) played to both ears for 1000 ms. Subjectively, the participant perceived this standard stimulus as two independent sounds at the two ears. The stimulus in the other interval (the comparison stimulus) consisted of identical white noise segments presented to the two ears for $x$ ms ($x < 1000$) followed by independent white noises presented to each ear for $y$ ms where $x + y = 1000$ ms. Clearly if the duration, $x$, of the correlated noise to the two ears is too short, the auditory system will not have time to build up a percept of a single compact sound originating on the frontal plane and will not distinguish this stimulus from one (the standard stimulus) where the sounds played to the two ears are independent. Hence, the threshold value, $x_t$, such that the comparison stimulus (left-and right-ear noises correlated for $x_t$ ms, and completely uncorrelated for $y = 1000 - x_t$ ms) is just detectable as different from the standard stimulus (two independent noises simultaneously presented to the two ears for 1000 ms) is a measure of the amount of time it takes for two correlated signals to give rise to a percept of a single, compact sound located on the frontal plane, that can be distinguished from a stimulus in which the left- and right-ear noises are uncorrelated.

The complementary experiment is one in which the comparison stimulus consists of left- and right-ear noises that are uncorrelated for the first $x$ ms, and correlated thereafter. The standard stimulus in this case is one in which the left- and right-ear noises are completely correlated for the total duration of the stimulus (1000 ms). The threshold value, $x_t$, such that the comparison stimulus is just distinguishable from the standard stimulus represents how long it takes to recognize that the left- and right- ear sounds are uncorrelated (giving rise to the perception of two independent sounds) before switching to a percept of a single compact sound located on the frontal plane.

These two time periods (the time it takes from sound onset to integrate the left- and right-ear sounds into a single percept; and the time it takes from sound onset to recognize that there are effectively two independent sound sources) will play a critical role in stream segregation. Experiment 1 was designed to determine if there are age-related changes in these abilities.

### 1.2. Stream integration and segregation in reverberant environments

Listeners living in a noisy, reverberant environment, not only receive direct waves from sound sources but also numerous filtered and time-delayed reflections of these waves off of environmental surfaces. In such environments, integrating the direct wave from the target source with its myriad reflections into a single, spatially-located sound image becomes more difficult as does the process of segregating the target source from other competing sound sources. When the time interval between a sound arriving at one ear, and a delayed copy of the sound arriving at the other ear 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 referred to as the "precedence effect" or "the law of the first wavefront" (Haas, 1951; Litovsky and Shinn-Cunningham, 2001; Wallach et al., 1949; Zurek, 1987; 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 (Litovsky et al., 1999). 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).

Hence it would also be informative to determine whether there were any age-related differences in: 1) the time it takes to integrate the left- and right-ear correlated sounds when there is an interaural delay of several milliseconds, and to 2) notice a switch from two uncorrelated sounds to a correlated sound when there is an interaural delay in the correlated sounds. Experiment 2 was designed to determine whether there were any age differences in the buildup of integration and segregation when there were interaural delays between correlated left- and right-ear noises.

## 2. Method

### 2.1. Participants

Twelve younger adults (6 females, 6 males), 19–22 years old (Mean = 20.5 yrs), recruited from the University of Toronto Mississauga, and twelve older adults (6 females, 6 males), 65–73 years old (Mean = 69.3 yrs), recruited from the local community participated in Experiments 1 & 2. None of the participants had any history of hearing disorders, and none used hearing aids. All participants gave their written informed consent to participate in the experiments and were paid a modest stipend for their participation.

All but one[1] of the participants had pure-tone, air-conduction thresholds ≤25 dB HL between .25 and 3 kHz (ANSI-S3.6, 2004). Interaural differences in this range were less than 15 dB. Fig. 1 shows that the audiometric thresholds for older participants were approximately 8 dB higher than those of younger adults for frequencies

[1] One of the older participants had a hearing level of 45 dB in the left ear at 3 kHz. All of the other thresholds were less than 25 dB HL at the remaining frequencies in both ears for frequencies ≤3 kHz. The average duration threshold for this individual was 1.1 standard deviation units above the mean duration threshold for older participants.

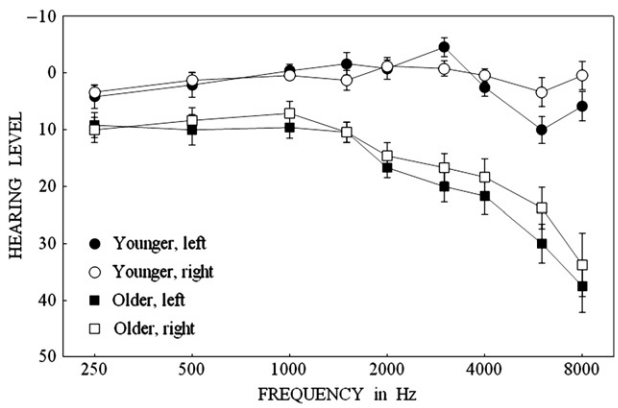


**Fig. 1.** Average hearing levels (ANSI-2004) as a function of frequency for the left- and right-ears of the younger and older adults in this experiment. Standard error bars are shown.

below 3 kHz, with this age difference increasing with frequency for frequencies above 2 kHz, indicating that the older adults were in the early stages of presbycusis.

### 2.2. Apparatus and stimuli

#### 2.2.1. Experiment 1

In the Integration Condition the standard stimulus consisted of independent, 1-s long, noise segments (bandwidth = 10 kHz, rise-fall times = 30 ms, interaural correlation = 0) presented over earphones to the two ears with no interaural delay. The comparison stimulus consisted of the same 10-kHz noise segment presented over the left- and right-earphones for $x$ ms (correlation = 1.0), which then switched (without interruption) to two independent 10-kHz noise segments (correlation = 0) presented over the left- and right-earphones, whose durations were $y = 1000 - x$ ms. In the Segregation Condition, the standard stimulus consisted of the same 10-kHz noise segment played over both earphones (correlation = 1.0). The comparison stimulus consisted of independent 10-kHz noise segments (correlation = 0) played over the two earphones for $x$ ms, followed by the same 10-kHz noise segment played over both earphones (correlation = 1.0). All noise segments were constructed by digitally generating random normal deviates at a sampling rate of 20 kHz, converting these digital signals to analog form using a Tucker Davis Technologies (TDT) DD1 digital-to-analog converters, filtering the analog version using a 10-kHz low pass filter (TDT FT5), and attenuating the filtered signals using TDT PA4 programmable attenuators before presenting them to a matched pair of Seinheiser earphones (HD 265) at a sound pressure level of 60 dBA in each ear. Sound pressure levels were calibrated by measuring the SPL at the end of the ear canal of a dummy head using the Brüel & Kjær Pulse Analyzer Platform. Independent noise segments were generated on each trial.

#### 2.2.2. Experiment 2

The only difference between the stimuli used in Experiments 1 and 2 was that an interaural delay was introduced between the two ears whenever the sounds were correlated, with the noise presented to the left ear leading that presented to the right ear, giving rise to the impression that the noise was at the left ear of the listener. All left- and right-ear sounds had simultaneous onsets and offsets with 30-ms rise and fall times. The effects of three different delays (1 ms, 3 ms and 5 ms) between correlated segments were explored in both integration and segregation conditions.

### 2.3. Procedure

#### 2.3.1. Experiment 1

Duration thresholds for detecting the difference between the standard and comparison stimuli were determined using an adaptive 2-interval, 2-alternative, forced-choice procedure (2I2AFC). On a trial, the standard stimulus was presented in one of the two intervals, the comparison in the other, with 1000 ms separating intervals 1 and 2. On half of the trials the standard was presented in the first interval and the comparison in the second, with the reverse being true for the other half of the trials. For each interval, the noise coming from the left headphone and the noise coming from the right headphone started and terminated at the same time. Fresh noise sounds were generated for each interval of each trial.

The participant's task was to identify which of the two intervals contained the comparison stimulus (the one whose initial segment differed in correlation from that of the standard stimulus). The participant initiated a trial by pressing a button on the response box. At the beginning of the first test session of each condition, the duration of the initial segment of the comparison stimulus was set to 500 ms. This duration decreased following three consecutive correct identifications of the interval containing the comparison stimulus, and increased following one incorrect identification, using a three-down, one-up procedure. The initial step size used in changing the initial duration was 32 ms, with the step size reduced by a factor of .5 after each reversal of direction until the minimum size of 1 ms was reached. In subsequent sessions in the same condition, the starting value was set to a lower value (depending on previous performance) to speed convergence. The two intervals were visually signaled by illuminating a light above the response button corresponding to each interval. Participants indicated their choice by pressing one of the buttons corresponding to the two intervals. Feedback was provided at each trial by flashing the light above the button corresponding to interval containing the comparison stimulus. The session was terminated after 12 reversals in direction. The threshold for that session was defined as the average duration achieved on the last 8 reversals. Test sessions were repeated at least four times for each participant, and the participant's average threshold was defined as the average of the three lowest thresholds achieved. Because pilot experiments with older adults indicated that the Integration Condition was easier than the Segregation Condition, participants (with the exception of two older adults) were tested in the Integration Condition first.

#### 2.3.2. Experiment 2

Experiment 2 was conducted after Experiment 1 using the same 2I2AFC procedure. The younger adults were tested in the Integration Condition followed by the Segregation Condition. They also completed 4 sessions at each delay before proceeding to the next delay. Older adults were also tested in the Integration Condition first. Before testing the older adults at the shortest delay, single sessions were conducted to determine the longest delay at which they could initially perform better than chance. Subsequently, they were tested at the shortest interaural delay (1 ms) for four sessions before proceeding to 3 ms interaural delay, and 5 ms for those who could perform better than chance at this interaural delay.

Six of the twelve older participants failed to discriminate between the standard and comparison stimuli when the initial segment was 500 ms long at one or more of the delays in the integration and/or segregation conditions. For purposes of data analysis, these participants were assigned a threshold delay of 500 ms. There were no such occurrences in younger adults. Hence the extent of the age difference is undoubtedly underestimated in the following analysis.

## 3. Results

### 3.1. Experiment 1

Fig. 2 indicates the minimal duration at which a change in the interaural correlation of the initial segment of a 1 s bandlimited Gaussian noise (bandwidth = 10 kHz) could be detected when the interaural correlation changed from 1 in the initial segment (Integration Condition) to 0 in the remainder of the 1 s noise burst, or from 0 in the initial segment (Segregation Condition) to 1 in the remainder of the noise burst. Note that the minimum duration for detecting a change from 1 to 0 represents the time it takes to notice a correlation, that is, to integrate the signals from the two ears into a single percept. Correspondingly, the minimum duration for detecting a change from 0 to 1 represents the time it takes to notice that the initial segment is uncorrelated, that is, to segregate the sounds arriving at the two ears into separate streams. Grey bars represent the data from younger participants and black bars represent the data from older participants. Fig. 2 shows that it takes older adults a longer time than younger adults to notice a correlation change in both the Integration and Segregation Conditions, and that younger adults have lower thresholds for segregation than for integration whereas the opposite appears to be true for older adults. This pattern of results was confirmed by a 2 (integration vs. segregation) by 2 (young vs. old) ANOVA with Condition (integration, segregation) as a within-subject variable, and Age (young, old) as a between-subjects variable. Specifically, there was a main effect of age ($F[1,22] = 10.20$, $p = .004$) and a significant Age by Condition interaction ($F[1,22] = 19.18$, $p < .001$). The main effect of Condition was not significant ($F[1,22] < 1$).

### 3.2. Experiment 2

Fig. 3 plots the minimal duration at which a change in the interaural correlation of the initial segment of a 1 s bandlimited Gaussian noise (bandwidth = 10 kHz) could be detected when the correlation changed from 1 to 0 in the initial segment (left panel, Integration Condition), or from 0 to 1 in the initial segment (right panel, Segregation Condition) for younger (unfilled circles) and older (filled squares) adults as a function of the interaural delay between the left- and right-ears. Because the participants in Experiment 2 were identical to those in Experiment 1, the Experiment 1 data are also shown here as having an interaural delay of 0 ms. Fig. 3 indicates that older adults took approximately 70 ms longer than did younger adults to integrate interaurally correlated initial noise segments (Integration Condition) at all of the interaural delays tested. Fig. 3 also indicates that older adults take a longer time than younger adults to segregate interaurally independent left- and right-ear noises. However, this age difference appears to be a function of interaural delay, being much larger for an interaural delay of 0 ms, than for any of the other delays. A 2 (Age) by 2 (Condition, integration, segregation) by 4 (Interaural Delay) ANOVA found significant main effects of interaural delay ($F[3,66] = 90.64$, $p < .001$), and Age ($F[1,22] = 5.57$, $p = .028$), but not of Condition ($F[1,22] = 1.64$, $p > .20$). In addition to main effects, there was a significant two way interaction between Condition and Delay ($F[3, 66] = 7.57$, $p < .001$), and a significant three-way interaction between Age, Condition, and Delay ($F[3,66] = 4.97$, $p = .004$). None of the other effects reached significance.

Fig. 3 suggests that the source of the three-way interaction is that the age difference in the integration condition is smaller than the age difference in the segregation condition at delay 0, but that the age difference between the segregation and integration conditions are comparable at the other delays. To confirm this observation, Bonferroni-corrected posthoc *t*-tests were conducted to compare the age difference in the integration condition to the age difference in the segregation condition at delays of 0, 1, 3, and 5 ms. At an interaural delay of 0 ms, the difference between the Segregation and Integration Conditions was significantly larger for older adults than it was for younger adults ($T[22] = 4.38$, $p < .005$, Bonferroni corrected). The equivalent comparisons at 1, 3, and 5 ms were not significant ($T[22] = -.09$, $p > .5$; $T[22] = .18$, $p > .5$; and $T[22] = .07$, $p > .5$, for 1,3 and 5 ms, respectively). Hence the contribution of Age to the three-way interaction reflected the fact that the threshold difference between the Integration and Segregation Conditions was larger for older than for younger adults at 0 ms, but not at longer delays.

To better understand the source of the two-way interaction between Condition (Integration vs. Segregation) and interaural

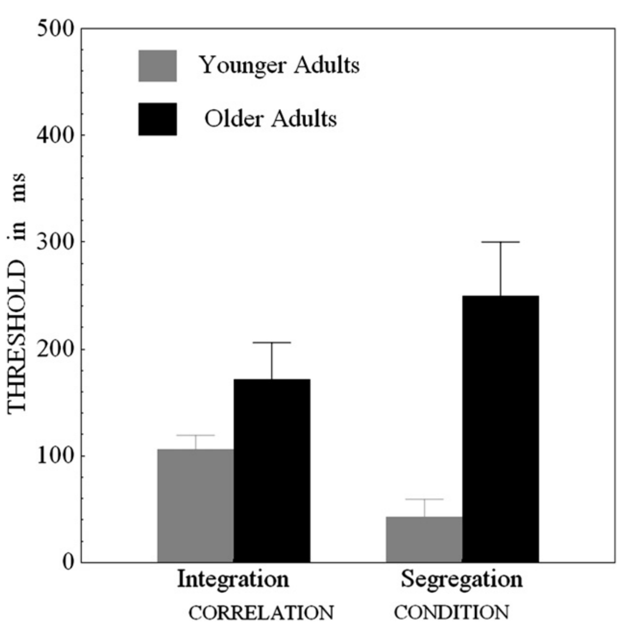


**Fig. 2.** Average threshold duration of the initial segment of a two-part binaural noise under two conditions: Integration, where the interaural correlation between the left- and right-ear signals was 1 in the initial segment, and 0 in the final segment; Segregation, where the interaural correlation between the left- and right-ear signals was 0 in the initial segment, and 1 in the final segment. Data are shown separately for younger and older adults. Standard error bars are also indicated.

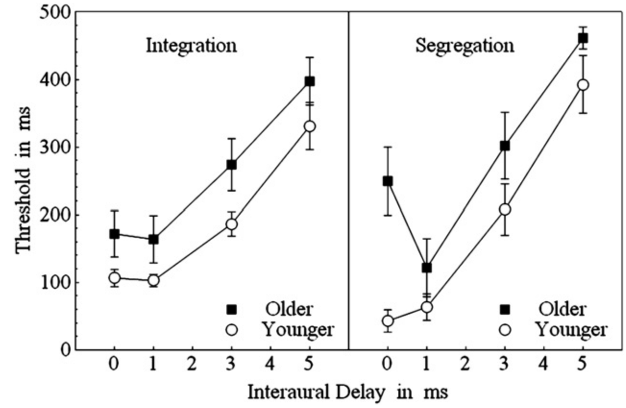


**Fig. 3.** The duration of the initial segment of a two-part binaural noise at which participants could detect a difference between the initial and final segments of the noise as a function of the interaural delay between the left- and right-ear signals. Average thresholds are shown separately for young and old adults under two conditions: Integration, where the interaural correlation between the left- and right-ear signals was 1 in the initial segment, and 0 in the final segment; Segregation, where the interaural correlation between the left- and right-ear signals was 0 in the initial segment, and 1 in the final segment. Standard error bars are shown.

delay, the data from Experiment 2 were collapsed over age and replotted in Fig. 4 as a function of interaural delay for delays >0 ms. Fig. 4 suggests that thresholds for segregation are lower than thresholds for integration at 1 ms, with the reverse being true at 5 ms. To confirm this, we conducted Bonferroni corrected *t*-tests of the difference between integration and segregation thresholds at interaural delays of 1, 3, and 5 ms. Differences between integration and segregation thresholds were significant at 1 ms ($T[23] = 2.79$, $p < .05$, Bonferroni corrected), and significant in the opposite direction at 5 ms ($T[23] = -3.77$, $p < .005$, Bonferroni corrected), but not significant at 3 ms ($T[23] = -1.25$, $p > .20$).

## 4. Discussion

### 4.1. Experiment 1

In the Integration Condition of Experiment 1, we examined the abilities of younger and older adults to detect a difference between two bandlimited white noises (BW = 10 kHz) where the interaural correlation for the standard stimulus was 0 for its entire duration (1 s), but the interaural correlation for the comparison stimulus started at 1 and then switched to 0 after *x* ms. Blauert and Lindemann (1986) reported that under earphone conditions, an interaural correlation of 1 for noise results in the impression of a compact auditory event centered in the middle of the head. However when the interaural correlation of the noise is 0, listeners perceived two respective events or auditory streams, one at each ear. Provided that the correlated and uncorrelated segments are long enough, a change from an interaural correlation from 1 to 0 is perceived as a change from a compact sound located in the middle of the head to two separate sounds located at each ear. Therefore, the minimum duration for detecting the presence of an initial correlated segment provides an estimate of the time it takes to build up and maintain a representation of a compact and centered noise image before it switches to two different images at the two ears. In the Segregation Condition of Experiment 1, the interaural correlation of the standard noise was always 1 with the initial interaural correlation of the comparison being 0 at the beginning before switching to 1 after *x* ms. The threshold for detecting the presence of an initial segment of uncorrelated left- and right-ear noises represents the minimum amount of time it takes to build up the perception of

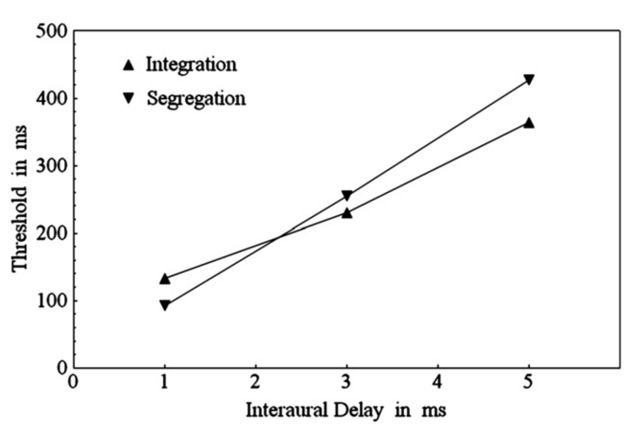


**Fig. 4.** The duration (averaged across younger and older participants) of the initial segment of a two-part binaural noise at which participants could detect a difference between the initial and final segments of the noise as a function of the interaural delay between the left- and right-ear signals. Two conditions are depicted: Integration, where the interaural correlation between the left- and right-ear signals was 1 in the initial segment, and 0 in the final segment; Segregation, where the interaural correlation between the left- and right-ear signals was 0 in the initial segment, and 1 in the final segment.

independent noises at each ear (two auditory streams) when it is followed by a longer, interaurally coherent sound. Fig. 2 shows that older adults required more time than younger adults to integrate correlated right- and left- ear noises, and to segregate uncorrelated left- and right-ear sounds into two auditory streams. However, segregation was easier (had a lower threshold) than integration for young adults, with the opposite being true for older adults. Hence older adults appear to be particularly disadvantaged relative to younger adults when it comes to using interaural cues to detect that the left- and right-ear sounds are independent, i.e., constitute different auditory streams. While younger adults can detect an initial lack of correlation as long as the uncorrelated segment of the comparison sound lasts for approximately 43 ms, older adults require, on average, 250 ms to detect an initial lack of interaural correlation in the comparison stimulus.

It is interesting to note that both younger and older adults are much better at detecting an uncorrelated segment in an otherwise correlated noise when the uncorrelated segment occurs in the middle rather than at the beginning of the noise. Li et al. (2009) found that younger adults can detect a switch of interaural correlation from 1 to 0 and back to 1 again in the middle of a 1 s bandlimited white noise (BW = 10 kHz) when the duration of the uncorrelated segment is only 4.5 ms. By way of comparison, younger adults needed 45 ms (Experiment 1, Segregation) to detect the uncorrelated segment when it was at the beginning of the noise. Li et al. also found that older adults needed almost twice as long (8.5 ms) as younger adults to detect a break in correlation in the middle of the noise, whereas the older adults in the present experiment needed an uncorrelated segment that was approximately 6 times longer than that required by younger adults when the uncorrelated segment occurred at the beginning of an otherwise correlated noise. Note that in the Li et al. experiment, the left- and right-ear noises were completely correlated at the beginning. The integration results of the present Experiment 1 indicated that younger and older adults need approximately 106 and 172 ms, respectively, to detect that the left- and right-ear noises were correlated. Hence, in the Li et al. experiment, both the younger and older adults had more than enough time (>490 ms) to fuse the left- and right-ear noises into a single compact sound before the uncorrelated segment was introduced. The comparison between these two experiments indicates that it is easier to detect the presence of an uncorrelated segment once the listener has had time to build up the perception of a fused compact sound than it is to detect an uncorrelated segment at the beginning of a sound and that the age difference is considerably larger when the uncorrelated segment appears at the beginning of the sound than when it interrupts an otherwise correlated sound.

The data from Experiment 1 also show that younger adults need a longer initial segment to detect a change from an interaural correlation of 1 to 0, than to detect a change from 0 to 1, with the opposite being true for older adults. Why might this be the case? Consider an explanation based on stream segregation. Typically, a strong cue that sound is being generated by a single source is that the onset of sound is nearly simultaneous in the two ears (<600 μs separating sound onsets, the maximum time it takes for a sound to cross the listener's head). In the present experiment sound onset was simultaneous. Hence, in the absence of any other cues that would support stream segregation, the default perception would be that of a single source. As the sound continues, a complete lack of an interaural correlation would signify the presence of independent sounds in the two ears. It is reasonable to assume that the sample length needed for determining that the left- and right-ear sounds are uncorrelated will depend on the auditory system's ability to accurately compute the interaural correlation that exists in the left- and right-ear signals. Suppose, as many studies have suggested (Pichora-Fuller et al., 2007; MacDonald et al., 2010; Grose and Mamo, 2010; see

Schmiedt, 2010, for a review), that the amount of temporal jitter in the auditory system increases dramatically with age. If there were no jitter, the auditory system would accurately compute, when the left- and right-ear signals were identical, that the interaural correlation between the two ears was 1. However, temporal jitter could reduce the auditory system's ability to detect an interaural correlation substantially, thereby decreasing the discriminability between a noise with an interaural correlation of 1 and another with an interaural correlation of 0. Such losses could explain why older adults find it more difficult than younger adults to detect a change in correlation in all conditions.

To see how a change in the level of temporal jitter could account for the fact that younger adults need a longer initial segment to detect a change from an interaural correlation of 1 to 0, than to detect a change from 0 to 1 while the opposite is true for older adults, we need to consider how jitter might affect discrimination accuracy in both conditions. Assume for the moment that the listener applies a series of contiguous temporal windows (Bernstein et al., 2001; Moore et al., 1988) of finite duration to the signal, beginning with signal onset. Assume further that it computes the strength of the interaural correlation in each of the temporal windows. Specifically, suppose the auditory system evaluates the strength of the relationship between the left- and right-ear signals by computing the squared normalized interaural correlation ($r^2$) in the first and second windows applied to each of the signal. Consider first the segregation condition where the standard signal has an interaural correlation of 1 throughout its length, whereas the interaural correlation for the comparison stimulus is 0 for $x$ ms, before changing to 1 for the remainder of the interval. The listener computes four $r^2$ values ($r^2_{S,1}, r^2_{S,2}, r^2_{C,1}, r^2_{C,2}$), where the letter subscripts S and C stand for standard and comparison respectively, and the numerical subscript represents the window number applied to each stimulus (first or second). In arriving at a decision as to which stimulus contains an initial uncorrelated segment, the hypothetical listener subtracts, for each of the two stimuli, the $r^2$ value obtained from the first window from that of the second window. We would expect that this difference would be larger, on average, for the comparison stimulus than it would be for the standard stimulus. Hence the appropriate strategy is for listeners to identify the stimulus with the largest difference in $r^2$ values between the first and second windows as the stimulus containing the initial uncorrelated segment. When the interaural correlations in the standard and comparison stimuli are reversed in the integration condition, the listener subtracts, for each of the two stimuli presented, the $r^2$ value obtained from window 2 from that of window 1. This hypothetical listener then identifies the stimulus containing the largest difference in $r^2$ values as the one containing the initial correlated segment.

Now suppose that there is temporal jitter in the interaural comparison such that by the time perfectly correlated left- and right-ear signals arrive at the point in the auditory system at which they are compared, the internal representations of the signals are no longer precisely identical. To see what happens to the psychometric functions under such conditions, we have (following Pichora-Fuller et al., 2007) modeled the amount of temporal jitter present in the auditory system in the following way. Suppose identical signals, $y(t)$, are presented to each ear. It is assumed that at the stage at which the two signals are compared, that the internal representation of the signal in one ear is a temporally jittered version of the signal in the other ear. That is, if $y(t)$ is the representation of the signal from one ear at the stage at which interaural comparisons are made, $y(t+\delta)$ is the representation of the signal from the other ear, where $\delta$ itself varies with time. Specifically, it is assumed that $\delta(t)$ varies according to the amplitude of a band-limited noise (bandlimit $= W_\delta$ Hz) whose RMS amplitude is $\sigma_\delta$ (expressed in seconds). In the simulations below, we have set the bandlimit of $\delta(t)$ to 100 Hz, and varied its RMS amplitude. Note that the addition of temporal jitter, $\delta(t)$, will reduce the interaural correlation, with the amount of the reduction increasing with $\sigma_\delta$. Fig. 5 specifies how the expected value of the normalized correlation coefficient between the jittered noises (when the interaural correlation is 1) varies as a function of $\sigma_\delta$, the RMS value of the 100 Hz band of noise that simulates how $\delta$ changes over time. Fig. 5 indicates that an RMS value of only 19 μs reduces the interaural correlation to approximately .8.

To simulate the decision process of our hypothetical observer, we assumed that the observer takes 45 independent amplitude samples during each rectangular window, and that the initial portion of the comparison stimulus never exceeded the length of the first window. The latter assumption allowed us to express the duration of the initial portion of the comparison stimulus as a fraction of the temporal window's total length as shown in Fig. 6. Simulations were conducted for 4 values of $\sigma_\delta$ (see the Appendix for details of these Monte Carlo simulations). Fig. 6 plots psychometric functions for the two conditions for this kind of ideal observer, for 4 values of $\sigma_\delta$. Note that when $\sigma_\delta$ is small, the psychometric function for the case in which the signals start off uncorrelated and then switch to correlated is steeper and to the left of the function for the condition in which the signal starts off correlated and switched to uncorrelated. Hence if temporal jitter is low, we expect lower thresholds for uncorrelated followed by correlated than for the reverse. However, as the value of $\sigma_\delta$ becomes larger, the slope of the psychometric function corresponding to uncorrelated followed by correlated becomes shallower, and its asymptotic value is lowered. The net result is that at higher values of $\sigma_\delta$ the two functions cross and detecting a switch from correlated to uncorrelated becomes easier than the reverse, depending on the value of percentage correct that is used to define the threshold (in the 3-down, 1-up procedure, threshold is defined as the 79.6% value of the psychometric function). Hence the Age by Condition interaction observed in Experiment 1 is consistent with there being a greater degree of temporal jitter in older than in younger adults.

It is interesting to note that as $\sigma_\delta$ increases, the asymptotic value reached by a psychometric function decreases more rapidly for the condition in which the initial segment is uncorrelated than it does when the initial segment is correlated (see Fig. 6). Hence, as temporal jitter increases, we would expect to find more individuals who simply cannot perform the task no matter how long the initial segment might be, because their psychometric functions never exceed the criterion for threshold (79.6% correct in this experiment), and that these failures would be more frequent when the initial segment was uncorrelated than when it was correlated.

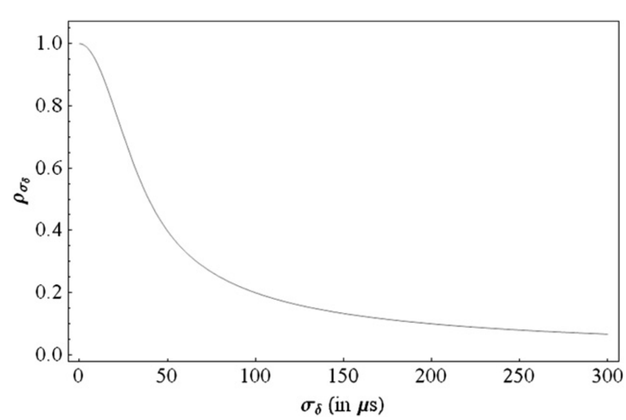


**Fig. 5.** The long term average internal interaural correlation, $\rho_{\sigma_\delta}$, as a function of the average magnitude of temporal jitter, $\sigma_\delta$, introduced at the point of comparison between the left and right-ear signals.

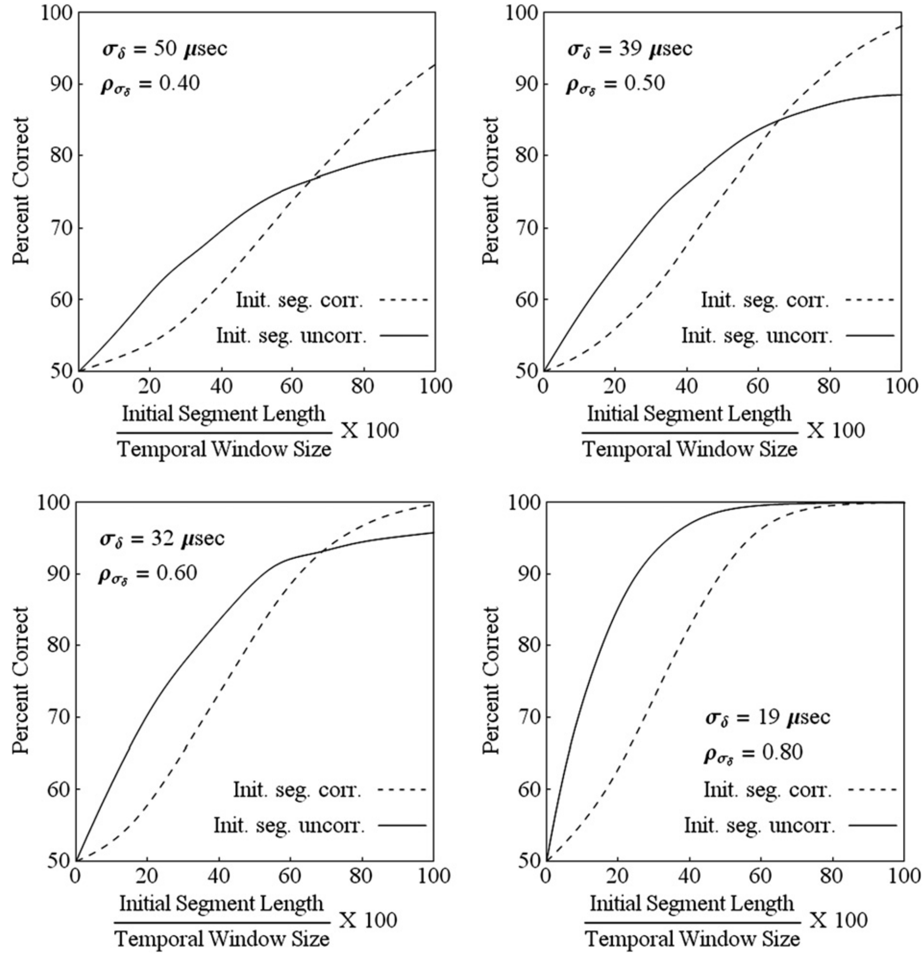


**Fig. 6.** Predicted percent correct as a function of the percentage of the first temporal window occupied by initial segment of the target stimulus for different degrees of temporal jitter ($\sigma_\delta$), which changes the hypothetical interaural correlation $\rho_{\sigma_\delta}$. As the amount of temporal jitter decreases from 50 μs (top left panel) to 19 μs (bottom right panel), the hypothetical interaural correlation shifts from .4 to .8, and the relative positions of the psychometric functions shift correspondingly.

### *4.2. Experiment 2*

In Experiment 2, a constant interaural delay of either 1, 3, or 5 ms was added to the stimuli from the two conditions. Fig. 3 shows that thresholds decrease monotonically as the interaural delay is reduced from 5 to 1 ms in both younger and older adults. However, for older adults in the segregation condition, thresholds, rather than decreasing or remaining the same as the interaural delay is further reduced from 1 to 0 ms, increase markedly. Why might this be the case? Recall that in the segregation condition, the interaural correlation in the comparison stimulus is initially 0. Hence any interaural delay detector in the auditory system would produce an indeterminate result when presented with such a stimulus, resulting in a perception that the stimulus is centrally-located (not lateralized). Note that when the interaural delay in the correlated segment is 0 ms, the resulting percept would also be centrally located. Hence, the only perceptual cue that can be used to distinguish the comparison stimulus from the standard stimulus when the interaural delay is 0 ms, is a change from diffuse, centrally-located noise to a compact centrally located noise. However, when the correlated segment has an interaural delay significantly greater than 0, the comparison stimulus can also be distinguished from the standard stimulus based on a change in laterality, as well as by a change in interaural correlation. Hence a switch from an interaural correlation of 0 to 1 in the segregation condition when there is a 1 ms delay provides an additional cue that can be used to distinguish between the standard and comparison stimuli, namely a change in laterality. If we now hypothesize that, in older adults, the initial uncorrelated segment has to be on longer to notice a change in interaural correlation from 0 to 1 than to notice that the correlated segment has an interaural delay, we would expect the duration threshold to be longer for an interaural delay of 0 ms than for an interaural delay of 1 ms. If this speculation is correct, we might expect segregation thresholds in older adults to continue to decrease as interaural delays are progressively shortened below 1 ms until the interaural delay is too short for them to detect a change in lateralization. On the other hand, if, in younger adults, it takes approximately the same amount of time to notice a lack of correlation as it does to note a change in laterality, there would be less of difference between duration thresholds in the segregation condition for interaural correlations of 0 and 1, as is the case in Fig. 3.

The fact that younger adults continue to outperform older adults for delays between 1 and 5 ms is consistent with the notion that temporal jitter increases with age. However, there is also a significant interaction between Condition and interaural delay. When the interaural delay is 1 ms, both younger and older adults find it easier to detect an uncorrelated initial segment than to detect a correlated one, with the reverse being true when the interaural delay is 5 ms. This pattern can be explained within a delay line version (Schneider and Zurek, 1989) of Durlach's equalization and cancellation (EC) model of binaural interaction (Durlach, 1972). This model assumes that the left- and right-ear signals are processed through parallel sets of delay lines before being compared. Consider the case in which the left-ear signal is a delayed version of the right-ear signal (*delay* = 1 ms). Now suppose the left-ear signal is processed through a delay line that imposes a zero ms delay, whereas the right-ear signal is processed through a delay line that imposes a delay of 1 ms. If there were no temporal jitter, the left-ear signal processed through the left-ear delay line whose value is $\tau = 0$, and the right-ear signal processed through a right-ear delay line whose value is $\tau = 1$ ms, would be identical, and give rise to a $r^2$ of 1.0. Of course, temporal jitter in either of these lines would reduce the value of $r^2$. If the amount of jitter turned out to be independent of the length of the delay line, this model would predict equivalent performance independent of the extent of interaural delay. However, if we make the further assumption that the amount of internal temporal jitter for a delay line increases with delay, we would predict that performance would decline as the interaural delay increases, and that for longer delays, it would be easier to detect a noise in which the initial segment was correlated before switching to uncorrelated than it would be to detect a noise in which the initial segment was uncorrelated before switching to correlated, the exact reverse of the pattern found for shorter delays. Interestingly, Pichora-Fuller and Schneider (1991,1992,1998) have shown, in a series of studies on binaural masking level differences (BMLDs), that a model in which temporal jitter increases with the length of the internal delay imposed on the signal provides a good account of the performance of younger listeners when interaural delays are introduced into either the signal or into the noise in a BMLD experimental paradigm.

### 4.3. Audiometric thresholds and sensitivity to interaural correlation

Because the audiograms of the older adults (see Fig. 1) suggest that they were in the early stages of presbycusis, we examined whether the duration thresholds for detecting a change in correlation were related to audiometric thresholds in both younger and older adults. First, for each individual, we averaged hearing levels across the two ears. Second, for the average across the two ears, we determined each individual's low-frequency (.25–2 kHz) and high-frequency (3–8 kHz) pure tone average (PTA) thresholds. Third, we then z-transformed these PTAs within each age group so that an individual's PTA is expressed relative to her or his group mean and standard deviation. To obtain a measure of an individual's overall sensitivity to a change in correlation, we averaged individual duration thresholds across the two conditions (Integration, Segregation), and four interaural delays (0, 1, 3, and 5 ms). These average duration thresholds were then z-transformed within each age group so that an individual's duration threshold for detecting a change in correlation was expressed relative to her or his group mean and standard deviation. Fig. 7 plots the normalized duration thresholds for detecting a change in correlation in the initial position as a function of their normalized low-frequency PTAs (upper panel), and normalized high-frequency PTAs (lower panel). Fig. 7 shows that sensitivity to a change in correlation in the initial position is not related to a person's low-frequency hearing for either younger (circles) or older (squares) adults, but is related to their high-frequency hearing. Moreover, the relationship between normalized duration thresholds and normalized PTAs is virtually identical for younger and older adults. An F-test failed to reject the null hypothesis that the high-frequency slope for the young equaled that of the old, $F[1,20] < 1$.

The correlation between high-frequency PTAs and sensitivity to changes in the interaural correlation from the initial to final segment of a broadband noise suggests that individuals (younger or older) with good high-frequency hearing are incorporating information from these high-frequencies in the decision processes leading to the identification of the noise with the correlation change. This finding is intriguing given that the preponderance of

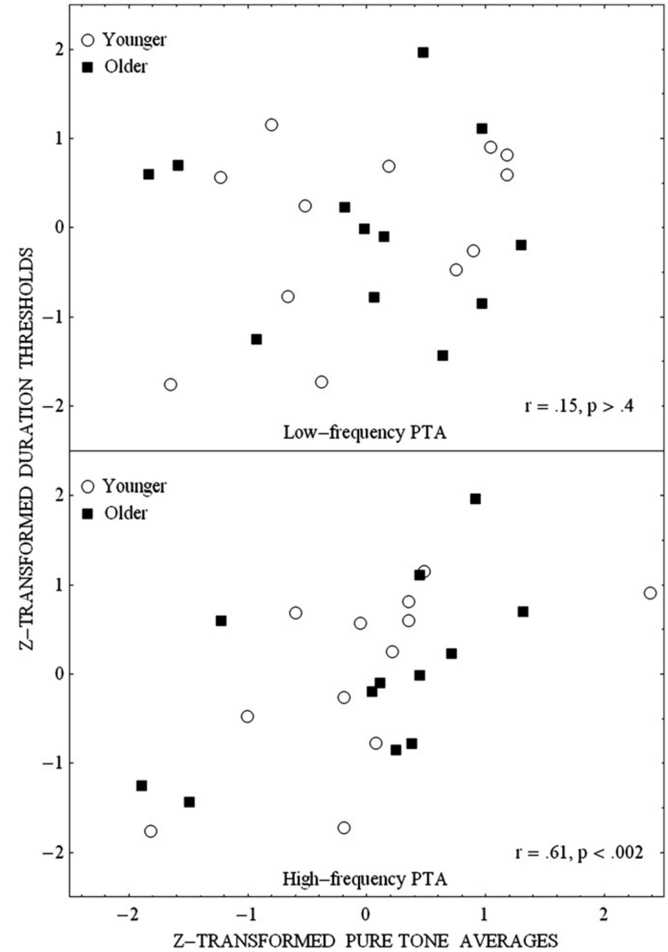


**Fig. 7.** Z-transformed duration thresholds as a function of low-frequency (top panel) and high-frequency (bottom panel) average pure tone thresholds (PTA). The duration thresholds were transformed into z-scores separately for younger and older adults. Correlation coefficients, *r*, are shown in each plot.

evidence suggests that it is difficult to detect a break in correlation based on high-frequency components alone (Akeroyd and Summerfield, 1999; Huang et al., 2009). However, Huang et al. found that 7 of 12 younger adults could detect a break in correlation in an otherwise correlated 1/3 octave noise centred at 3200 Hz when the interaural delay was 4 ms. When the interaural delay was 0 ms, 10 of the 12 could detect the break in correlation. Hence some participants are capable of using high frequency information to detect a break in correlation. Individuals with especially good high-frequency hearing (younger or older) appear to be capable of utilizing the information in the high-frequency region to determine whether or not the left- and right-ear signals are correlated. The extent to which high-frequency sensitivity and temporal jitter contribute independently to the listener's ability to detect a change in interaural correlation is not clear. Phase locking in the primary auditory afferents in humans could extend into the high-frequency range and overlap the frequency range used to calculate high-frequency PTAs. If the loss of high-frequency information increases the degree of temporal jitter in the nervous system (due to the loss of phase-locking information from this region), then the two variables would be interconnected, and this interconnection would explain why high-frequency sensitivity is correlated with the listener's ability to detect a change in interaural correlation in the initial position. However, if lower sensitivity in the high-frequency region directly increases temporal jitter, we would also expect to find a stronger connection between low-frequency sensitivity and temporal jitter since phase-locking is much more precise in the lower frequencies. Since we failed to find a correlation between the ability to detect a change in interaural correlation and low-frequency sensitivity, this suggests that temporal jitter and auditory thresholds are relatively independent of one another, as has been found for other measures of temporal processes (e.g., gap detection, see Schneider and Pichora-Fuller, 2001). Hence, it is more likely that high-frequency sensitivity is simply positively correlated with the overall state of the auditory system. In that case, individuals with high-frequency sensitivity would simply have better auditory systems and, hence, lower temporal jitter.

To ascertain the extent to which interaural differences might account for the data, we also computed the absolute value of the interaural difference for each participant at each of the audiometric frequencies. We then averaged these values for younger and older adults separately in the high- and low-frequency regions using the same definition of high- and low-audiometric frequencies as used in computing pure-tone averages. Then we z-transformed these average interaural differences within each age group so that an individual's interaural difference is expressed relative to her or his group mean and standard deviation. These z-transformed average interaural differences were then correlated with the z-transformed duration thresholds separately for each group. None of these four correlation coefficients approached significance ($p > .2$ in all four instances). Hence, there is no indication that the extent of a participant's interaural differences in either the high- or low-frequency region was associated with duration thresholds in this experiment.

### 4.4. Implications for everyday listening

In noisy environments, listeners have to be able to parse the auditory scene into its component sound sources to be able to attend to one or more of them and inhibit the processing of information from the others. When sound sources are located to the left and right of a listener, a lack of interaural correlation would be consistent with both sources being active, whereas a strong interaural correlation would be expected if only one source was active. The present results would suggest that older adults would take a considerably longer time to determine that there were two sound sources (one to the left and the other to the right) than would younger adults when both sound sources had simultaneous or near simultaneous onsets because they would need a longer sample to notice that the interaural correlation was low. Hence they would likely fuse information from the two sources during this period which would lead to considerable interference. Indeed older adults often complain that it is difficult to follow a conversation when everyone starts to talk at the same time. In other words a sluggish binaural system would make it more difficult to parse the auditory scene.

## Acknowledgements

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## Appendix

Let $f[t]$ specify how the amplitude of a bandlimited Gaussian noise (bandlimit $= W_f$ Hz) varies over time ($t$ in seconds). The long term average power in $f[t]$ is $\sigma_f^2 = N_{0f}W_f$, where $N_{0f}$ is the spectrum level of the noise. If we now add a delay, $\delta$, to the signal ($\delta$ in seconds), the delayed signal becomes $f[t+\delta]$. Now let's assume that $\delta$ is also a function of time in seconds, i.e., $\delta = g[t]$, where $g[t]$ is also a bandlimited Gaussian noise (bandlimit $= W_g$ Hz), whose long term average power is $\sigma_\delta^2 = N_{0,\delta}W_\delta$, where $N_{0,\delta}$ is the spectrum level of $g[t]$.

We start by noting that the auto-correlation function of a bandlimited Gaussian noise is

$$\frac{\mathrm{N}_0 \sin[2\pi W\tau]}{2\pi\tau}, \tag{A1}$$

and that the normalized auto-correlation function is obtained by dividing the auto-correlation function by the average power. Hence the normalized auto-correlation function for $f[t]$ is

$$\frac{\sin\left[2\pi W_f\tau\right]}{2\pi W_f\tau}. \tag{A2}$$

Now we can use the normalized auto-correlation function to determine the correlation, $r$, between $f[t]$ and $f[t+\delta]$ for a fixed value of $\delta$. Hence

$$r[\delta] = \frac{\sin\left[2\pi W_f\delta\right]}{2\pi W_f\delta}. \tag{A3}$$

Now $\delta$ also varies over time. Because $\delta = g[t]$ is a bandlimited Gaussian noise, we know that if we sample $g[t]$ every $1/2W_\delta$ seconds, these sample values are independent random variables with a normal distribution whose mean is 0 ($\mu = 0$), and whose standard deviation is $\sigma_\delta$. Hence the expected value of $r[\delta]$ is

$$\begin{aligned}\rho_{\sigma_\delta} = E[r[\delta]] &= \int_{-\infty}^{\infty} \frac{\sin\left[2\pi W_f\delta\right]}{2\pi W_f\delta}\left(\frac{e^{-\frac{\delta^2}{2\sigma_\delta^2}}}{\sqrt{2\pi}\sigma_\delta}\right)\mathrm{d}\delta \\ &= \frac{Erf\left[\sqrt{2}\pi W_f\sigma_\delta\right]}{2\sqrt{2\pi}W_f\sigma_\delta},\end{aligned} \tag{A4}$$

where

$$Erf[z] = \frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2}\mathrm{d}t \tag{A5}$$

Hence Eq. (A4) specifies how the expected value of the interaural correlation varies with the RMS value ($\sigma_\delta$) of the noise band used to temporally jitter the signal.

### A1. Decision strategy used in constructing psychometric functions

On each trial the hypothetical observer is presented with two signals, a standard and a comparison. We assume that the observer applies consecutive rectangular temporal windows to the signals at the left- and right-ear. In this particular example we assume that the observer takes 45 samples of the left- and right-ear stimuli in each window. Recall that the interaural correlation for the initial portion of the comparison signal differs from that of the standard. To simplify calculations we also assume that this initial portion of the comparison stimulus does not exceed the window size. Hence if the initial portion of the comparison stimulus is 1/9 of the size of the temporal window, the expected value of the squared interaural correlation between the first 5 left- and right-ear samples in the first window will differ between the standard and comparison stimuli, while the expected value of the squared interaural correlation of the remaining 40 samples from the first window will be identical in both the standard and comparison signals. Note that in the second window, the expected value of the squared interaural correlation will always be the same for both standard and comparison.

We now assume that the observer computes the square of the internal interaural correlation, $r^2$, for both stimuli in temporal windows 1 and 2. The internal interaural correlation is the correlation between the left- and right-ear signals in each window after jitter is added. Note that $r^2$ is an estimate of the effective strength of the relationship between the left- and right-ears. Hence four values of $r^2$ are computed $(r^2_{1,1}, r^2_{1,2}, r^2_{2,1}, r^2_{2,2})$, where the first subscript indicates the stimulus (the first or second stimulus presented on a trial), while the second subscript specifies the temporal window (first or second). In the integration condition the observer computes two differences $[(r^2_{1,1} - r^2_{1,2}), (r^2_{2,1} - r^2_{2,2})]$ and identifies the comparison stimulus as the one with the larger difference. In the segregation condition the observer computes differences $[(r^2_{1,2} - r^2_{1,1}), (r^2_{2,2} - r^2_{2,1})]$ and again identifies the comparison stimulus as the one with the larger difference. Note that because these correlations are based on samples, their effective values will vary from trial to trial.

### *A2. Using Monte Carlo techniques to construct psychometric functions*

To construct psychometric functions, we assumed that the number of independent amplitude samples taken in each temporal window was 45, and that the hypothetical observer's decision was based on comparisons between the first and second temporal windows of each stimulus (standard and comparison). The interaural correlation of both the standard and comparison stimuli was identical except for the initial portion of the comparison stimulus, which occupied $(j/45)$ 100% $(1 < j < 46)$ of the first window of the comparison stimulus. For each of four values of temporal jitter, $\sigma_\delta$, we computed the expected value of the internal interaural correlation, $\rho_{\sigma_\delta}$, corresponding to an external interaural correlation of 1.0, using (A4). In the Integration condition, the first $j$ paired (left- and right-ear) sample values occupying window one of the comparison stimulus were drawn from a bivariate unit normal distribution (using Mathematica's MultinormalDistribution function) where the population value of the correlation between the two sets of $j$ values was set to $\rho_{\sigma_\delta}$.

The remaining 45-$j$ paired values in the first window of the comparison stimulus were generated assuming an interaural correlation value of 0. For the second window of the comparison stimulus and for each of the windows of the standard stimulus, 45 pairs were generated assuming an interaural correlation of 0. Fresh sample values were generated on each trial of the 2I2AFC procedure.

To construct the paired samples for the two windows of the standard stimulus in the Segregation condition, two sets of 45 paired values were drawn from a bivariate unit normal distribution where the population value of the correlation between the two sets of paired values was $\rho_{\sigma_\delta}$. To construct the initial portion of the comparison stimulus for this condition, the first window consisted of $j$ pairs sampled from a bivariate normal distribution whose population correlation was 0. The remaining 45-$j$ pairs were generated from a bivariate normal distribution whose population correlation was $\rho_{\sigma_\delta}$. Another 45 pairs were generated from the same bivariate normal distribution to constitute the second window of the comparison stimulus.

To determine a single point on a psychometric function 10,000 trials were simulated for each combination of $j = \{5, 10, 15, 20, 25, 30, 35, 40, 45\}$ and $\rho_{\sigma_\delta}$ (19, 32, 39, and 50 μs). The smooth curves shown in Fig. 7 represent spline fits to these data points (Mathematica, BSpline function).

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