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Binaural Listening in Young and Middle-Aged Adults: Interaural Phase Differences and Speech-in-Noise Measures

Caitlin Cotter

A dissertation submitted to the Graduate Faculty of
JAMES MADISON UNIVERSITY
In
Partial Fulfillment of the Requirements
for the degree of
Doctor of Audiology

Communication Sciences and Disorders

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Table of Contents

List of Tables

List of Figures

Abstract

Difficulty understanding speech in the presence of noise is a common complaint of middle-aged and older adults with and without hearing loss. There is an incomplete picture of what contributes to difficulties understanding speech-in-noise in adults who have normal audiograms. As humans we listen binaurally, so declines in binaural processing may contribute to speech-in-noise difficulties. We examined the effects of age on the upper frequency limit of interaural phase difference (IPD) detection and IPD detection at fixed frequencies. We also examined a speech-in-noise measure of spatial separation across young and middle-aged, normal-hearing individuals.

Participants were young (n=12) and middle-aged (n=8) adults with normal and symmetrical hearing from 250-8000 Hz. Two interaural phase difference tasks were undertaken. The first assessed interaural phase difference discrimination across frequencies and the second assessed interaural phase difference discrimination at fixed frequencies (500, 750, 1000, 1125 Hz). In addition, the speech-in-noise measure of benefit from spatial separation was assessed by having subjects complete the words-in-noise test with speech and noise at 0° and again with speech at 0° and noise at 90°.

The young group had significantly higher (better) upper frequency limits for interaural phase difference discrimination. There was no statistically significant difference between the IPD discrimination at fixed frequencies for the young and middle-aged group, contrary to what was hypothesized. The young group also did not have a greater benefit from spatial separation compared to the middle-aged group.

The outcomes from this study add to a growing body of literature suggesting a decline in the upper frequency limit of IPD discrimination with advancing age. This negative effect of aging begins in middle-aged, normal-hearing listeners. The results from this study also suggest that factors other than age and IPD discrimination affect spatial processing in middle-aged adults with clinically normal audiograms. Knowing what contributes to difficulty understanding speech-in-noise will aid in counseling patients and will improve approaches to aural rehabilitation.

Chapter I

Introduction

The purpose of this study is to examine effects of age on the upper frequency limit of interaural phase difference (IPD) discrimination and IPD discrimination limens at fixed frequencies. Also, this study will examine relationships between the upper frequency limits of IPD discrimination and the speech-in-noise measure of spatial separation across young and middle-aged, normal-hearing individuals. This was measured using two psychoacoustic measures, IPD discrimination across frequencies and IPD discrimination at fixed frequencies, and one speech-in-noise measure, the Words-in-Noise test (WIN), to assess the benefit from spatial separation of speech and a multitalker babble masker. It was hypothesized that the upper frequency limit of IPD discrimination and IPD discrimination at individual frequencies will be reduced in middle-aged adults. It was also hypothesized that spatial separation will be poorer in middle-aged adults and that poorer IPD thresholds (lower upper frequency limit) will correlate with poorer speech-in-noise measures.

Chapter II

Review of the Literature

Introduction

Binaural hearing provides a listener with many cues that aid in the localization of a sound source and the ability to detect a signal in noise. Interaural time and intensity differences provide important information about the location of a sound source (Moore, 2008a). Interaural differences also aid when listening to a signal in the presence of background noise. If the signal and background noise originate from different locations, the ability to detect the signal is improved by comparing interaural differences reaching the two ears (Moore, 2008a). Spatially separating the signal and masker also provides a more favorable signal-to-noise ratio (SNR) for the ear closer to the signal, improving the ability to detect the signal (Moore, 2008a). For the purpose of this study, the focus will be on interaural time differences (ITDs) not interaural level differences (ILDs).

ITDs are used to localize low-frequency, non-complex sounds below 1500 Hz (Yost, 2007; Moore, 2008a). Low-frequency sounds have long wavelengths that easily bend around objects such as a human head. The ear closer to the signal will receive input slightly before the lagging ear; hence, there is a time difference between the two ears (Yost, 2007). ITDs correspond to interaural phase differences (IPDs) when the signal is a sinusoidal tone (Moore, 2008a). For low-frequency sounds, a clear phase difference occurs between the two ears depending on the origin of the signal (Pickles, 2008).

One acoustic aspect of sound used in binaural hearing is temporal fine structure (TFS). TFS is comprised of the relatively fast amplitude fluctuations in a signal waveform. The carrier frequency of a sinusoidally amplitude-modulated (SAM) signal determines the TFS (Blauert, 1997; Yost, 2007; Moore, 2008b). Localization of non-amplitude modulated tones using IPDs relies on the comparison of interaural differences in the fine structure of a signal. Research has demonstrated that increasing age typically results in a decrease in TFS sensitivity in binaural processing across a variety of tasks (Pichora-Fuller & Schneider, 1991, 1992; Strouse, Ashmead, Ohde, & Grantham, 1998; Ross, Fujioka, Tremblay, & Picton, 2007; Grose & Mamo, 2010; Hopkins and Moore, 2011; Moore, Vickers, & Mehta, 2012 Füllgrabe, 2013).

Age-related declines in binaural hearing

Age-related declines in binaural hearing have been reported on a wide variety of behavioral tasks. For example, research has been completed examining localization (Dobreva, O'Neill, & Paige, 2011), masking level difference (Pichora-Fuller & Schneider, 1991; 1992; 1998; Grose, Poth, & Peters, 1994; Strouse et al., 1998), and interaural phase differences (Ross et al., 2007; Grose & Mamo, 2010; Hopkins & Moore, 2011; Moore et al., 2012; Füllgrabe, 2013). Hearing sensitivity was not controlled for in the majority of the studies examining binaural hearing in older adults, in the sense that some individuals had normal hearing sensitivity while others had varying degrees of sensorineural hearing loss. Therefore, the findings may reflect combined effects of aging and hearing loss. Of particular interest to the present study are age-related declines in the binaural processing of temporal fine structure, which can be evaluated using interaural phase differences.

Recent studies have reported that age-related deficits in binaural listening occur as early as middle age and continue to decline with advancing age (Ross et al., 2007; Grose & Mamo, 2010; Hopkins & Moore, 2011). These reports have focused on perceiving interaural phase differences that occur in the fine structure of sinusoidal stimuli, rather than the temporal envelope. Ross et al. (2007) studied aging in binaural hearing using behavioral and physiological measures. Ross et al. (2007) found a decline in the upper frequency limit of behavioral IPD detection starting in middle age. Specifically, the mean thresholds indicating the highest frequency at which younger, middle-aged, and older adults were able to behaviorally detect IPDs were 1203 Hz, 705 Hz, and 638 Hz, respectively (Figure 1). Cortical P1-N1-P2 change responses, elicited by the change in interaural phase of an amplitude-modulated pure tone, showed a similar pattern to the behavioral results. IPD change responses disappeared between 1500 and 1250 Hz for the young group, between 1250 Hz and 1000 Hz for the middle-aged group, and between 1000 and 750 Hz for the older group.

Ross et al. (2007) observed high variability amongst the behavioral IPD data (Figure 1). For example, the range of thresholds obtained during behavioral IPD testing for the young group was 770-1683 Hz and the range for both the middle-aged and older groups was 300-1400 Hz. While the trend of decreasing IPD thresholds with increasing age can still be observed in the Ross et al. (2007) data, the distribution of thresholds in the middle-aged and older groups significantly altered the mean thresholds in the middle-aged and older group.

Grose and Mamo (2010) also found declines in IPD discrimination starting in middle age. Grose and Mamo (2010) altered the stimulus paradigm from the Ross et al.

(2007) procedure and found less variability in the data, suggesting that IPD discrimination may be less variable when the phase change occurs within a stimulus rather than across stimuli. Figure 1, adapted from Grose and Mamo (2010), displays the 25th to 75th percentiles and median thresholds from the study alongside the data from Ross et al. (2007). The median thresholds indicating the highest frequency at which younger, middle, and older adults were able to discriminate IPDs were approximately 1250 Hz, 1050 Hz, and 950 Hz, respectively.

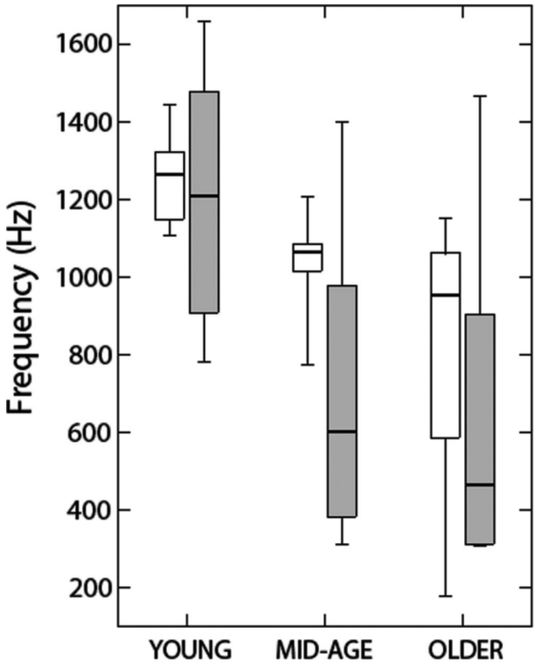

Figure 1. Figure adapted from Grose and Mamo (2010). Open rectangles represent the 25th to 75th percentile of upper frequency limit for IPD discrimination from Grose and Mamo (2010). The shaded rectangles represent the data from the Ross et al. (2007) study. The bold lines within the rectangles represent the median values.

Grose and Mamo (2010) also examined IPD discrimination at fixed frequencies in young, middle-aged, and older adults. Results supported the notion that IPD sensitivity is reduced starting in middle-age. Specifically, listeners from the young, middle-aged, and older groups reached the π-radian limit, indicating the listener was performing at ceiling, at approximately 1500 Hz, 1250 Hz, and 1000 Hz respectively.

Hopkins and Moore (2011) studied changes in TFS sensitivity using an IPD discrimination task (what they refer to as the TFS-LF task) and discrimination of harmonic and frequency-shifted tones (what they refer to as the TFS2 task). The TSF-LF task was developed by Hopkins and Moore (2010) to find IPD discrimination limens at fixed frequencies by requiring listeners to identify the stimulus containing the IPD, which was perceived as a change in the position of the sound. Results showed that normal-hearing young listeners performed significantly better than the normal-hearing older listeners. Speech reception thresholds (SRT) in the presence of modulated noise were also tested, and were found to be correlated with TSF-LF and TSF2 scores. However, the correlation between SRTs in noise and TSF-LF scores was not significant after separating out the effect of audiometric thresholds. These results were consistent with previous studies indicating that TFS sensitivity is important when listening to a signal embedded in modulated background noise (Lorenzi Husson, Ardoint, Debruille, 2006; Hopkins & Moore, 2009; Hopkins & Moore, 2011).

Taken together, findings from recent research examining changes in TFS sensitivity with age provides converging evidence that behavioral processing of TFS declines at higher frequencies on binaural tasks focused on interaural phase differences, and that this pattern begins in middle age. One possible explanation of this frequency-by-age interaction is that age-related declines in the upper frequency limit of neural phase locking are occurring and disrupting the fidelity with which the acoustic cues are being encoded. Although these age-related changes in upper frequency limit of IPD discrimination have been reported, it is still unknown how this age-related upper frequency reduction is related to understanding speech in the presence of background noise.

Aging effects on spatial processing

One definition of spatial processing refers to the ability to follow a signal originating from one direction while ignoring a signal originating from a different direction (Glyde, Hickson, Cameron, & Dillon, 2011). Understanding speech in the presence of background noise typically improves when the speech signal and noise signal originate from different locations in space. If speech perception improves when the speech and noise signals are separated, this would demonstrate benefit from spatial separation. An improvement in speech intelligibility can be measured when spatially separating speech and noise signals by as little as 10º (Dirks & Wilson, 1969). One reason an improvement in speech recognition is likely observed with spatial separation of a signal and masker is because of interaural time and intensity differences (Dirks & Wilson, 1969; Bronkhorst & Plomp, 1988; Moore, 2008a). Another proposed reason for this improvement is the more favorable SNR the ear closer to the signal receives due to the head shadow effect (Bronkhorst & Plomp, 1988; Moore, 2008a).

Multiple research studies have found age-related declines in spatial processing (Divenyi & Haupt, 1997; Dubno, Ahlstrom, & Horwitz 2002; Divenyi, Stark, & Haupt, 2005; Kim, Frisina, & Frisina, 2006; Murphy, Daneman, & Schneider, 2006; Marrone, Mason, & Kidd, 2008). Among the studies that found a significant effect of age, there are only several that controlled for hearing loss in a way that allowed normal-hearing, young listeners to be compared with seemingly normal-hearing, older listeners (Dubno et al., 2002; Kim et al., 2006; Murphy et al., 2006; Marrone et al., 2008). However, amongst the studies controlling for hearing loss, normal hearing was typically defined as thresholds less than or equal to 20 or 25 dB HL for octave frequencies from 0.25 or 0.5 KHz to 3 or 4 KHz (Dubno et al., 2002; Kim et al., 2006; Murphy et al., 2006; Dubno et al., 2008, Marrone et al., 2008). It is unclear if elevated thresholds in the higher frequencies in the older group contributed to the reduced benefit observed for the older listeners (Dubno et al., 2002; Marrone et al., 2008).

Dubno et al. (2002), Kim et al. (2006), and Marrone et al. (2008) found statistically significant reduced benefit from spatial separation in older adult listeners. Dubno et al. (2002) reported a spatial-separation benefit of 6.1 dB for young listeners, which was significantly different from the spatial-separation benefit of 4.9 dB for older listeners. Similarly, Divenyi and Haupt (1997) found a significant age effect when studying older adults with no more than a moderate hearing loss. Age effects were present even after effects of hearing loss were statistically controlled for in the older listeners.

Conflicting research has found no significant effect of age on spatial processing (Gelfand, Ross, & Miller, 1988; Dubno, Ahlstrom, & Horwitz, 2008; Cameron, Glyde, & Dillon, 2011; Ahlstrom, Horwitz, & Dubno, 2014). In the majority of the research with no significant age effect, normal-hearing listeners were required to have thresholds less than or equal to 15 or 20 dB HL for octave frequencies 0.25-8 KHz (Gelfand et al., 1988; Cameron et al., 2011). Hence hearing loss was more controlled and was less likely to impact results.

In 2008, Dubno et al. assessed spatial-separation benefit using the Hearing In Noise Test (HINT). The benefit for the younger and older listeners differed by approximately 1 dB, which was not statistically significant. Although not statistically significant, the 1 dB difference between the younger and older listeners was comparable to the 1.2 dB difference in benefit from spatial separation found by Dubno et al. (2002).

A review of the literature regarding spatial processing abilities in older adults by Glyde, Hickson, Cameron, and Dillon (2011) revealed a lack of literature in agreement on the subject of aging and spatial processing. Many previous studies regarding spatial processing and aging have not controlled for variables such as hearing loss and cognition (Glyde et al., 2011). Also, the definition of normal hearing is not consistent across research investigating aging effects on spatial processing.

Purpose

In summary, age-related declines in binaural hearing have been found starting in middle-age. There remains a lack of consensus in research regarding age-related changes in spatial processing. Multiple research studies have shown a decrease in spatial processing abilities related to aging, while other research, with more conservative normal hearing criteria, has not.

This dissertation will evaluate the relationships between age-related declines in IPD and spatial separation within the same individuals. This dissertation will aim to clarify the following hypotheses:

1. The upper frequency limit of IPD discrimination, as reflected by a task using 180º, or π radian IPDs, will be significantly reduced in middle-aged adults.

2. IPD discrimination at carrier frequencies from 500-1125 Hz will be reduced in middle-aged adults. A significant age by frequency interaction is expected, as age differences will increase as carrier frequency increases.

3. Benefit from spatial separation, the difference in 50% point signal-to-babble ratios from spatially separating multitalker babble and a speech signal, will be significantly poorer in middle-aged adults.

4. Poorer IPD thresholds (lower upper frequency limit) will correlate with poorer speech-in-noise measures. Individuals who require more favorable signal-to-babble ratios will be the same individuals with a limited frequency range over which IPDs of 180° can be discriminated; individuals that can discriminate IPDs at higher frequencies will be able to perform well with less favorable signal-to-babble ratios.

Chapter III

Materials and Methods

Data collection consisted of three behavioral measures: the IPD across frequencies test, the IPD for fixed frequencies test, and the Words-in-Noise test measured in conditions with speech and babble delivered from the same azimuth or spatially separated. The test order and the order of conditions for each test were randomized. Data for each subject was collected during one test session. A typical test session lasted approximately four hours.

Subjects

Twenty subjects participated in the study. Subjects were divided into two groups: young (n = 12; age range = 21-24; mean age = 22.5) and middle-aged (n = 8; age range = 37-48; mean age = 43.1). All subjects had hearing thresholds within normal limits, defined as less than or equal to 25 dB HL at octave frequencies 250 Hz to 8000 Hz. All subjects had symmetrical hearing, with no more than a 10 dB difference between ears at each frequency. All subjects had normal tympanograms at the time of testing, suggesting normal outer and middle ear function. Subjects were right-handed, monolingual native English speakers. No subjects were taking any prescription medications related to sleep, seizures, attention, or memory at the time of testing. The subjects did not have a history of neurological disorders or otological disease. Subjects were recruited from James Madison University and the surrounding community through the use of flyers and word of mouth. All subjects were compensated $10 per hour for participating. All procedures were approved by the institutional review board at James Madison University prior to data collection.

Methods common to interaural phase difference conditions

Stimuli were generated using custom MATLAB (version 7.5; MathWorks, Natick, MA) programs that were developed for this study. The output of the computer used for testing was routed through Tucker-Davis Technologies (Alachua, FL) System II sound attenuators (PA4) and a headphone buffer (HB6) and was delivered to the subject's left and right ears through ER-3A insert earphones with double-length tubing. Stimuli were presented at 80 dB SPL. Custom MATLAB (version 7.5; MathWorks, Natick, MA) programs were developed for the psychoacoustic procedures. Subjects were seated in a double-walled, sound-attenuating sound booth during testing.

Interaural Phase Difference Across Frequencies

Stimuli

Stimuli and procedures for the IPD tasks were based on those of Grose and Mamo (2010). The stimuli for the IPD across frequency task consisted of sinusoidally amplitude modulated (SAM) tones. Tone duration was 800 ms. Amplitude modulation rate was 5 Hz and the modulation depth was 100%. There were four periods of amplitude modulation throughout the stimulus.

The standard stimulus was diotic, meaning the carrier frequency was in phase at both ears. The signal stimulus was dichotic, meaning the carrier frequency was π-radians out of phase between the right and left ear during the second and fourth periods of modulation. The phase of the temporal envelope was identical in all conditions. Subjects could not detect the moment at which the π-radian phase reversal took place during the stimulus because it took place during the modulation minimums (Figure 2).

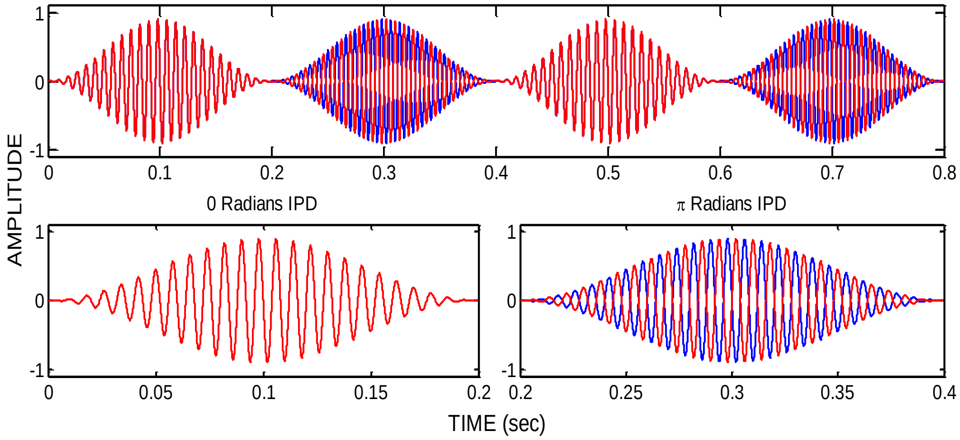

Figure 2. Example of a stimulus waveform from the across-frequency IPD task. ***Top panel:*** Stimuli for left (blue) and right (red) ears. Interaural phase of the carrier frequency changed at the amplitude minima. ***Bottom Left Panel:*** First AM cycle shows zero phase difference between channels. ***Bottom Right Panel:*** Second AM cycle with π-radians interaural phase difference.

Procedure

The IPD across frequencies task measured the ability to discriminate between 0 and π radian IPDs as a function of varied SAM tone carrier frequencies. A three-alternative forced choice procedure using a three-up, one-down adaptive rule was used during testing. The three-up, one-down procedure converged upon the 79.7% correct point on the psychometric function. The carrier frequency of the SAM tone was the independent variable. Initially, the carrier frequency of the SAM tone changed in half-octave steps; after four reversals in frequency direction, the carrier frequency of the SAM tone varied in step sizes of one-quarter octave. After twelve reversals of frequency direction, the threshold estimation track was terminated; the mean of the last eight reversals was taken as threshold.

For each trial, the subject heard three stimuli: two standard stimuli and one signal stimulus. The order of stimuli was randomized for each trial. The subject was instructed to listen for the stimulus that sounded different from the other two and to mouse-click on the number corresponding to that stimulus on the computer monitor. After the subject made a selection, the background of the number changed to indicate if the subject chose correctly or incorrectly. If the correct answer was chosen for three consecutive trials, the carrier frequency increased by a half- or quarter-octave, depending on the number of frequency reversals, making the task more difficult. If the subject answered incorrectly, the carrier frequency decreased by a half- or quarter-octave, depending on the number of frequency reversals, making the task easier. The procedure continued until there were twelve reversals in carrier frequency direction. The threshold was estimated by taking the geometric mean of the final eight reversals.

A minimum of three runs were completed for each subject. Additional runs were completed for subjects if tracking functions or thresholds became variable. The final threshold was estimated by calculating the mean threshold of all runs. The final threshold estimates the highest frequency at which subjects could discriminate the phase static signal from the phase dynamic signal.

Interaural Phase Difference at Fixed Frequencies

Stimuli

The stimuli for the IPD fixed frequencies task were sequences of two tone bursts at 500, 750, 1000, or 1125 Hz. The tone bursts had 300 ms duration with a 50 ms inter-stimulus interval. The tone bursts were shaped with a raised-cosine onset of 75 ms and an offset ramp of 25 ms The tone burst plateau had a 200 ms duration. The standard stimulus tone bursts were diotic, meaning there was no phase difference between the left and right ears. The signal stimulus contained a diotic leading tone burst and a dichotic trailing tone burst. The dichotic tone burst contained an IPD (Figure 3).

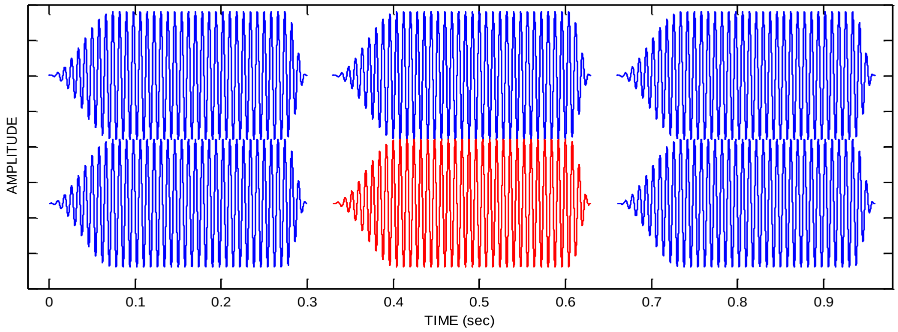

Figure 3. Example of stimulus waveforms from the fixed-frequency IPD task. Waveforms along the top of the panel are for the left ear, and lower waveforms are for the right ear. In this example, the test stimulus has an IPD in the second interval.

Procedure

The just-noticeable IPD was measured at four frequencies, 500 Hz, 750 Hz, 1000 Hz, and 1125 Hz. These frequencies span a range that is expected to show a robust age by frequency interaction based on the data of Grose and Mamo (2010) and Ross et al.

(2007). A three-alternative, forced-choice procedure using a three-up, one-down adaptive rule was used during testing. The three-up, one-down procedure converged upon the 79.7% correct point on the psychometric function. The independent variable was the frequency of the tone burst. The time difference between ears (in degrees) initially varied in step sizes of the square root of two). After four reversals in IPD direction, the time difference between ears varied in step sizes of the square root of the square root of two . The threshold estimation track was terminated after twelve reversals in IPD direction.

For each trial, the subject heard three tone bursts sequentially. During each trial, the subject heard two standard stimuli and one signal stimulus. The order of the standard and signal stimuli was randomized for each trial. The subject was instructed to listen for the stimulus that sounded different from the other two and to use the mouse to click on the number corresponding to that stimulus on the computer monitor. The background of the number changed to indicate if the subject chose the correct or incorrect stimulus. If the subject answered correctly three times in a row, the time difference between the two ears got smaller, making the task more difficult. If the subject answered incorrectly, the time difference between the two ears got larger, making the IPD easier to detect. Subjects were performing at chance when a diotic stimulus could not be discriminated from a signal with a time difference corresponding to π radians. The procedure was terminated once there were twelve reversals in carrier frequency direction. The threshold was estimated by taking the geometric mean of the final eight reversals.

A minimum of three replications were completed, at all four frequencies, for each subject. A fourth replication was completed for subjects with high intra-subject variability at any of the four frequencies. The final threshold was estimated by calculating the mean threshold of all replications for one frequency. The final threshold represented the mean time difference, in microseconds, between ears at which the subject could differentiate between the diotic and dichotic tone bursts at that frequency.

Speech-in-Noise

The Words-in-Noise test (WIN; Wilson, 2003) was administered to assess the ability for an individual’s speech-in-babble understanding to benefit from spatially separating the speech and multitalker babble. Data was collected for two conditions. The first condition consisted of speech and multitalker babble masking noise both originating from 0° azimuth relative to the subject’s position (S0N0). The second condition consisted of speech originating from 0° azimuth and multitalker babble originating from 90°; this was the speaker to the participant’s right side (S0N90). Figure 4 illustrates the arrangement of the loudspeakers. The center of the speakers were 42 inches above the floor, which is approximately ear-level for an average height listener in the seated position. The subject’s head was approximately 57 inches from the speaker. Multitalker babble was calibrated using the Larson-Davis sound level meter (system 824) and half-inch microphone (Larson Davis #2541) to be 80 dB SPL. Words were calibrated to range from 104 to 80 dB SPL depending on the signal-to-babble ratio.

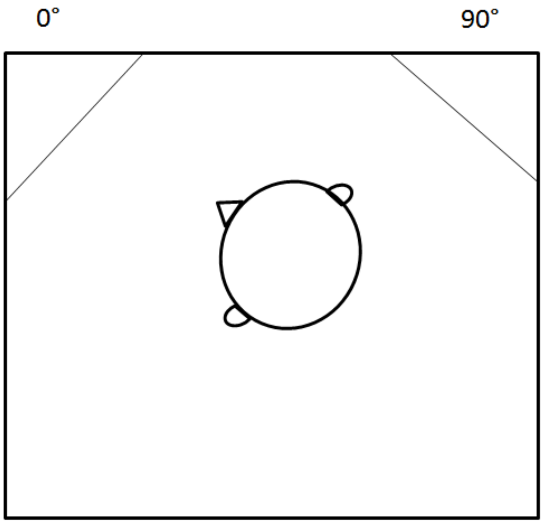

Figure 4. Schematic layout of speech-in-noise testing. When speech was at 0 degrees azimuth and multitalker babble at 90 degrees azimuth, the babble was presented from the speaker at the participant's right side.

The speech and mutlitalker babble were played using a Sony CD player. The output of the CD player was routed through a Grason-Stadler Instruments 16 (GSI-16) audiometer. The output of the GSI-61 audiometer was routed to two Grason-Stadler sound field speakers located in a double-walled, sound attenuating booth, where the subject was sitting. For the S0N0 condition, the dial setting for channel one of the audiometer, which played the multitalker babble, was 79 dB HL. The dial setting for channel two, which played the speech, was also 79 dB HL. Both channels were routed to the same speaker, which corresponded to 0° azimuth. For the S0N90 condition, the dial of channel one, the multitalker babble, was set to 85 dB HL. The dial for channel two, the speech, was set to 82 dB HL. Channel one was routed to the speaker at 90° azimuth and channel two was routed to the speaker at 0° azimuth. All dial settings were calibrated using the same segment of multitalker babble to produce 80 dB SPL where the subject's head was positioned. Prior to testing each subject, the calibration track, provided on the WIN CD, was used to calibrate both channels of the audiometer to 0 dB VU.

The WIN CD used for testing consisted of two lists of 35 monosyllabic words and multitalker babble presented at seven signal-to-babble ratios (24, 20, 16, 12, 8, 4, and 0 dB SBR). Five words were presented at each signal-to-babble ratio. For each list, there were eight different word randomizations on the CD. A third list with four randomizations was used for practice purposes only. Lists one and two were presented in each of the two spatial conditions. Each subject was assigned a randomization of list one and two for the S0N0 condition and a different set of list one and two randomizations for the S0N90 condition, for a total of 70 words per condition.

The subject was told to listen for the female voice reading words in the presence of background noise. The subject was instructed to write down all the words they could hear, even when the female voice got quiet and more difficult to understand. They were also told that the background noise and speech may come from the same speaker or from different speakers. The number of words written down correctly was added up for each signal-to-babble ratio. At the end of each list, the total number correct was determined by adding the total number of words written down correctly for all seven signal-to-babble ratios. The 50% point threshold was obtained by using the chart located on the WIN score sheet. The benefit from spatially separating the speech and masker (dependent variable Spatial Separation Benefit) was obtained by subtracting the mean threshold for the S0N90 condition from the mean threshold for the S0N0 conditions.

Chapter IV

Results

Upper frequency limit of IPD discrimination (IPD across-frequency)

A one-way ANOVA with a between-subjects factor of Group (two levels: young and middle-aged) was used to assess the difference in the upper frequency limit of IPD discrimination. As expected, the ANOVA revealed a significant group difference ($F(1, 17) = 5.549$ $p = .031$, partial $\eta^2 = .246$), indicating that the upper frequency limit of IPD detection was significantly reduced (poorer) in middle-aged listeners. Figure 5 illustrates the difference between the IPD discrimination upper frequency limit of the young and middle-aged groups.

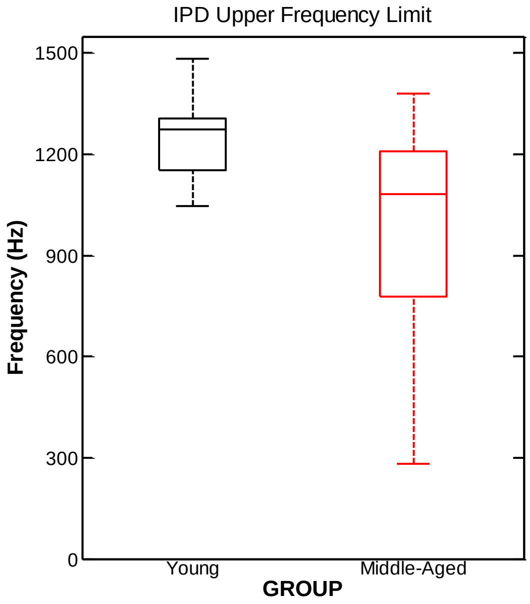

Figure 5: The upper frequency limit of IPD discrimination, as reflected by a task using π radian interaural phase difference, for the young (black rectangle) and middle-aged (red rectangle) groups. The rectangles encompass the 25th to 75th percentiles. The horizontal

lines inside the rectangles represent the median. The vertical lines encompass the 10th and 90th percentiles.

IPD discrimination at fixed frequencies

A repeated-measures ANOVA was performed to determine if IPD discrimination at 500, 750, 1000, and 1125 Hz changes with age. Factors were Group (between-subjects, two levels: young and middle-aged) and Frequency (within-subjects, four levels: 500, 750, 1000, and 1125 Hz). The main effect of Group was not significant ($F(1.245, 19.919) = .809$, $p = .405$, partial $\eta^2 = .048$), indicating that ITD discrimination was not significantly different between the young and middle-aged subjects. The main effect of Frequency was also not significant ($F\ (1.245, 19.919) = 3.471$, $p = .070$, partial $\eta^2 = .178$), indicating that ITD discrimination was not significantly different across frequencies. The Group by Frequency interaction was not significant ($p > .05$), indicating that there was no interaction between the two groups across the frequencies tested, contrary to what was hypothesized. It was hypothesized that an Age by Frequency interaction would be significant, reflecting larger age-related declines as the carrier frequency increased (Grose and Mamo, 2010). Post-hoc comparisons revealed no significant Group differences at individual frequencies. Figure 6 displays the ITD discrimination thresholds for the IPD discrimination at fixed frequencies task.

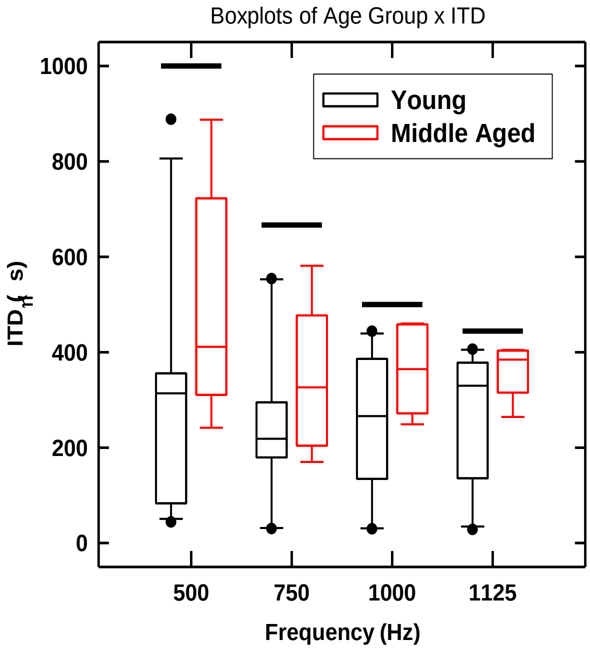

Figure 6: Boxplot illustrating the ITD discrimination thresholds at 500, 750, 1000, and 1125 Hz for the young (black rectangles) and middle-aged (red rectangles) groups. The bold, black horizontal lines represent the upper limits of performance, the ITD that corresponds to a 180° phase difference between ears.

Speech-in-noise

A repeated-measures ANOVA was performed to determine any significant differences in the performance of listeners for the S0N0 condition compared to the S0N90 condition. The factors were Group (between-subjects, two levels: young and middle-aged) and Location (within-subjects, two levels: S0N0 and S0N90). The repeated-measures ANOVA revealed a significant difference for Location (F (1, 18) = 32.180, p = <.001, partial η^2 = .641), indicating that listeners performed at lower (better) signal-to-babble ratios in the spatially-separated condition, S0N90, than when the speech and noise came from the same loudspeaker, S0N0. The performance of the two groups for the S0N0 and S0N90 conditions is illustrated in Figure 7.

A one-way ANOVA with a factor of Group (between-subjects, two levels: young and middle-aged) was performed to determine any significant differences between the benefit from spatial separation for the young and middle-aged groups. The one-way ANOVA was not significant (F (1, 18) = .153 p = .700, partial η^2 = .008), indicating no significant difference for the benefit of spatial separation between the young and middle-aged groups. The benefit from spatial separation data is presented in Figure 7.

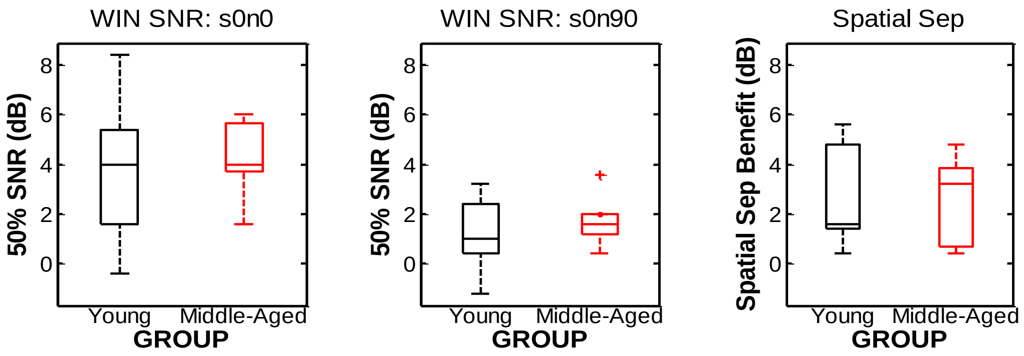

Figure 7: Left panel: Boxplots illustrating the WIN 50% points for young (black rectangles) and middle-aged (red rectangles) groups for the S0N0 conditions. **Middle panel**: WIN 50% points for the young and middle-aged groups for the S0N90 conditions. **Right panel:** Benefit from spatial separation, as reflected by the difference between the WIN scores for the S0N0-S0N90 for the young and middle-aged groups.

Correlation between upper frequency limit and spatial separation

It was expected that the upper frequency limit of IPD discrimination would be significantly related to benefit from spatial separation; a wider frequency range over which interaural timing cues could be processed might be expected to improve binaural processing of speech. However, no significant correlation was found (r = -.179, p = .465), indicating that the upper frequency limit of IPD discrimination cannot be used as a predictor for benefit from spatial separation. The lack of correlation can be seen in Figure 8.

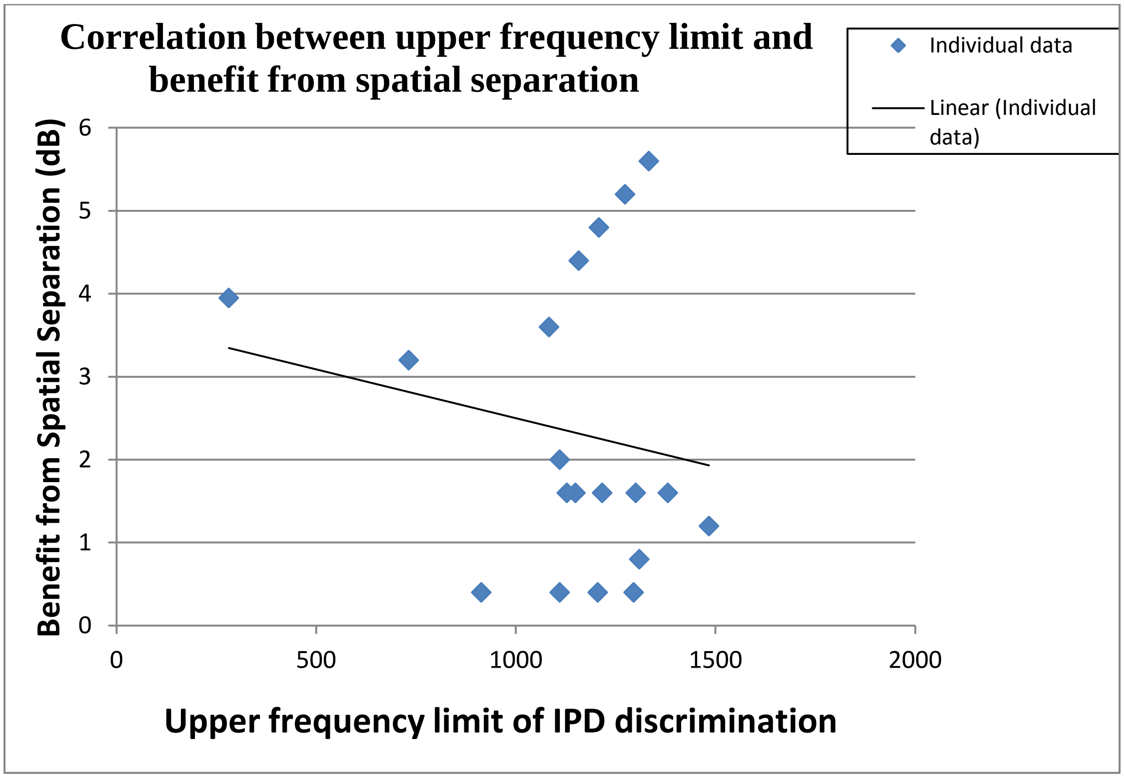

Figure 8: Scatter plot illustrating the correlation between the upper frequency limit of IPD discrimination and the benefit from spatial separation. The blue diamonds represent individual data for both the young and middle-aged subjects. The black line is the linear trendline for the data.

Chapter V

Discussion

The purpose of this study was to examine the effects of age on the upper frequency limit of interaural phase difference (IPD) discrimination, IPD discrimination limens at fixed frequencies, and benefit from spatial separation. It was hypothesized that 1) the upper frequency limit of IPD discrimination, as reflected by a task using 180º, or π radian IPDs, would be significantly reduced in middle-aged adults; 2) IPD discrimination at carrier frequencies from 500-1125 Hz will be reduced in middle-aged adults and a significant age by frequency interaction is expected, as age differences have been reported to increase as carrier frequency increases; 3) benefit from spatial separation, the difference in 50% point signal-to-babble ratios from spatially separating multitalker babble and a speech signal, will be significantly poorer in middle-aged adults; and 4) poorer IPD thresholds (lower upper frequency limit) will correlate with poorer speech-in-noise measures. Negative effects of aging were seen as early as middle-age. Statistical analysis of the data revealed that the middle-aged group had significantly lower (poorer) upper frequency limits of IPD discrimination. However, there was no significant difference for the IPD discrimination at fixed frequencies task and the benefit from spatial separation between the young and middle-aged groups.

Upper frequency limit of IPD discrimination declines with age

Declines in the ability to discriminate IPDs occur in the aging auditory system. The negative effects of aging are observed even in middle-aged individuals with normal hearing. This is consistent with previous research which also found a decreased ability to discriminate IPDs in middle-aged adults (Grose & Mamo, 2010; Ross et al., 2007).

Phase locking and neural synchrony in the central auditory system are necessary in order for the brain to utilize temporal fine structure information (i.e. frequency), including interaural phase and time differences (for a review, see Moore, 2008b). Aging negatively affects neural synchrony, causing a reduced ability for neurons to phase-lock to an incoming auditory signal (Clinard, Tremblay, & Krishnan, 2010). Reduced neural synchrony and phase-locking in the central auditory system may contribute to age-related declines in the aging auditory system. Because interaural phase and time differences aid in speech-in-noise processing, it would be expected that reduced neural synchrony and phase-locking would also influence speech-in-noise abilities. The upper frequency limit of IPD discrimination results for the young group in the current study are expected and are very consistent with the upper frequency limit of IPD discrimination reported for young subjects in previous research (Ross et al., 2007; Grose and Mamo, 2010).

Table 1 compares the IPD discrimination data from the current study to findings from Ross et al. (2007) and Grose and Mamo (2010).The median upper frequency limit of IPD discrimination for the middle-aged group in the current study was also expected and consistent with the median reported by Grose and Mamo (2010). Median thresholds for the middle-aged group for both the current study and Grose and Mamo (2010) were higher (better) than the mean threshold reported by Ross et al. (2007). The methods used in the Grose and Mamo (2010) study as well as the current study, in which the phase transition occurs within the stimulus as opposed to Ross et al. (2007) in which the phase transition occurs across stimuli, may have led to the higher (better) and less variable thresholds for the middle-aged group. Ross et al. (2007) also had several middle-aged subjects performing at or below chance, which may contribute to their mean threshold being lower than that of the current study and Grose and Mamo (2010).

Table 1. Upper frequency limits of pi radian IPDs compared across studies

	IPD Discrimination Threshold (Hz)		
	Current Study (median)	Ross et al. 2007 (mean)	Grose and Mamo (2010) (median*)
Young Group	1274	1203	1267
Middle-Aged Group	1110	705	1075

* Median values from Grose and Mamo (2010) were estimated (see Figure 1).

IPD discrimination at fixed frequencies

The current study did not find a significant effect of age on IPD discrimination at fixed frequencies. This was not expected because several studies have found a significant effect of age on IPD discrimination at fixed frequencies (Grose & Mamo, 2010; Hopkins & Moore, 2011; Moore et al., 2012). Also, because the upper frequency limit of IPD discrimination significantly changed with age in the current study, it was expected that the middle-aged group would have significantly poorer IPD discrimination thresholds at fixed frequencies, especially at 1000 and 1125 Hz. It was expected that an age by frequency interaction would be present indicating that there is a larger effect of age on IPD discrimination at high frequencies compared to IPD discrimination at lower frequencies. This age by frequency interaction was observed by Grose and Mamo (2010) who reported no significant difference between the young and middle-aged groups at 250 and 500 Hz and a significant difference between the young and middle-aged groups at 750, 1000, and 1125 Hz.

The ages of the young and middle-aged subjects may have influenced the results from the current study. Table 2 shows the age ranges of subjects included in the current study, as well as for studies that found a significant effect of age on IPD discrimination at fixed frequencies. The mean age of the older subjects for all of the other studies is higher than the mean age of the subjects in the middle-aged group for the current study. The more advanced age of the subjects may have resulted in a more significant difference between the younger and older subjects. The difference in age is especially large between the current study and Hopkins and Moore (2011) who compared results from a young group to results from subjects aged 63-69. Including slightly older subjects in the middle-aged group, for example, subjects who are in their 50's, may reveal a more significant effect of age on IPD discrimination at fixed frequencies. Also, running an older group of subjects who are 60 years of age and older may reveal age-related changes in IPD discrimination at fixed frequencies.

Table 2: Subject age for IPD at fixed frequency studies

Study	Younger Subjects Age	Older Subjects Age
Current Study	21-24 (mean = 22.5)	37-48 (mean = 43.1)
Grose & Mamo (2010)	18-27 (mean = 22.2)	40-55 (mean = 47.5)*
Hopkins & Moore (2011)	20-35	63-69
Moore et al. (2012)	N/A (only tested subjects ages 61-83)	61-83 (mean = 69)

* Age range for middle-aged group from Grose and Mamo.

In the current study, performance at the lower frequencies may have been influenced by changes in the stimulus level and the stimulus duration compared to the stimulus used by Grose and Mamo (2010). The stimuli for the IPD at fixed frequency task in the current study were presented at a level of 80 dB SPL. The stimuli used by Grose and Mamo (2010) were presented at a level of 65 dB SPL. However, a study by Zwislocki and Feldman (1956) demonstrated that the change in stimulus level from 65 dB SPL to 80 dB SPL should not affect the just noticeable difference in dichotic phase. The performance at the low frequencies may have also been affected by increasing the stimulus duration from 200 ms, used by Grose and Mamo (2010), to 300 ms, used in the current study.

Benefit from spatial separation

In the current study, the benefit obtained by spatially separating the speech signal and the masker was similar for both the young and middle-aged groups. Therefore, no significant age-related differences were observed, suggesting that both young and middle-aged listeners are able to use interaural difference cues to aid in listening to speech in the presence of noise. This was not expected, as it was hypothesized that the young group would have a significantly larger benefit from spatial separation than the middle-aged group. There is discrepancy in the literature regarding age-related changes in benefit from spatial separation. The results from the current study are consistent with results from Ahlstrom et al. (2014) and Dubno et al. (2008) who did not find significant differences between the spatial separation benefit of young and older listeners. However, the results from the current study are not consistent with results from Dubno et al. (2002), who did find a significant difference of benefit from spatial separation for younger and older listeners.

Differences in the methodology of the studies investigating the effects of age on spatial separation benefit may contribute to the inconsistent conclusions. The criterion used to constitute normal hearing is different between studies. For example, Dubno et al. (2002) defined normal hearing as thresholds less than or equal to 20 dB HL at octave frequencies from 0.25 kHz to 4.0 kHz while the current study defined normal hearing as less than or equal to 25 dB HL at octave frequencies from .25 kHz to 8 kHz. It is unclear if potentially elevated thresholds in the higher frequencies, above 4 kHz, contributed to the reduced benefit observed for the older listeners and the significant difference between the groups found by Dubno et al. (2002).

The difference in age between the older group of the Dubno et al. (2002) study and the current study may have also contributed to the difference in observed benefit from spatial separation. The mean age of the older group in the Dubno et al. (2002) study was 68.5; however, the mean age of the middle-aged group in the current study was 43. Running an older group of listeners through the current study will allow for a more accurate comparison between results from the current study and the Dubno et al. (2002) results. However, the age of the older group from the Ahlstrom et al. (2014) and the Dubno et al. (2008) studies was similar to the age of the older listeners in the Dubno et al. (2002) study, indicating that there are differences other than age between the studies that must contribute to the different findings.

Different speech-in-noise measures may also contribute to differences between studies. The current study used the WIN with multi-talker babble to assess benefit from spatial separation. The WIN was used to assess benefit from spatial separation because it is a relatively simple task that requires participants to repeat monosyllabic words. The background noise was multitalker babble and subjects were tested at fixed signal-to-babble ratios (24, 20, 16, 12, 8, 4, and 0 dB SBR). Using a different and more difficult speech-in-noise measure or different background noise may have resulted in different results. For example, Dubno et al. (2002) used the Hearing in Noise Test (HINT) which requires subjects to repeat entire sentences played in the presence of speech-shaped noise. The signal-to-noise ratio was varied by a certain step size to converge on the 50% correct sentence recognition. Ahlstrom et al. (2014) used consonant-vowel and vowel-consonant syllables in the presence of speech-shaped noise at a fixed +4 signal-to-noise ratio to assess benefit from spatial separation. Differences in speech-in-noise measures may contribute to the different findings.

Future Research

The results from the current study suggest that neither age nor IPD measures are good predictors of benefit from spatial separation. Glyde et al. (2011) suggests that cognition may play an important role in spatial processing abilities. Correctly understanding speech in the presence of background noise requires several components of cognition, including working memory, attention, fast processing speed, auditory closure, and language skills (Glyde et al., 2011). Changes in cognition experienced during aging may contribute to the difficulties understanding speech-in-noise observed in middle-aged and older listeners. A cognitive measure could have been included in the methodology of the current study to assess the cognitive abilities of the subjects. Future research should evaluate the correlation between a cognitive measure and the benefit from spatial separation in young, middle-aged, and older listeners.

The outcomes from this study add to a growing body of literature suggesting a decline in IPD discrimination with aging. This negative effect of aging begins in middle-aged, normal-hearing listeners. This knowledge can be used as a counseling tool in clinic when educating patients on changes in the auditory system with age. Future research may look at training IPD discrimination and evaluate potential aural rehabilitation options for people with a reduced ability to discriminate IPDs. The results from this study also suggest that factors other than age and IPD discrimination affect spatial processing in middle-aged adults with normal hearing. Knowing what contributes to difficulty understanding speech-in-noise will aid in counseling patients and will improve approaches to aural rehabilitation. More research needs to be completed to identify what contributes to the difficulty of understanding speech in the presence of background noise experienced by aging adults with normal hearing.

Conclusions

(1) The young group had higher (better) upper frequency limits for IPD discrimination of a 180° phase difference.

(2) There was no significant difference between IPD discrimination at fixed frequencies.

(3) There was also no age by frequency interaction for IPD discrimination at fixed frequencies. The difference between IPD discrimination in the young and middle-aged group was not significant at any frequency.

(4) The younger group did not have a greater benefit from spatial separation compared to the middle-aged group.

(5) There was no significant correlation between upper frequency limit of IPD discrimination and the benefit from spatial separation.

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