Degradation in Binaural and Spatial Hearing and Auditory Temporal Processing Abilities as a Function of Aging

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Abstract:

Objectives: Sensorineural hearing loss is common with advancing age, but even when hearing is normal or near normal in older persons, performance deficits are often seen for suprathreshold listening tasks such as understanding speech in background noise or localizing the direction sounds are coming from. This suggests there is also a more central source of the problem. Objectives of this study were to examine as a function of age (young adult to septuagenarian) performance on: 1) a spatial acuity task examining lateralization ability, and a spatial speech-in-noise (SSIN) recognition task, both measured in a hemi-anechoic sound field using a circular horizontal-plane loudspeaker array, and 2) a suprathreshold auditory temporal processing task and a spectro-temporal processing task, both measured under headphones. Further, we examined any correlations between the measures.

Design: Subjects were 48 adults, aged 21 to 78, with either normal hearing or only a mild sensorineural hearing loss through 4000 Hz. The lateralization task measured minimum audible angle (MAA) for 500 and 4000 Hz narrowband noise (NBN) bursts in diffuse background noise for both an on-axis (subject facing 0˚) and off-axis (facing 45˚) listening condition at signal-to-noise ratios (SNRs) of -3, -6, -9, and -12 dB. For 42 of the subjects, SSIN testing was also completed for key word recognition in sentences in multi-talker babble noise; specifically, the separation between speech and noise loudspeakers was adaptively varied to determine the difference needed for 40% and 80% correct performance levels. Finally, auditory temporal processing ability was examined using the Temporal Fine Structure test (44 subjects), and the Spectro-Temporal Modulation test (46 subjects).

Results: Mean lateralization performances were poorer (larger MAAs) in older compared to younger subjects, particularly in the more adverse listening conditions (i.e., for 4000 Hz, off-

axis, and at poorer SNRs). Performance variability was notably higher for older subjects than for young adults. The 4000 Hz NBN bursts produced larger MAAs than did 500 Hz NBN bursts. The SSIN data also showed declining mean performance with age at both criterion levels, with greater variability again found for older subjects. Spearman rho analyses revealed some low to moderate, but significant correlation coefficients for age versus MAA and for age versus SSIN results. Results from both the TFS and STM showed decreased mean performance with aging, and revealed moderate, significant correlations, with the strongest relationship shown with the TFS test. Finally, of note, extended-high-frequency (EHF) hearing loss (measured between 9000 and 16,000 Hz) was found to increase with aging, but was not seen in the young adult subjects.

Conclusions: Particularly for more adverse listening conditions, age-related deficits were found on both of the spatial hearing tasks and in temporal and spectro-temporal processing abilities. It may be that deficits in temporal processing ability contribute to poorer spatial hearing performance in older subjects due to inaccurate coding of binaural/interaural timing information sent from the periphery to the brainstem. In addition, EHF hearing loss may be a coexisting factor that impacts performance in older subjects.

Key Words:

Presbycusis, Aging, Localization, Lateralization, Spatial Acuity, Spatial Hearing, Minimum Audible Angle, Spatial Hearing, Spatial Speech-in-Noise, Spatial Release from Masking, Temporal Processing, Extended High-Frequency Hearing Loss

List of Abbreviations:

dB	decibels
EHF	Extended High Frequency (>8000 Hz)
HL	Hearing Level
Hz	Hertz
ILD	Interaural Level Difference
IPD	Interaural Phase Difference
ITD	Interaural Time Difference
LSO	Lateral Superior Olivary
MAA	Minimum Audible Angle
MSO	Medial Superior Olivary
NBN	Narrow Band Noise
SD	Standard Deviation
SL	Sensation Level
SNR	Signal-to-Noise Ratio
SPL	Sound Pressure Level
SRM	Spatial Release from Masking
SSIN	Spatial Speech-in-Noise
STM	Spectro-Temporal Modulation test
TFS - AF	Temporal Fine Structure – Adaptive Frequency test
2AFC	2-Alternative Forced-Choice

INTRODUCTION

Presbycusis, or age-related hearing loss, is very common, affecting approximately one-third of adults between the age of 65 and 74, and more than half of adults aged 75 years and older (e.g., NIDCD website, 2024; ISO 2000; Cruickshanks et al. 1998). Presbycusis occurs due to degeneration of the auditory system that occurs with aging as well as the impact of a lifetime of noise exposure. It is well established that age-related hearing loss can be associated with depression, cognitive decline, dementia or Alzheimer's disease, and generally poorer functional and psychosocial outcomes (Davidson & Guthrie 2019; Ralli et al. 2019; Rutherford et al. 2018; Zheng et al. 2017; Thomson et al. 2017; Pichora-Fuller 2015; Lin et al. 2013, 2011). Therefore, early diagnosis and treatment of hearing problems is crucial for healthy aging.

A number of mechanisms contribute to presbycusis, the most well-known being of a peripheral nature, including the progressive death of outer hair cells in the cochlea resulting in hearing sensitivity loss as evidenced by elevated hearing thresholds, especially in the high frequencies (for reviews of the aging auditory system, see Fischer et al. 2020; Keithley 2020). However, even when hearing thresholds are normal or close to normal in elderly individuals, performance deficits are often seen with advanced age on suprathreshold auditory processing tasks such as understanding speech in background noise or localizing the direction sounds are coming from (Fullgrabe et al. 2015; Freigang et al. 2014; Briley & Summerfield 2014; Dobreva et al. 2011; Dubno et al. 2008; Pichora-Fuller & Souza 2003; Abel et al. 2000; Martin & Jerger 2000; Studebaker et al. 1997; Abel & Hay 1996; Stuart & Phillips 1996), indicating that there are also other, more central underpinnings to the decreased functional auditory abilities seen with aging (see Gallun 2021 for a review). In other words, audibility and detection of sounds are not the only issue.

Central aspects of hearing deficits in the aging population are not as well understood as the peripheral and are likely multifactorial. One factor that has been implicated as potentially contributing to poorer auditory processing with aging is cognitive decline and an associated loss in working memory capacity (e.g. Lentz et al. 2022; Murphy et al. 2018; Gordon-Salant & Cole 2016; Humes et al. 2013); however, even when this is controlled, poorer performances are still seen in many older adults, suggesting it is also not the sole source of the problem. Another factor suspected to occur in the aging human auditory system, particularly in those with a significant history of noise exposure but relatively normal hearing thresholds, is cochlear synaptopathy (e.g., see Wu et al. 2019; Viana et al. 2015). Cochlear synaptopathy may occur at any age following loud noise exposures and refers to a disruption in the function of cochlear ribbon synapses between inner hair cells of the cochlea and auditory nerve fibers. This may result in subsequent neuronal degeneration and inaccurate encoding of sounds from the auditory nerve to the brainstem. Further, general neuronal degeneration with aging can occur across the auditory nervous system.

One specific hypothesis in our research laboratory's ongoing studies on the impact of aging on hearing is that precise timing of neural activity within the binaural *brainstem* pathway declines with age (i.e., decreased synchrony). Interaural time differences (ITDs) and interaural level differences (ILDs) for sounds received binaurally vary with horizontal-plane sound source position, and these cues are encoded by the auditory brainstem circuit to assist with localization of the direction of sound as well as to perform an initial segregation of different sound sources (for reviews, see Bronkhorst 2015, 2000; Grothe et al. 2010; Colburn et al. 2006). Although there may also be age-related changes at higher levels in the ascending auditory pathway that additionally make critical contributions to source segregation (e.g. Yao et al. 2015;

Middlebrooks & Bremen 2013), the brainstem sound pathway is the lowest neural circuit to perform this analysis, and its outputs contribute to source segregation at the cortex (Neher et al. 2011; Grothe et al. 2010; Hawley et al. 2004). Consistent with this hypothesis is a body of evidence suggesting that auditory temporal processing ability and neural synchronization decline with age, even when the impact of peripheral hearing loss is removed or reduced, and that this decline leads to a decreased ability to segregate multiple sound sources (Fullgrabe et al. 2018, 2015; Grose et al. 2016; Ozmeral et al. 2016a,b; Gallun et al. 2014; Grose & Mamo 2012, 2010; Hopkins & Moore, 2011; Pichora-Fuller, 2003; Snell et al. 2000; Gordon-Salant & Fitzgibbons 1999; Snell 1997; Fitzgibbons & Gordon-Salant 1994). Such age-related declines reduce access to binaural cues needed for auditory space perception and good speech understanding in competing noise.

The current study examined the impact of aging on subjects ranging from young adult to septuagenarian on two tasks of suprathreshold spatial hearing abilities as measured in a large hemi-anechoic sound chamber, and on tests of temporal and spectro-temporal sound processing ability measured under headphones. The first spatial hearing task pertained to determining the direction from which a sound is coming. Sound localization is important for awareness of one's environment and can be important to safety; for example, knowing the direction a vehicle is coming from when crossing a busy street. There is some evidence from previous studies of performance on sound localization/lateralization tasks that spatial acuity ability can decline in aging subjects (Srinavasan et al. 2021; Freigang et al. 2014; Briley & Summerfield 2014; Dobreva et al. 2011; Abel et al. 2000; Abel & Hay 1996). For example, examining subjects ranging in age from young adult to 81 years old, Abel et al. (2000) and Abel and Hay (1996) found poorer performance for older subjects on horizontal plane localization in sound field for

broadband noise stimuli and 1/3-octave band noise centered at 500 or 4000 Hz. Dobreva et al. (2011) examined localization accuracy in the front hemifield (+90˚ to -90˚) in adults aged 19 to 81 years old. They reported decreasing localization accuracy/precision for older adults compared to young adults for broadband, high-pass, low-pass, and narrowband noise (NBN) low-frequency targets, which the authors believed was due to age-related central declines in auditory temporal processing ability. Srinivasan et al (2021), using a headphone virtual simulation of binaural listening in the front hemifield (+90˚ to -90˚), reported that localization acuity was poorer with aging for NBN at 500 and 4000 Hz.

Of note, however, is that, in these previous studies, hearing loss of up to a moderate degree was seen in some of the older subjects, which may have been a confounding factor for examining age effects. Therefore, in the current study, we attempt to better control the impact of peripheral hearing loss by including only subjects with either normal hearing or hearing loss of only a mild degree through 4000 Hz, so that inaudibility of the stimuli is precluded. We also excluded subjects with significant cognitive dysfunction. Further, we used a front hemifield, horizontal lateralization task for both a standard on-axis listening condition (subject facing 0˚) and a more difficult off-axis listening condition (subject facing 45˚), with testing done in a large hemi-anechoic sound chamber. Included were both low-frequency (500 Hz) and high-frequency (4000 Hz) narrowband noise (NBN) stimuli, presented in diffuse background noise.

The second task used in the current study was a suprathreshold, Spatial Speech-In-Noise (SSIN) task. When significant peripheral hearing loss is excluded in older subjects, they are not expected to show deficits in speech recognition in *quiet* environments; however, many show deficits when listening in more *adverse* listening conditions such as competing speech or background noise (e.g., see Fullgrabe et al. 2015; Dubno et al. 2008; Pichora-Fuller & Souza 2003; Martin &

Jerger 2000; Gordon-Salant & Fitzgibbons, 2001; Studebaker et al. 1997; Stuart & Phillips 1996). In the novel SSIN task we used, the signal to noise ratio was fixed and the separation between the speech and background noise loudspeakers was varied to determine that needed for a specified percent correct performance level. A similar method was used to test SSIN performance in young normal hearing subjects by Ahrens et al (2020) and Ozmeral and Higgins (2022). It is well established that separation of an interfering noise from a target sound may result in significant spatial release from masking (SRM) in normal-hearing young listeners - - this SRM effect can be fairly well predicted from models of binaural analysis based on ITDs and ILDs (for reviews, see Colburn et al., 2006; Bronkhorst, 2000). There is some evidence that aging may contribute to less benefit from SRM (e.g. Patro et al. 2024; Gallun et al. 2013). The current study is unique in that we measured both lateralization ability and performance on the SSIN task in the same subjects.

Finally, because inaccurate coding of spatial cues is expected to result in poor binaural processing ability (see Bernstein and Trahiotis, 2019), performances on two suprathreshold sound processing tasks were measured under headphones in this same group of subjects; specifically, the Temporal Fine Structure – Adaptive Frequency (TFS-AF) test (Füllgrabe & Moore 2017) and the Spectro-Temporal Modulation (STM) test (Mehraei et al. 2014; Bernstein et al. 2013). We hypothesized that not only would poorer performance be evidenced on the suprathreshold spatial hearing tasks with advancing age, but that these might have as one underpinning a declining ability with aging for processing of temporal cues of sounds.

MATERIALS AND METHODS

Subjects

Subjects were 48 adults, aged 21 to 78. Approval was obtained from the Colorado Multiple Institutional Review Board for use of human subjects. Subjects were paid for participation.

Inclusion criteria for subjects of all ages included either normal hearing or only a mild sensorineural hearing loss, which was defined as bilateral hearing thresholds $\leq$ 40 dB HL at audiometric frequencies from 250 Hz to 4000 Hz inclusively, in both ears, with no air-bone gaps > 10 dB. All subjects were also required to show symmetrical hearing thresholds between the ears through 8000 Hz, defined as $\leq$ 10 dB difference at any given audiometric frequency, and normal (Type A) tympanograms bilaterally. None of the subjects wore hearing aids.

Figure 1 shows individual audiograms and means for subjects divided into three groupings by age: younger adults (aged 21 to 39), middle-aged (aged 42 to 59), and older adults (aged 60 to 78), including hearing thresholds measured for the extended high frequency (EHF) range from 9000 to 14,000 Hz. While the older subjects do show some hearing sensitivity loss in the highest audiometric frequencies, and even more in the EHF range, the audibility of the suprathreshold stimuli presented for the study was not largely impacted. Note that due to output limits in the EHF range for the audiometer/headphone, a number of older subjects had no response at the maximum output level (maximum was 70 dB HL at 10,000 and 11,200 Hz, 65 dB HL at 12,500. 55 dB HL at 14,000 Hz, and 30 dB HL at 16,000 Hz); when this occurred, a value 5 dB higher than the maximum was assigned to that individual for purposes of calculating the mean thresholds. In Figure 1, arrows indicate that a number of older subjects had no response values assigned, so that the actual mean hearing threshold at that frequency was unmeasurable but

would be poorer than shown. Due to the low maximum output, 16,000 Hz is not plotted in Figure 1, but notably all younger subjects had threshold responses <30 dB HL, while some of the subjects in the middle-aged group and all of the subjects in the oldest group had no response at 30 dB HL.

(place Figure 1 about here)

None of the subjects had a history of otologic or neurologic disorders. In addition, none of the subjects showed a cognitive deficit upon screening with the Montreal Cognitive Assessment (MOCA) test (Nasreddine et al. 2005).

Data for the spatial acuity/lateralization task were collected on all 48 subjects. There were more female subjects than males (35 females and 13 males); however, males were spread across both the younger and older age ranges. For a subset of 42 of the 48 subjects (31 females, 11 males), data were also available for the SSIN task. SSIN data were not available on the other 6 subjects either because their performance had previously been measured using the same test materials in a pilot study with different measurement parameters, or because they were non-native English speakers (i.e. English was their second language). For the Temporal Fine Structure (TFS) test, data were available for 44 of the subjects (31 females, 13 males), and for the Spectro-Temporal Modulation (STM) test, data were available for 46 of the subjects (34 females, 12 males), with the remaining subjects lost to follow-up. See Table 1 for specification of the numbers of male and female subjects per decade of life with available data for each of the measures.

(place Table 1 about here)

Equipment and Procedures

Standard air-conduction audiograms with thresholds from 250 through 8000 Hz inclusively were obtained with a Madsen Astera audiometer (Natus, Middleton, WI, USA) using ER-3A insert earphones (Etymotic Research, Chicago, IL, USA), as part of the enrollment screening. The extended high-frequency range was also measured from 9000 Hz through 16,000 Hz with Sennheiser HAD 200 circumaural headphones. Bone conduction thresholds were obtained at 500, 1000, 2000, and 4000 Hz via a Radioear B-71W bone oscillator. Tympanograms were obtained with an Interacoustics Titan measurement system (Middelfart, Denmark).

Assessment of spatial acuity ability

Testing examining spatial acuity ability to determine the minimum audible angle (MAA) in the frontal horizontal plane was completed across two 2-hour sessions. All testing was done in a large, hemi-anechoic sound chamber, fully treated with sound/echo-absorbing wedges except for a small part of the floor area where the subject sits, which is carpeted and has additional sound-absorbing material. A 64-loudspeaker array is available in the chamber, with stimulus presentation controlled by an Antelope Galaxy 64-channel Digital-to-Analog Convertor (Antelope Audio, San Francisco, CA, USA) and eight Crown CT8150 8-channel analog speakers (Crown Audio, Elkhart, IN, USA) in the control room. Speakers were Gallo Acoustics Micro's (Scotland, UK). There was a two-way intercom between the control room and the test chamber, and a camera in the chamber for experimenter observation of the subject during testing. The camera has infrared capability for viewing the subject even when the room is darkened.

For testing on the spatial acuity task, subjects were seated in a height-adjustable chair in the center of the circular horizontal loudspeaker array (Figure 2), with the chair adjusted so that the

subject's ear canal opening was at the height of the loudspeakers. Testing was done with the room dark to preclude visualization of the precise location of the loudspeakers, but an LED light came on between trials at the location of the loudspeaker directly in front of the subject, to indicate to them the orientation they should maintain during the test session. Further, the subject wore a Polhemus Fasttrack electromagnetic position tracking headset (Colchester, Vermont, USA) so that orientation of the forward-facing head position could be monitored during testing. The head tracker also had an LED light at the end of the frontal wand and the subject was instructed to keep that light in line with the light on the loudspeaker in front of them throughout the testing session.

The spatial acuity task was custom programmed using MATLAB. Stimuli were 500 and 4000 Hz narrowband noise (NBN) bursts filtered forward and backwards (using Matlab *filtfilt*) with a 1/3rd octave, 4th order Butterworth filter centered on the target frequency. The low-frequency and high-frequency stimuli were used to help evaluate effects of ITDs and ILDs. For pure-tone or narrowband stimuli, ITDs are known to be most effective at low frequencies. For high frequencies, the cues are ILDs and envelope ITDs. Stimuli were presented at 60 dB SPL in diffuse multi-speaker broadband noise. In separate runs, four fixed signal-to-noise ratios (SNRs) were tested for each stimulus: -3, -6, -9, and -12 dB. The order of testing of the two stimulus frequencies was randomized across subjects and sessions, with SNR progressively worsening (from -3 to -12) with each run. Practice runs were used to ensure that subject understood the task and was familiar with the sound of each NBN stimuli before beginning test runs.

In the first session, all testing was done in the "on-axis" listening condition; that is, the subject was seated facing the loudspeaker at 0˚. The set-up is illustrated in Figure 2, part A - - used for target stimuli for this task were the darker shaded loudspeakers from +45 to -45˚ inclusively.

Loudspeakers were spaced 5˚ apart from 0˚ to 30˚, which covered the range of final MAA values for the vast majority of subjects, with slightly larger spacing for the two wider angle loudspeakers. Noise emanated from loudspeakers placed at 30˚ to 330˚, in 30˚ increments, but was never co-located with the target stimuli.

A 2-alternative forced choice (2AFC) procedure was used. The first stimulus was always presented from the loudspeaker at 0˚ (directly in front of the subject) and the second stimulus was presented from a loudspeaker within +/- 45˚. The subject's task, using 2 buttons on a handheld keypad, was simply to indicate if they believed the second stimulus had been presented to the right or to the left of the first stimulus. A 2-down, 1-up procedure (Levitt, 1971) was used for each run (two correct responses before a decrease in step size, but an increase in step size for every incorrect response) to determine the 70.7% correct point. Two interleaved runs were done simultaneously to avoid any pattern being perceived by the subject. The first presentation of the 2nd stimulus was always from a loudspeaker at 45˚ (+/-), an easy task, then presentations continued to smaller angles, with an initial two-speaker step size for 3 reversals (change in direction of the stimulus angle difference), and then a single speaker step size for 6 more reversals. Whether the 2nd stimulus was presented to the right or left of the first (+/-) was randomized. Note that, if the subject's performance was excellent, there was the possibility of no angle with both presentations at 0˚, which always counted as a reversal. The MAAs for each of the two interleaved runs, calculated as the mean of the last six reversals, were averaged to obtain the final MAA value that was used in analyses of the data. If the two interleaved runs showed very disparate values (which infrequently happened but occasionally did when a subject became tired and their attention momentarily wandered), another set was done after the subject took a rest break, and the two lowest MAA values of the four were the ones averaged for analysis.

In a second session done on a different day, the same testing was done but in the more difficult, "off-axis" listening condition, i.e., the subject was seated facing the 45˚ loudspeaker as illustrated in Figure 2, Part B. The first stimulus was still presented from the loudspeaker at 0˚ (in this off-axis condition, this is at -45˚ relative to the subject's gaze) and the second stimuli was still presented from a loudspeaker within +/- 45˚ of the initial presentation (that is, from 0˚ to -90˚ relative to the subject's gaze). Thus, the stimuli for the off-axis condition were primarily presented more laterally, toward the left ear of the subject.

(place Figure 2, parts A,B, about here)

Assessment of Spatial Speech-In-Noise (SSIN) ability

The SSIN task was completed in the hemi-anechoic sound chamber in another session, on a different day, with the lights in the test chamber remaining on during testing. For this testing, subjects were also seated in the chair in the center of the circular horizontal loudspeaker array with loudspeakers at ear height. The SSIN task was custom programmed using MATLAB. Assessed was the ability of the subject to repeat target words from the Harvard IEEE (IEEE 1969) corpus of sentences. These stimuli represent everyday conversational but low-contextual speech, and each sentence has 5 key words. The sentence materials and their recording method are described in Nelson et al. (2003); however, for the current study, we used only the sentences spoken by a *female* native American English speaker. The background noise we used was six-talker babble from the Connected Speech Test (Cox, 1987). The audio file is publicly available at the HARL Memphis website - https://harlmemphis.org/connected-speech-test-cst/. Calibration was done by generating a noise stimulus with the same spectrum as the long-term average speech spectrum of the experimental stimuli (IEEE sentences, or babble noise) and measuring the sound

pressure level of the noise in dB(A). For the current study, the IEEE sentences were presented at an average conversational level of 60 dB(A).

Four fixed SNR conditions were tested in separate runs: -3, -6, -9, and -12 dB. Additionally, two tracks were interleaved within a single test condition: one track was based on a 40% correct performance criterion (≥2 of the 5 key words repeated correctly), and the second track was based on an 80% correct performance criterion (≥4 of the 5 key words repeated correctly). For each presentation, subjects were instructed to repeat aloud as many of the words in the sentence as possible, and guessing was encouraged.

The sentences were always presented from 0° azimuth (the loudspeaker directly in front of the subject), and the babble noise was presented from another loudspeaker located within +/- 90˚ of the subject on the horizontal axis with random positive or negative presentations. Available *noise* loudspeakers for this task were at the following azimuths: 0°, +/-5°, +/-10°, +/-15°, +/-20°, +/-25°, +/-30°, +/-45°, +/-60°, +/-75°, and +/-90° (darker plus lighter shaded loudspeakers in Figure 2 Part A). The separation between the signal and noise loudspeaker was modified adaptively, starting at +/-90° and proceeding down to as small as a 5° difference, to assess the subject's ability to accurately separate the target speech from the background babble. Specifically, the program first decreased or increased the spatial separation (based on the track criterion) by three loudspeakers until 4 reversals were observed in a track, then the program moved to a single speaker step size. Testing continued for 20 sentences per track (40 sentences total). The spatial separation of the speech and noise loudspeakers that was needed to achieve 40% and 80% correct for each SNR condition was calculated by averaging across the final 10 trial locations for each track.

Assessment of temporal and spectro-temporal sound processing ability

Two suprathreshold psychoacoustic tests were completed with testing in a sound-treated booth under Sennheiser HD-25 headphones (Wedemark, Germany). These tasks were custom programmed using MATLAB software (Natick, MA, USA), with stimuli delivered binaurally from a desktop PC in the control room via use of a Fireface UCX Digital-to-Analog Convertor (RME, Haimhausen, Germany) and Magni 3 amplifiers (Schitt Audio, Newhall, CA, USA) to the headphones. Subjects sat at a desk and used a computer mouse to indicate their responses on a monitor screen placed in front of them. The installation files for these tests were downloaded from the University of Cambridge Auditory Perception Group in the Department of Psychology webpage (https://www.psychol.cam.ac.uk/hearing, 2018).

The first task was the Temporal Fine Structure - Adaptive Frequency (TFS-AF) test. The stimuli and procedures used were identical to those of Füllgrabe and Moore (2017). The TFS-AF assessment uses an adaptive, two-interval, 2AFC procedure, with visual feedback for listener responses. The objective is to determine the highest frequency at which a listener can perceive a fixed interaural phase difference (IPD). Thus, a higher value indicates better performance.

Specifically, for this task, the stimulus frequency was adaptively modified using a 2-down, 1-up procedure to determine 70.7% correct performance (Levitt, 1971). Stimuli were presented at each test frequency at approximately 30 dB SL (Sensation Level, i.e., dB above each individual's measured hearing thresholds), and two intervals were presented sequentially with a 500 msec gap between each presentation. Intervals consisted of four, 400-msec pure tones presented successively and separated by 100 msec gaps. For each trial, a target and standard interval were randomly generated. The standard interval consisted of four pure tones at a given frequency with

a 0-degree IPD, which resulted in a stationary perception in the head (diotic presentation). In contrast, the target interval added a fixed IPD of 30˚ for the second and fourth pure tones to create the perception of a diffuse, moving pure tone within the listener's head (dichotic presentation). On the computer monitor, the listener was presented with two boxes, labeled '1' and '2', which were highlighted during their corresponding stimulus presentation interval. Listeners were instructed to select the interval that corresponded to the perception of a sound that was moving. Feedback was given as a green box containing the word "correct" or a red box containing the word "incorrect". Following eight reversals, the trial ceased and a geometric mean of the final six reversal frequencies resulted in a threshold estimate for the given IPD.

The second task used was the Spectro-Temporal Modulation (STM) test (for a detailed description, see Bernstein et al. 2013). This task is also an adaptive 2AFC assessment. It uses diotic presentation as it applies a set temporal modulation and spectral density to an octave-band noise carrier, which is the same at both ears. The STM evaluates the minimum modulation depth the listener can detect, and thus, for this task, a lower or more negative number indicates better performance. Stimuli were presented at 85 dB(A) over the headphones at a set four-octave noise carrier, spectral ripple density (cycles per octave; c/o), modulation rate (in Hz), and direction. There were 3 different modulation conditions in the testing protocol: 1) 1000 Hz center frequency, 2 c/o, 4 Hz, upward direction, 2) 4000 Hz center frequency, 4 Hz, 4 c/o, upward direction, and 3) broadband noise, 4 Hz, 2 c/o, no direction. Conditions were determined based on Mehrai et al. (2014), a study that reported these conditions as significant when comparing processing ability between normal hearing and hearing-impaired listeners.

In this second task, listeners were presented with a pair of sequential stimuli, one consisting of noise and the other containing the set modulation. Stimuli were 500ms in duration and

presentations were separated by 200 ms silence gaps. The starting modulation depth was 0 dB and varied by a three-down, one-up adaptive track that resulted in a 79.4% correct point (Levitt, 1971). Feedback was provided to the listener visually with “correct” and “incorrect” text prompts. Trials consisted of 9 reversals overall, whereas depth was initially adjusted by 6 dB then 4 dB following the first reversal, and then by 2 dB following the third reversal. The average modulation depth across the last six 2-dB step size reversals was used to calculate the modulation threshold.

Statistical analyses

Analyses of the data included both age as a continuous variable and analysis of performance by three age groupings: younger adults (aged 21 to 39), middle-aged (aged 42 to 59), and older adults (aged 60 to 78). Non-parametric correlation analyses using the Spearman rho rank-order correlation coefficient (r_s; SPSS v28 statistical software) were used. The Spearman rho was chosen over the parametric Pearson product-moment correlation coefficient (r) because the distribution of data for all variables in this study did not meet the assumptions of normality and homoscedasticity; however, it is notable that when the data were separately analyzed using the parametric statistic, results were similar. For examination by age groupings, results are displayed descriptively as box-and-whisker plots, which show the median, lower, and upper quartiles, and variability of the data.

RESULTS

Spatial Acuity/Lateralization by Age

Shown in the two left panels of Figure 3 are scatterplots of individual MAA results as a function of age for each stimulus (Part A: 500 Hz and Part B: 4000 Hz) at each of the four SNRs for the

on-axis subject orientations. A larger value indicates poorer performance on this task. Solid lines indicate the linear regression trends. The right panels in Figure 3 are box-and-whisker plots of MAA results at each SNE for the three age groupings: younger adults (n = 14), the middle group (n = 17) and the older adults (n = 17). As can be seen, there were relatively minimal differences by age for the 500 Hz stimulus (top row), albeit a slight reduction in performance for a few subjects older than age 60. Greater performance variability was found across all ages for the 4000 Hz stimuli (bottom row). Most subjects had an average calculated MAA <5˚ for 500 Hz and <10˚ for 4000 Hz, indicating this was a relatively easy task for either stimulus. Spearman correlation analyses done for the 500 Hz stimulus revealed a low but significant correlation between age and MAA at an SNR of 3 dB (r_s = .38, p = .007) and at 12 dB SNR (r_s = .50, p < .001). For the 4000 Hz stimulus, there were no significant correlations between age and MAA at any SNR.

(place Figure 3 about here)

Figure 4 shows comparable data but for the harder condition of the *off*-axis subject orientation. Note that the vertical axis ranges are different for on-axis condition plots (Figure 3) versus the off-axis condition plots (Figure 4) in order to best display the data. The scatterplots for this harder, off-axis condition show poorer performances in general than for the on-axis orientation for both the 500 Hz stimulus (Part A) and the 4000 Hz stimulus (Part B). Further, the impact of aging is more pronounced in this condition, especially at the two poorest SNRs (-9 and -12 dB) for 4000 Hz stimuli, with the two oldest subjects showing large MAA values ranging from 23˚ to 37˚. Even young subjects had more difficulty in the off-axis condition for the 4000 Hz stimulus than for the 500 Hz stimulus, but variability in performances was notably higher for older subjects. Correlation analyses done for the 500 Hz stimulus revealed low but significant

correlations between age and MAA at all four SNRs: 3 dB (r_s = .36, p = .013), 6 dB (r_s = .34, p .019), 9 dB (r_s = .36, p = .012) and 12 (r_s = .40, p = .005). For the 4000 Hz stimulus, there were also low but significant correlations between age and MAA at SNRs of 3 dB (r_s = .34, p = .017), 6 dB (r_s = .30, p = .038), and 9 dB (r_s = .39, p = .007) and a moderate, significant correlation at 12 dB SNR (r_s = .51, p < .001).

(place Figure 4 about here)

Spatial Speech-in-Noise by Age

Shown in the left panels of Figure 5 are scatterplots of individual SSIN results (i.e., speaker separation needed, in degrees, for the given percent correct) as a function of age for each of the four SNRs for 40% correct performance (Part B) and for the harder 80% correct performance criterion (Part B). A larger value indicates poorer performance on this task. Solid lines indicate the linear regression trends. The right panels in Figure 5 are box-and-whisker plots of SSIN results for the three age groupings: younger adults (n = 12), the middle group (n = 15) and the older adults (n = 15). It can be seen that performance generally decreased with decreasing SNR. Performance also tended to decline with advancing age for both percent correct performance criteria, with, again, greater variability in performance for older than for younger subjects. For the 40%-correct criterion, Spearman correlation analyses revealed a low but significant correlation between age and performance at SNRs of 6 dB (r_s = .43, p = .004) and 9 dB (r_s = .45, p = .003), and a moderate, significant correlation at 12 dB SNR (r_s = .55, p < .001). For the harder, 80% correct criterion, there was a low but significant correlation between age and performance at an SNR of 3 dB (r_s = .35, p = .02), and a moderate, significant correlation at 12 dB SNR (r_s = .51, p < .001).

(place Figure 5 about here)

Temporal and Spectro-Temporal Processing Ability by Age

Shown in the left panels of Figure 6 are scatterplots of individual results for the TFS test (Part A) and the STM test (Part B). Note that for TFS a smaller value indicates poorer performance, while for STM a larger value indicates poorer performance. Solid lines indicate the linear regression trends. The right panels in Figure 6 are box-and-whisker plots of the results for the three age groupings: younger adults (n = 13 for both TFS and STM), the middle group (n = 14 for TFS, 17 for STM) and the older adults (n = 15 for TFS, 17 for STM).

For TFS (Figure 6, Part A), although there is variability in individual performance across ages, the linear trend line indicates declining performance with age. Spearman correlation analyses between age and performance on this task revealed a moderate, significant (negative) correlation coefficients between age and performance: $r_s = -.68$, $p < .001$. For the STM test (Figure 6, Part B), the linear trend lines indicate that the broadband stimulus is the easiest for subjects and 4000 Hz the hardest, and, again, declining performance with age. Correlation analyses between age and performance on this task revealed low to moderate, significant correlation coefficients for all three stimulus types: broadband ($r_s = .56$, $p < .001$), 1000 Hz ($r_s = .47$, $p < .001$) and 4000 Hz ($r_s = .59$, $p < .001$).

(place Figure 6 about here)

Correlations Between the Measures

It was of interest to examine whether there was a relationship between results on the spatial acuity/lateralization task and the SSIN task for the same subjects, i.e., whether or not the poor

performers on one task were also the poor performers on the other task, regardless of age, for the 42 subjects with testing on both tasks. To this end, a scatterplot is shown in Figure 7 for individual performances on the most difficult listening condition for each task, because these were where there was greater performance variability shown. Specifically, shown are individual MAAs from the lateralization task for 4000 Hz at -12 dB SNR in the off-axis condition, compared to SSIN scores at -12 dB SNR for each performance criterion (40% and 80% correct). Solid lines indicate the linear regression trends. It can be seen that, although there is fairly substantial performance variability, there is a tendency for poorer performance on one task to correspond to poorer performance on the other task. Spearman correlation analyses revealed only a low, albeit significant correlation, only for the harder, 80% correct criterion (r_s = .35, p = 0.022).

(place Figure 7 about here)

The top two panels of Figure 8 show scatterplots of individual results for the spatial acuity/lateralization task for the most difficult condition (4000 Hz at -12 dB SNR in the off-axis condition) versus the TFS (Part A) and versus the STM results for each stimulus type (Part B). Solid lines show the linear regression trends. The trend lines illustrate that performance on TFS and STM generally worsens (smaller TFS value and larger STM value) as the MAA for lateralization worsens. For the TFS test, despite a downward trend, the correlation analyses did not reach the level of significance; however, for the STM test, low but significant correlations were found for all three stimuli: broadband (r_s = .45, p = .002), 1000 Hz (r_s = .37, p = .011) , and 4000 Hz (r_s = .31, p = .035). The bottom two panels of Figure 8 show comparable results for the SSIN task in the most difficult condition (-12 dB SNR for 80% correct) versus the TFS (Part C) and STM results (Part D). The trend lines illustrate that performance on TFS and STM generally

worsens as the SSIN result worsens. For the TFS test, correlation analysis revealed a low but significant (negative) correlation coefficient: r_s = -.43, p = .005. For the STM test, correlation analyses revealed a significant correlation only for the 4000 Hz stimulus (r_s = .47, p = .002).

(place Figure 8 about here)

Finally, we examined correlations between performance on these tasks and hearing thresholds. First, there were moderate to strong significant correlations between hearing thresholds and age at 500 (r_s = .57, p<.0001), 1000 (r_s = .53, p<.0001) and 4000 Hz (r_s = .61, p<.0001). For the spatial acuity task with the 500 Hz stimulus, performance was not significantly correlated with hearing thresholds at 500 Hz for either on- or off-axis stimulus configurations at any SNR. With the 4000 Hz stimulus, significant correlations were found for the off-axis condition at SNRs of 3 dB (r_s = .330, p=.022), 9 dB (r_s = .304, p=.036) and 12 dB (r_s = .537, p<.001); the 6 dB condition did not reach significance (p = 0.075). Next, SSIN performance for the 80% criterions (the most difficult task) showed no significant correlations with hearing thresholds at 500, 1000 or 4000 Hz. Performance on the TFS task was also not significantly correlated with hearing thresholds at 500 or 1000 Hz. For the STM task, for the 1000 Hz condition there was a significant correlations with the 1000 Hz hearing threshold (r_s = .339, p=.020) and for the 4000 Hz condition there was also a significant correlation with the 4000 Hz hearing threshold (r_s = .356, p=.014).

DISCUSSION

Overall, the results indicate demonstrable aging effects on spatial hearing in terms of both spatial acuity/lateralization and spatial speech-in-noise results, primarily in more difficult listening conditions. For spatial acuity, the conditions in which envelope ITD or ILD cues must be used

(4000 Hz, off-axis) resulted in the most notable performance deficits in the older subjects, as expected. A stronger aging effect for an off-axis orientation is consistent with previous research by Briley and Summerfield (2014) who reported declining frontal plane lateralization ability with aging for the more peripheral regions of frontal space. Our SSIN results are also consistent with previous research that has shown reduced SRM with aging (e.g., Patro et al. 2024; Zobel et al. 2019). We did, however, find considerable variability in performances with aging on both spatial hearing tasks, with some older subjects performing as well as young subjects, but others performing much more poorly. This is also consistent with previous research; for example, about half of the subjects over age 60 in Briley and Summerfield (2014) performed about as well as younger subjects but half performed substantially worse. Finally, although the correlation was low, a significant relationship was found for performances between spatial acuity/lateralization and SSIN in the most difficult listening condition for each task, regardless of age, which suggests that both tasks tap into some similar aspect of hearing ability.

There was also a clear decline in temporal and spectro-temporal sound processing with advancing age as measured with both the TFS and STM tests, with the strongest relationship between aging and declining performance found using the TFS. When performance on these tasks was compared to performance on the spatial hearing tasks, in the more difficult listening conditions for the latter where variability was greatest, there were some low but significant correlations. Although the aging effect showed stronger correlations with the TFS and STM results, the latter finding suggests that deficits in temporal processing ability may in general underlie poorer performance on spatial hearing tasks regardless of age.

In an attempt to reduce the impact of peripheral hearing loss seen with age, we restricted enrollment to include only up to a mild hearing loss through 4000 Hz, which ensured audibility

of stimuli used in the study. Correlations between performance on the tasks and hearing thresholds reached significance in some cases, but in all cases the correlations were fairly low, ~0.3, suggesting that audibility *per se* was likely not a primary factor contributing to the declines in performance on the spatial acuity, TFS and TFS tasks with aging. These results, in part, are consistent with findings of the studies by Bernstein and Trahiotis (2016, 2018 and 2019) where they reported that even a slight hearing loss at 4000 Hz of > 7.5 dB resulted in significant performance declines, relative to the subjects with HL < 7.5 dB in tone detection in noise at 500 and 4000 Hz as well as the ability to lateralize 500 and 4000 Hz tones. They then used a computational model of peripheral monaural temporal encoding followed by binaural extraction of ITD to reveal that the data could be explained by reduced monaural temporal encoding, e.g., increased jitter, preceding the extraction of ITD. This finding is consistent with more recent computational models of cochlear synaptopathy, where reductions in the number of ribbon synapses leads to reduced phase locking in the monaural neural pathways leading to the binaural brainstem nuclei that compute ITD (Budak et al., 2022).

The present results along with the prior are consistent with a hypothesis that the declines in listening performance on these tasks may be due in part to the sequalae of cochlear synaptopathy (Kujawa and Liberman 2009). Animal studies reveal that both natural aging and even moderate noise exposure in young animals can cause temporary hearing threshold shifts that quickly recover, but permanent loss of auditory nerve to hair cell synapses (Furman et al., 2013; Kujawa and Liberman 2009; Parthasarathy and Kujawa 2018). This aging- and/or noise-induced cochlear synaptopathy *may* be a potential cause for the phenomenon commonly called “hidden hearing loss,” characterized by poor performance on hearing tasks such as speech in noise perception despite normal audiological thresholds (Schaette and McAlpine 2011; Kohrman et al 2019).

Indeed, individuals with histories of moderate noise exposure, but normal thresholds, can develop behavioral symptoms consistent with hidden hearing loss (Fullgrabe et al, 2015; Bernstein et al., 2013). In humans, some loss of synapses begins already in early adulthood (Wu et al., 2019) with additional losses of ~7.5% per decade (Viana et al., 2015; Makary et al, 2011).

However, it is notable that the older subjects in our study did show poorer hearing at 6000 and 8000 Hz on average than younger adults, and also substantially decreased hearing in the EHF range (Figure 1). This is not surprising as it has long been known that EHF loss increases with aging (e.g., see Matthews et al 1997), but it is important to consider that this may be an additional factor underlying the poorer performance by many older subjects on spatial hearing tasks. Recently, for example, Patro et al. (2024) investigated performance of young to middle-aged subjects (age 20 to age 56) and reported that EHF-range hearing loss appeared to be a significant contributor to suprathreshold performance deficits in the middle-aged group, producing less SRM on a speech-in-noise test. Further, EHF loss has also been implicated in some limited studies as a potential factor in poor localization ability (Liberman et al. 2016; Brungart & Simpson 2009; Best et al. 2005). For example, Liberman et al. (2016) reported that subjects with EHF hearing loss reported more difficulty localizing the direction of sounds than subjects without EHF loss. Unfortunately, because EHF hearing loss in the current study was seen only in older subjects, it was not possible to determine how much EHF hearing loss contributed to poorer performances on the spatial hearing tasks versus the impact of temporal processing deficits. Moreover, EHF hearing loss may be an indicator of the presence of cochlear synaptopathy in more apical cochlear regions subserving lower frequency hearing (Mepani et al., 2021; Mishra et al., 2022). Future research in this area may better illuminate this issue.

In conclusion, this study confirms that aging effects are seen on average in suprathreshold spatial hearing abilities measured with both a spatial acuity/lateralization task and a spatial speech recognition in noise task, even when any effect of significant cognitive deficits and/or hearing loss in the standard audiometric range is excluded. The results of this study suggest that these suprathreshold performance deficits may possibly have as an underpinning a decrease in temporal and spectro-temporal processing ability with aging, and also a contribution from EHF-range hearing loss typically seen in older patients. Notable, however, is that some of the subjects in the oldest age group performed much better than did other older subjects, suggesting an unequal impact of aging across individuals that may be due to any number of factors contributing to degeneration in the auditory system such as the extent of lifetime noise exposure and the presence of cochlear synaptopathy.

In any case, hearing health professionals should remain alert to the fact that some elderly persons may present to a clinic with reports of difficulty understanding speech in noise or localizing the direction of sounds despite having normal or near-normal hearing in the standard audiometric frequency range. Awareness of this problem can be beneficial in counseling and in decisions regarding rehabilitation for these patients. For example, if an active elderly patient complains of suprathreshold hearing deficits but does not show hearing loss of the degree usually considered for hearing aids, very mild gain hearing aids or other assistive hearing devices may still be appropriate for improvement of the SNR that may lead to functional improvement in their daily life.

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Table 1. Numbers of subjects with available data for each measure by gender and decade of life. *Key:* SSIN: Spatial Speech in Noise; TFS: Temporal Fine structure; STM: Spectro-Temporal Modulation; F=female, M=male.

	Lateralization			**SSIN**			**TFS**			**STM**		
Decade of Life	**F**	**M**	***Total***	**F**	**M**	***Total***	**F**	**M**	***Total***	**F**	**M**	***Total***
20s	7	1	***8***	6	1	***7***	6	1	***7***	6	1	***7***
30s	3	3	***6***	3	2	***5***	3	3	***7***	3	3	***7***
40s	5	1	***6***	4	1	***5***	4	1	***5***	5	0	***5***
50s	8	3	***11***	7	3	***10***	7	3	***10***	8	3	***11***
60s	9	2	***11***	8	1	***9***	8	2	***10***	9	2	***11***
70s	3	3	***6***	3	3	***6***	3	3	***6***	3	3	***6***
Total	***35***	***13***	***48***	***31***	***11***	***42***	***31***	***13***	***44***	***34***	***12***	***46***

Figure Legends

Figure 1. Individual audiograms and extended high-frequency hearing thresholds (in dB HL), and means for each of three age groupings of subjects: younger adults (aged 21-39), middle-aged (aged 42-59), and older adults (aged 60-78). For calculation of means, when a subject had no response at the maximum output limit of the audiometer at that frequency, which occurred only in the EHF range, a value 5 dB higher was assigned (see text for more description). Arrows indicate that many older subjects had no responses at the output limits at those extended high frequencies, so that the actual mean threshold is assumed to be poorer than that shown.

Figure 2. Illustration of loudspeaker spacing in the horizontal array around the subject in the hemi-anechoic test chamber. Part A: subject is seated facing 0˚; dark shading indicates loudspeakers that were used for stimulus presentations for spatial acuity testing in the *on*-axis condition. Light shading indicates loudspeakers that were also used for spatial speech-in-noise (SSIN) testing. Part B: subject is seated facing 45˚; shading indicates loudspeakers that were used for stimulus presentations for spatial acuity testing in the *off*-axis condition.

Figure 3. Spatial acuity/lateralization data for the *on*-axis listening condition (subject seated facing 0˚) for each dB SNR (3, 6, 9, 12). Part A (top row) shows results for the 500 Hz stimulus and Part B (bottom row) for the 4000 Hz stimulus. Left panels show individual data scatterplots of minimum audible angle (MAA, in degrees) by age (in years). A lower MAA value indicates better performance. Solid lines indicate the linear regression trend for each SNR. Right panels show box-and-whisker plots with the median, lower and upper quartiles, and variability of the data, for three age groupings: younger adults (aged 21-39), middle-aged (42-59), and older adults (60-78).

Figure 4. Spatial acuity/lateralization data for the *off*-axis listening condition for each dB SNR (3, 6, 9, 12). Part A shows results for the 500 Hz stimulus and Part B for the 4000 Hz stimulus. Left panels show individual data scatterplots of minimum audible angle (MAA, in degrees) by age (in years). A lower MAA value indicates better performance. Solid lines indicate the linear regression trend for each SNR. Right panels show box-and-whisker plots with the median, lower and upper quartiles, and variability of the data, for three age groupings: younger adults (aged 21-39), middle-aged (42-59), and older adults (60-78).

Figure 5. Spatial speech-in-noise (SSIN) data. Part A shows results for the 40% correct criterion and Part B for the 80% correct criterion, for each dB SNR (3, 6, 9, 12). Left panels show individual data scatterplots of the speech and noise loudspeaker separation needed (angle, in degrees) for the given performance criterion by age (in years). A lower value indicates better performance. Solid lines indicate the linear regression trend for each SNR. Right panels show box-and-whisker plots with the median, lower and upper quartiles, and variability of the data, for three age groupings: younger adults (aged 21-39), middle-aged (42-59), and older adults (60-78).

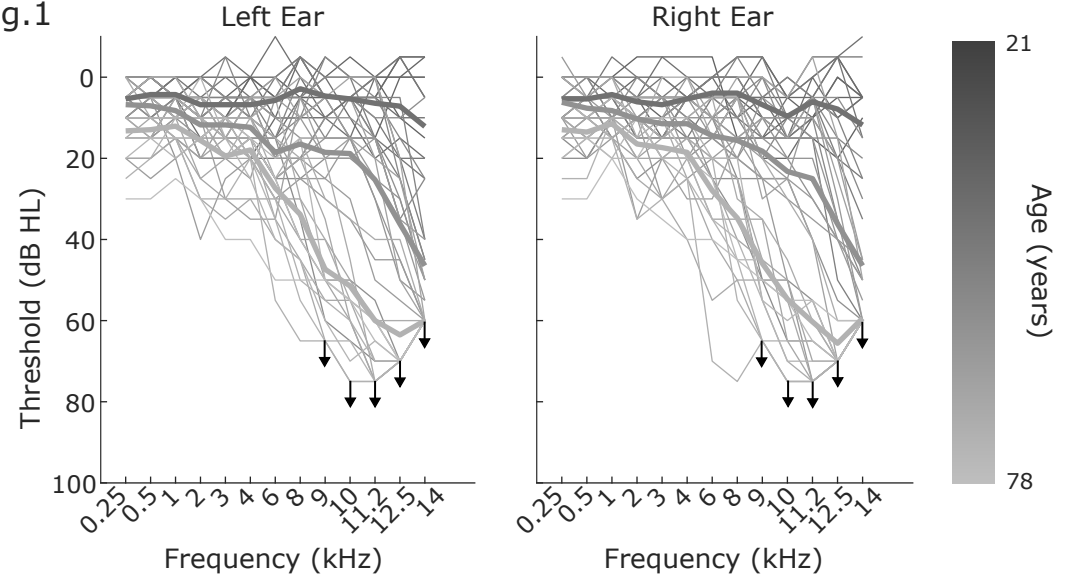
Figure 6. Data for the temporal and spectro-temporal processing tasks. Part A shows results for the TFS test, and Part B for the STM test for each stimulus type (broadband, 1000 Hz, and 4000 Hz), by age (in years). Left panels show individual data scatterplots, with solid lines indicating the linear regression trends. For TFS (Part A), performance is plotted as the highest frequency at which each subject could discriminate a difference relative to 0˚, so a higher number indicates

better performance. For STM (Part B). performance is plotted as the minimum modulation depth each listener could detect for each stimulus, so a lower number indicates better performance. Right panels show box-and-whisker plots with the median, lower and upper quartiles, and variability of the data, for three age groupings: younger adults (aged 21-39), middle-aged (42-59), and older adults (60-78).

Figure 7. Scatterplot of individual results for spatial-speech-in-noise (SSIN; in degrees separation needed for the speech and noise) for that task's most difficult SNR (-12 dB) for both the 40% and 80% correct criteria, versus individual results for spatial acuity/lateralization (minimum audible angle/MAA, in degrees) for that task's most difficult listening condition (4000 Hz stimulus at -12 dB SNR in the off-axis/45˚ listening condition).

Figure 8. Top two panels: scatterplots of individual results for the spatial acuity results (MAA, in degrees) for that task's most difficult listening condition (4000 Hz stimulus at -12 dB SNR in the off-axis/45˚ listening condition) versus TFS test results (Part A) and versus STM results for each stimulus type (broadband, 1000 Hz, and 4000 Hz) in the right panel (Part B). Bottom two panels: scatterplots of individual results for spatial-speech-in-noise (SSIN; in degrees separation needed for the speech and noise) for that task's most difficult SNR (-12 dB) for the 80% correct criteria versus the TFS test result (Part C) and versus the STM test for each stimulus type in the right panel (Part D).

Fig.1


Left Ear
Right Ear
Threshold (dB HL)
0
20
40
60
80
100
0.25
0.5
1
2
3
4
6
8
9
10
11.2
12.5
14
Frequency (kHz)
Age (years)
21
78

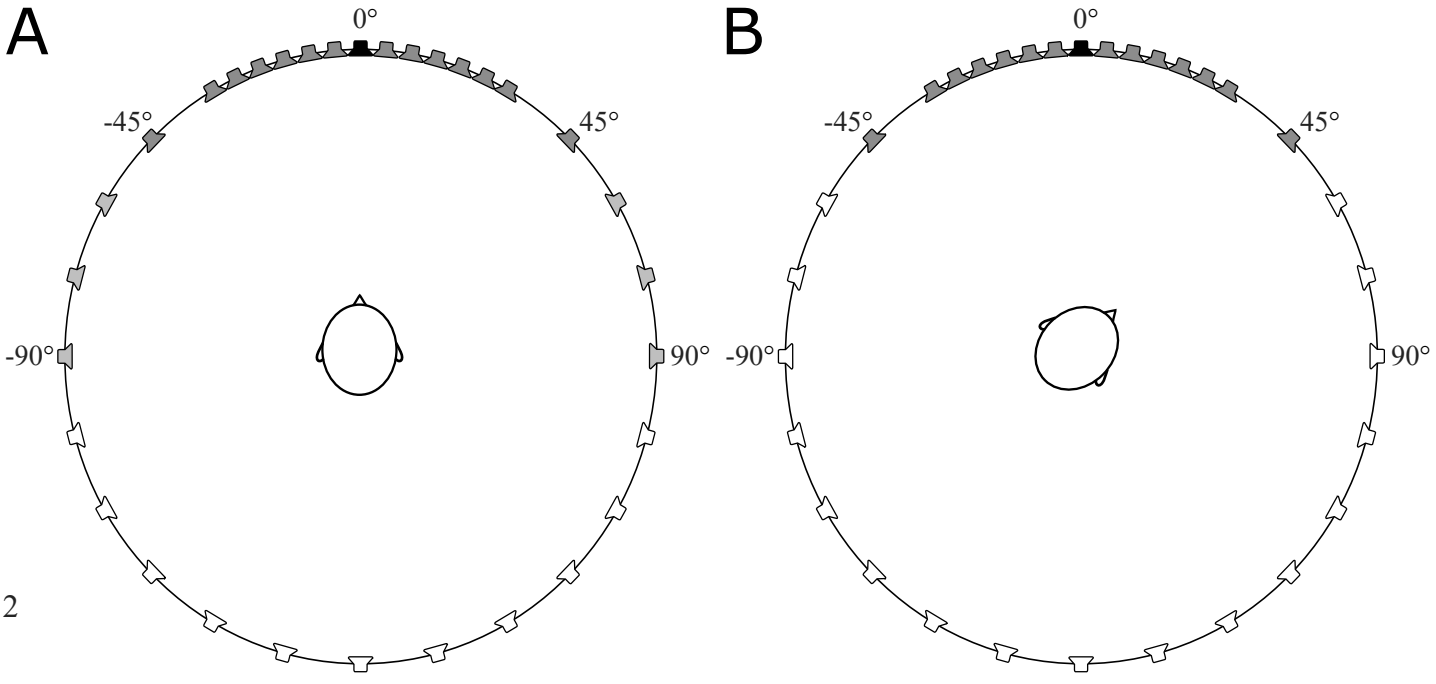


Fig. 2

Fig. 3

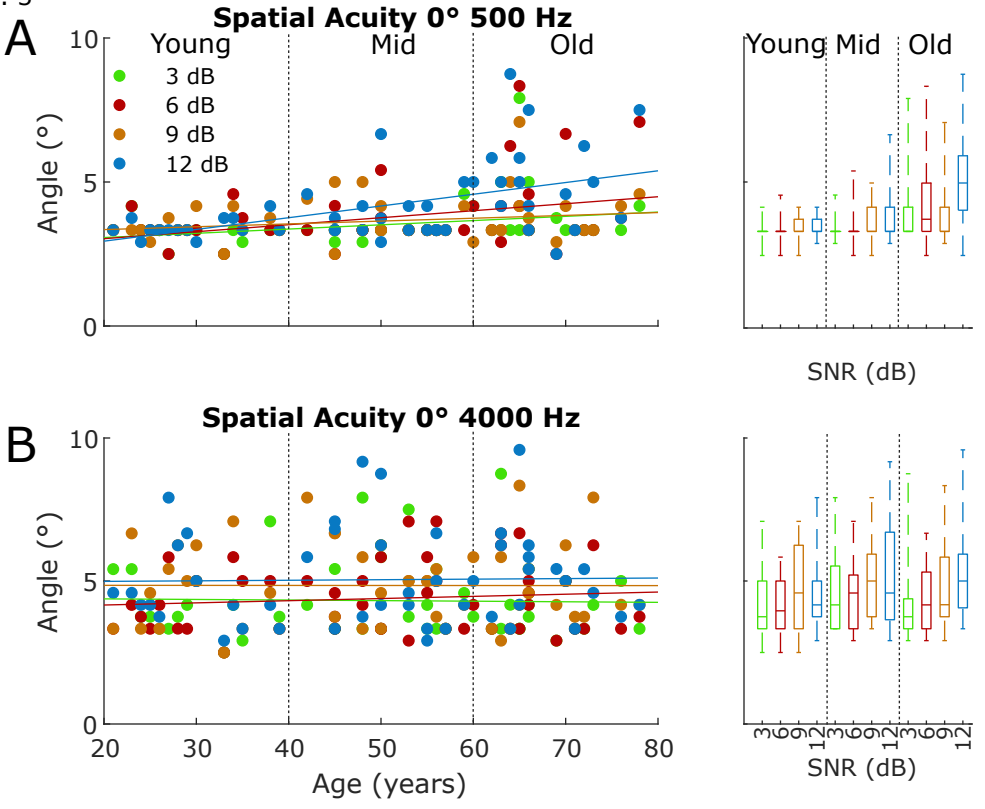
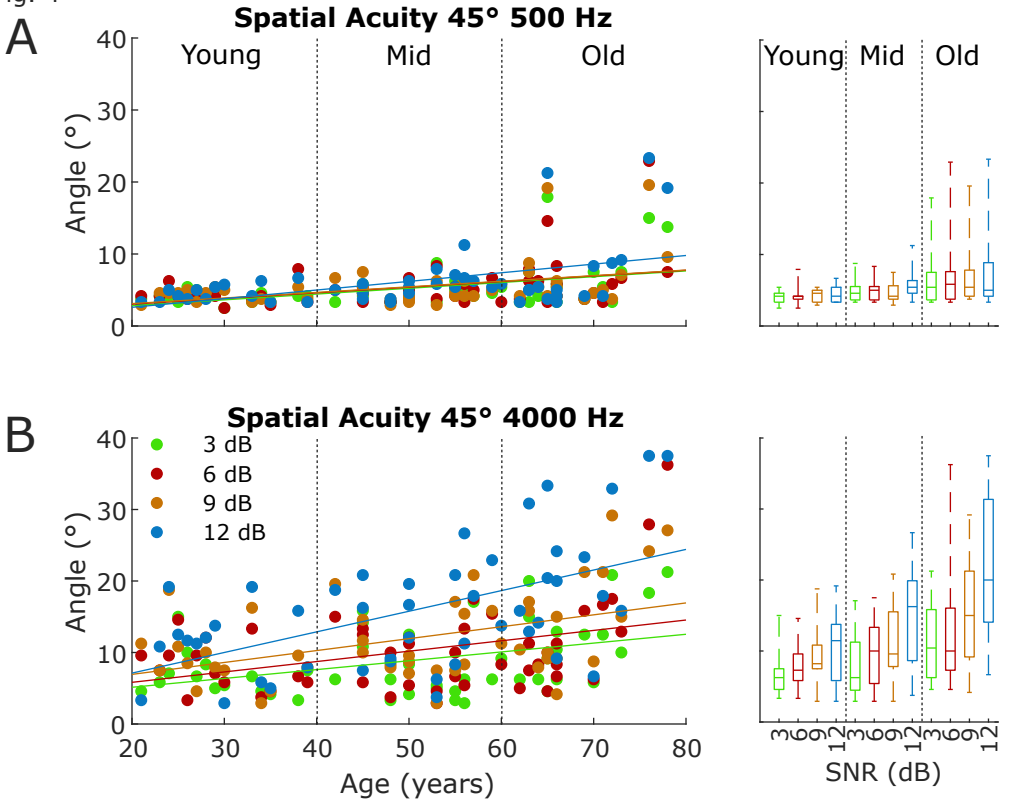

A
Spatial Acuity 0° 500 Hz
Young
Mid
Old
3 dB
6 dB
9 dB
12 dB
Angle (°)
10
5
0
Young
Mid
Old
SNR (dB)
B
Spatial Acuity 0° 4000 Hz
Angle (°)
10
5
0
20
30
40
50
60
70
80
Age (years)
3
6
9
12
3
6
9
12
3
6
9
12
SNR (dB)

Fig. 4


A
Spatial Acuity 45° 500 Hz
Young
Mid
Old
Angle (°)
0
10
20
30
40
Young
Mid
Old
B
Spatial Acuity 45° 4000 Hz
3 dB
6 dB
9 dB
12 dB
Angle (°)
0
10
20
30
40
20
30
40
50
60
70
80
Age (years)
3
6
9
12
3
6
9
12
3
6
9
12
SNR (dB)

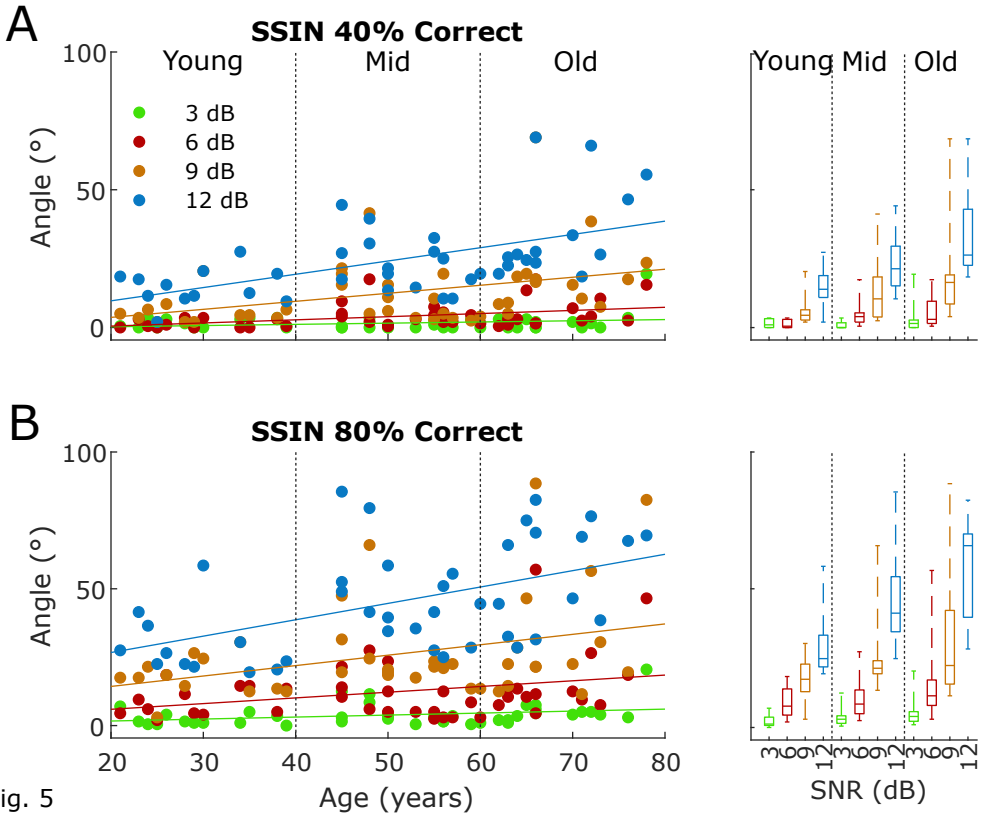

A
SSIN 40% Correct
Young
Mid
Old
3 dB
6 dB
9 dB
12 dB
Angle (°)
100
50
0
Young Mid Old
B
SSIN 80% Correct
Angle (°)
100
50
0
20
30
40
50
60
70
80
Age (years)
3
6
9
12
SNR (dB)

Fig. 5

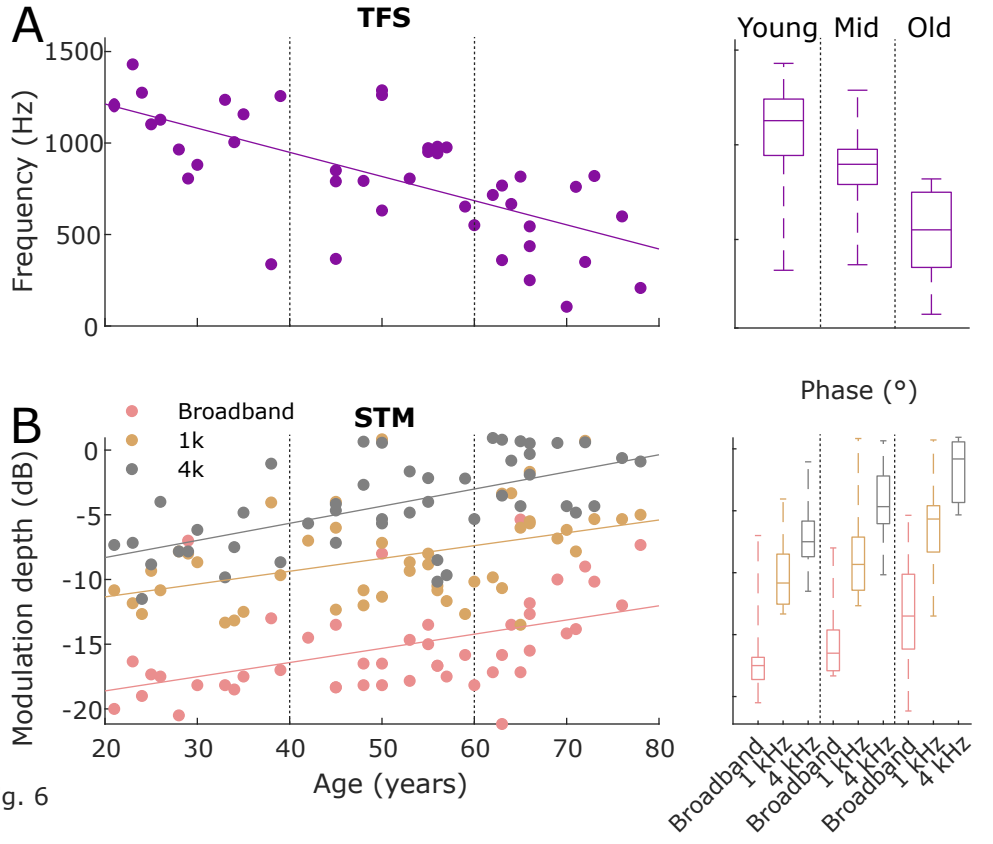
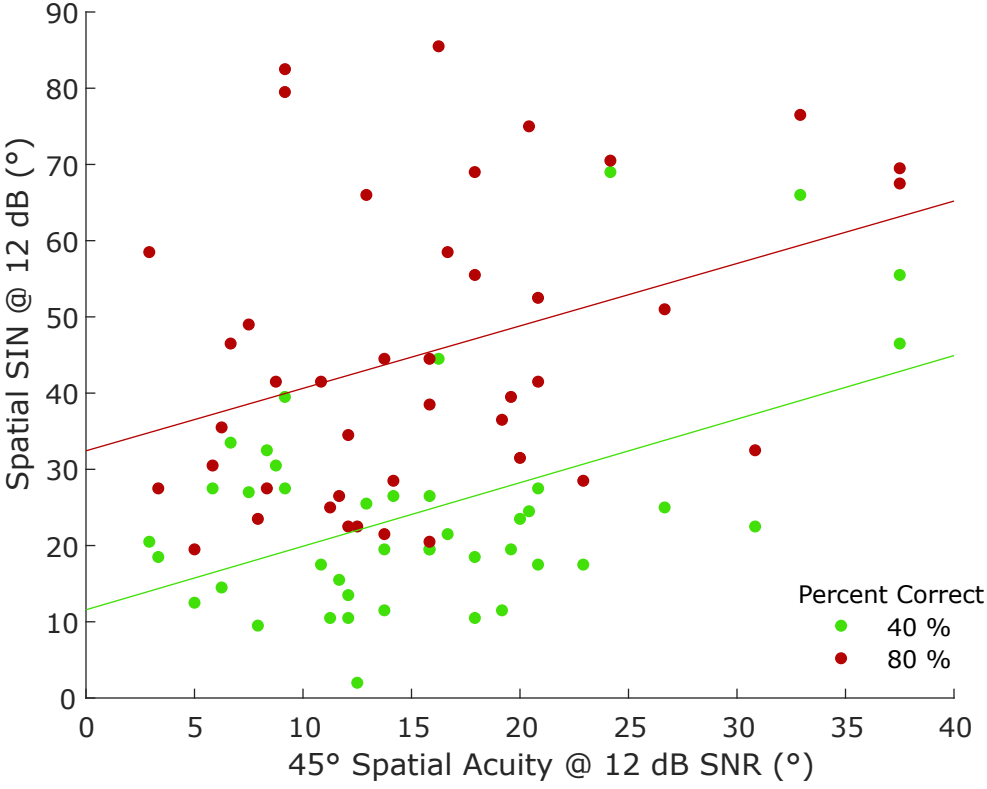

A
TFS
Frequency (Hz)
1500
1000
500
0
Young
Mid
Old
B
STM
Broadband
1k
4k
Modulation depth (dB)
0
-5
-10
-15
-20
20
30
40
50
60
70
80
Age (years)
Phase (°)
Broadband
1 kHz
4 kHz
Broadband
1 kHz
4 kHz
Broadband
1 kHz
4 kHz

Fig. 6

Fig. 7


Spatial SIN @ 12 dB (°)
45° Spatial Acuity @ 12 dB SNR (°)
0
10
20
30
40
50
60
70
80
90
0
5
10
15
20
25
30
35
40
Percent Correct
40 %
80 %

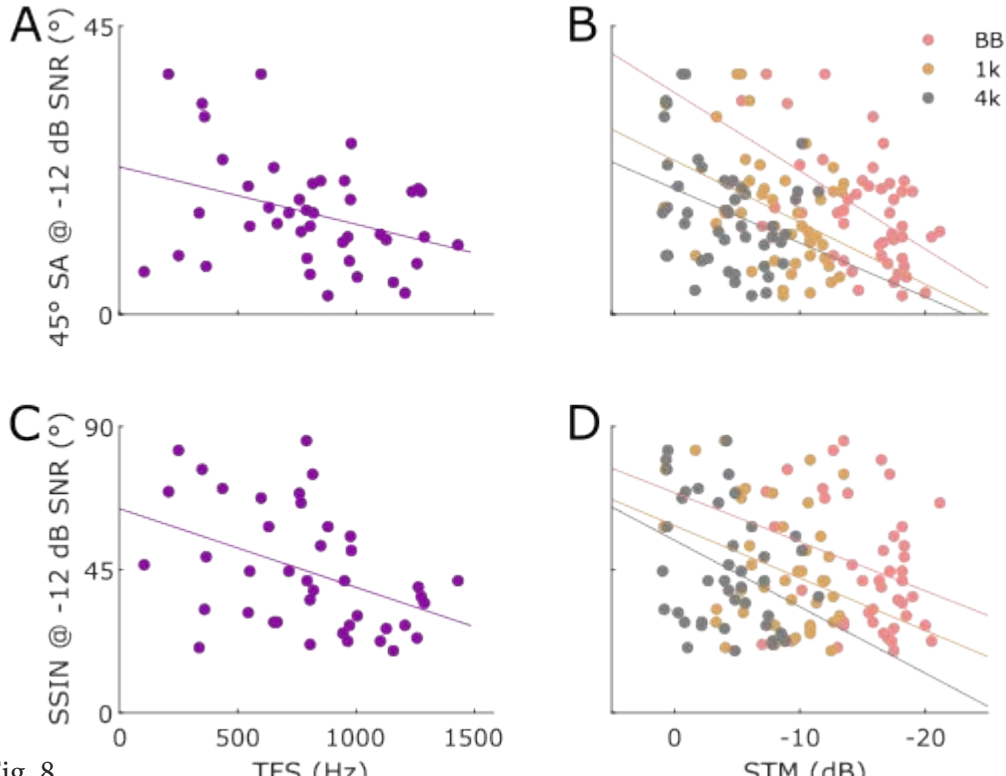

A
B
C
D
45° SA @ -12 dB SNR (°)
SSIN @ -12 dB SNR (°)
45
0
90
45
0
500
1000
1500
TFS (Hz)
0
-10
-20
STM (dB)
BB
1k
4k

Fig. 8