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Differences in Auditory Perception Between Young and Older Adults When Controlling for Differences in Hearing Loss and Cognition

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Abstract

This study was designed to examine age effects on various auditory perceptual skills using a large group of listeners (155 adults, 121 aged 60–88 years and 34 aged 18–30 years), while controlling for the factors of hearing loss and working memory (WM). All subjects completed 3 measures of WM, 7 psychoacoustic tasks (24 conditions) and a hearing assessment. Psychophysical measures were selected to tap phenomena thought to be mediated by higher-level auditory function and included modulation detection, modulation detection interference, informational masking (IM), masking level difference (MLD), anisochrony detection, harmonic mistuning, and stream segregation. Principal-components analysis (PCA) was applied to each psychoacoustic test. For 6 of the 7 tasks, a single component represented performance across the multiple stimulus conditions well, whereas the modulation-detection interference (MDI) task required two components to do so. The effect of age was analyzed using a general linear model applied to each psychoacoustic component. Once hearing loss and WM were accounted for as covariates in the analyses, estimated marginal mean thresholds were lower for older adults on tasks based on temporal processing. When evaluated separately, hearing loss led to poorer performance on roughly 1/2 the tasks and declines in WM accounted for poorer performance on 6 of the 8 psychoacoustic components. These results make clear the need to interpret age-group differences in performance on psychoacoustic tasks in light of cognitive declines commonly associated with aging, and point to hearing loss and cognitive declines as negatively influencing auditory perceptual skills.

Keywords

aging, psychoacoustics, cognition, working memory, principal component analysis

Introduction

It is well-established that aging negatively affects auditory and speech perception. Three general hypotheses have been put forth concerning the mechanisms underlying these perceptual difficulties experienced by older listeners: (1) peripheral cochlear damage – audibility loss plus suprathreshold processing deficits associated with cochlear pathology; (2) central auditory factors, such as changes to auditory centers of the brainstem and cortex; and (3) cognitive changes, involving non-auditory areas of the cortex used in various aspects of linguistic and cognitive processing (CHABA, 1988). These three hypotheses have been tested to varied degrees, with the lion's share focusing on the peripheral and cognitive hypotheses for speech perception (see Gordon-Salant et al., 2020). Less work has been conducted related to the central and cognitive hypotheses as they relate to auditory perception. The primary purpose of this study is to evaluate the contributions of age-related factors including hearing loss and cognitive declines to a variety of perceptual abilities. This study provides the first comprehensive evaluation of the role of cognition (measured via working memory (WM)) on a large set of auditory perceptual tasks.

Producing a data set well-suited to establish this connection, Humes et al. (2013) conducted a large-scale study that assessed the relative contributions of peripheral, central and cognitive factors to speech perception in older listeners. Humes et al., found that cognitive skills, along with psychoacoustic factors, predicted speech perception by older listeners, accounting for about 60% of the variance. In this study,

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Humes et al., measured auditory abilities on a range of psychoacoustic tasks, providing a rich data set that can also be used to establish the roles of age-related factors, hearing loss, and cognition on a range of auditory perceptual abilities. By using tasks that require complex representations within the central auditory system (such as binaural masking, informational masking (IM), and modulation detection interference) and measuring perception in listeners with a wide range of hearing abilities, we may also be able to address whether central auditory changes have perceptual consequences in older listeners.

As Humes et al. (2013) noted, a major hurdle to establishing the contribution of central changes associated with age is the high prevalence of hearing loss among adults over the age of 60 years (Cruickshanks, 2010). Peripheral neurophysiological changes are one hallmark of age-related hearing loss, with such hearing loss also linked to additional atrophy in higher auditory centers including the auditory cortex (Peelle & Wingfield, 2016). As a result, it can be difficult to separate central-auditory aging effects from those associated with peripheral hearing loss. Notably, repeatedly and consistently across studies, hearing thresholds have been found to be significant predictors of speech understanding by older adults in quiet and in background noise, often accounting for 30–80% of the total variance in speech-understanding performance [see review by Humes & Dubno (2010)]. Further complicating this endeavor is that cognitive factors (broadly defined) also have been implicated as significant contributors to individual differences in speech-understanding performance for both unamplified and amplified speech (c.f. Akeroyd, 2008; Houtgast & Festen, 2008; Humes & Dubno, 2010; Humes et al., 2013).

Willott (1996) categorized the two main mechanisms by which aging might impact the central auditory system—central effects of biological aging (i.e. typical neurophysiological changes occurring due to increased age independent of peripheral hearing loss) and central effects of peripheral pathology, the latter being a less direct connection between aging and central auditory function mediated by the presence of peripheral hearing loss. Most of the evidence supporting the central effects of biological aging derive from anatomical or physiological studies in laboratory animals and humans [see Willott et al. (2001) and Gordon-Salant et al. (2020) for reviews]. Psychoacoustic experiments, which represent one of the possible approaches to evaluating central auditory perceptual abilities in older adults, also are susceptible to peripheral auditory changes (i.e., hearing loss). Perceptual abilities that are mediated by central auditory processing (e.g., binaural hearing, some measures of temporal processing, auditory grouping/segregation) have been demonstrated to be significantly altered by the presence of sensorineural hearing loss (SNHL). For example, SNHL is associated with elevated masked thresholds in steady and fluctuating noise (Florentine et al., 1980; Festen & Plomp, 1990; Leek & Summers, 1993), changes to some temporal processing abilities (Reed et al., 2009), binaural perception (c.f. Akeroyd, 2014; Durlach et al., 1981), and pitch perception (Moore & Peters, 1992). As a result, the co-occurrence of SNHL and aging contributes to the difficulty teasing apart the relative contributions of biological aging and peripheral hearing loss.

Due to the complex nature of the auditory system, no single psychoacoustic test is sufficient to fully characterize the complexities of central auditory processing. As reported by Humes et al. (2013), measures on six different psychoacoustic tests loaded onto five principal components (PC) indicating little redundancy among those measures. As a result, a number of different psychoacoustic tasks may be necessary to characterize the perceptual skills mediated by central auditory processing. In a given study, typically the effects of aging have been reported for a single auditory ability, most often with a focus on either temporal or binaural processing with the latter using stimuli with temporally based cues. In many cases, increasing age is associated with a decline in temporal processing abilities (Fitzgibbons & Gordon-Salant, 1994; Füllgrabe et al., 2015; Grose et al., 2016; He et al., 2008; Snell, 1997; Strouse et al., 1998; Wallaert et al., 2016), but this trend is not always evident (He et al., 2008; Whiteford et al., 2017). Binaural hearing abilities such as sound localization based on interaural time/phase differences (Koerner et al., 2020; Strouse et al., 1998; Vercammen et al., 2018) and binaural masking (Eddins et al., 2018; Grose et al., 1994) have been shown to decline in older listeners, as does the perception of pitch (Alain et al., 2001; He et al., 1998; Moore & Peters, 1992). Similar results have been found for fundamental-frequency discrimination (Souza et al., 2011) and the perception of dynamic pitch contours (Shen et al., 2016).

The complexity of the stimuli used in psychoacoustic studies and the methods used to measure perception also require cognitive effort on the part of the listener, and both advancing age (e.g., Salthouse, 2009) and hearing loss (Lin et al., 2013) are associated with a decrease in cognitive abilities. As noted by Humes et al. (2012) in an extensive review of the literature on "central presbycusis", including many binaural- and temporal-processing measures, attempts to measure central-auditory performance in older adults may be confounded by the presence of both peripheral hearing loss and diminished cognitive processing. "Pure" central-auditory effects of biological aging are challenging to identify without controlling for both peripheral hearing loss and cognitive function. The dataset from Humes et al. (2013) enabled statistical control of these two potential confounders while examining remaining differences between the young and old adults in that study.

Although measurement of cognitive skills has become effectively mandatory for speech perception studies involving older listeners, this practice remains rare for psychoacoustic studies. In the few studies that exist, links between WM and temporal processing have been identified in normal-hearing populations (Broadway & Engle, 2011) and, using a group of older and younger listeners with normal hearing, Füllgrabe et al. (2015) identified a relationship between cognitive declines and poorer sensitivity to temporal fine structure. One might predict that cognitive status could be a strong predictor of performance on psychoacoustic tasks, in light of the evidence for its importance in speech perception.

Given the complex relationships among these age-related variables, the data of Humes et al. (2013) provide a good opportunity to address the contributions of hearing loss, cognition, and other age-related factors on a variety of auditory perceptual abilities. In their study, participation of the older listeners was only limited to exclude those with severe hearing loss or signs of mild-moderate cognitive impairment. As a result, listeners in the older group had a range of hearing levels and a range of scores on cognitive assessments. This data set allows for an assessment of the effects that hearing levels, cognitive status, and other age-related factors have on psychoacoustic abilities. Performance on seven different psychoacoustic tasks was measured with several stimulus conditions for each task. The tasks were selected to span a wide range of auditory abilities that are thought to be related to auditory segregation and grouping abilities and spectro-temporal processing. These tasks included modulation detection, modulation detection interference, anisochrony detection, diotic and dichotic listening, harmonic mistuning, IM, and auditory streaming. Stimuli were designed to reduce the potential impact of hearing loss by using stimuli that were moderately high in level and confined, whenever possible, to low or mid-frequency regions. By considering both hearing loss and cognitive factors, we can attempt to elucidate age-related changes in auditory perceptual skills associated with central-auditory function using the Humes et al., data set. This work takes a step toward determining the role that cognitive factors have in auditory perception and also establishes whether older listeners experience difficulty in tasks believed to be mediated by central auditory processing (e.g., temporal processing, binaural masking, and IM).

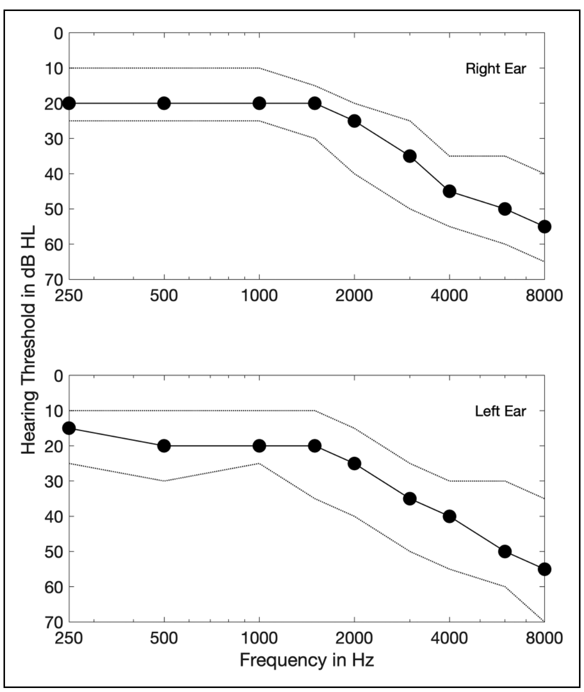

Figure 1. Median hearing thresholds of the test ear (filled circles) and interquartile ranges (dotted lines without symbols) for the older adults.

Methods

Subjects

Subjects were all those included in the analyses of Humes et al. (2013, p. 98 older adults and 28 younger adults), and an additional 23 older adults and 6 younger adults who completed a subset of the tasks in the Humes et al., study. The older group was comprised of 121 subjects ranging in age between 60 and 88 years (Mean = 69.0 y; 61 female). Inclusion criteria for the older listeners were bilaterally symmetric hearing levels, no evidence of middle-ear pathology (air-bone gaps <10 dB and normal tympanograms bilaterally), no signs of dementia (Mini Mental Status Exam, MMSE > 25; Folstein et al., 1975), and had English as a native language. Pure-tone average thresholds at 0.5, 1, 2, and 4 kHz (PTA4k) were required to be less than 60 dB HL (ANSI, 2004) in the test ear. For the monaural tasks, the right ear was tested unless the right ear did not meet the inclusion criteria for the study (N = 7). Median audiograms for the right and left ears of the older group are illustrated in Figure 1.

Thirty-four subjects were young normal-hearing adults ranging in age from 18 to 30 years (M = 22.5 y; 26 female). These subjects had hearing thresholds ≤25 dB HL between 250 and 8,000 Hz in both ears. Mean audiometric thresholds for every frequency and for both ears were less than or equal to 10 dB HL. These subjects also had no signs of dementia (MMSE > 25) and had English as a native language. The test ear was always the right ear for the monaural tasks for the young subjects.

Stimuli and Procedures

Subjects in this study completed a variety psychophysical non-speech tasks, as described by Humes et al. (2013). Stimuli and procedures for each psychoacoustic task are described briefly here, and the reader is referred to Humes et al. (2013) for greater detail regarding the experimental details. These subjects also completed a set of WM tests. Because the results on the WM tests are relevant to the interpretation of psychoacoustical findings, these tests are also described.

Common Psychoacoustic Procedures. Stimuli were presented monaurally through Etymotic Research ER-3A insert earphones, except in the IM and binaural detection tasks where stimuli were presented to both ears. Tonal stimuli (for anisochrony detection, stream segregation, modulation detection interference, inharmonicity detection, and IM) were presented at 80 dB SPL per tone. When noise stimuli were used (modulation detection, masking level difference (MLD)), the noise was presented at 80 dB SPL overall. Signal detection/discrimination thresholds were measured using a standard/two-alternative forced-choice 2-down, 1-up staircase method (except streaming). Starting levels for each task were the same for all listeners and were selected to be at least 2–3 steps sizes above estimated threshold. This criterion was achieved for all tasks but IM, where many thresholds were higher than the track starting level (both for young and older listeners). Stimulus levels did not exceed 105 dB SPL in any of the experiments. Five replicate thresholds were measured for each experimental condition.

Psychoacoustic Task Details

Modulation Detection (Broadband). Listeners detected the just-noticeable modulation depth of a sinusoidal modulator of 5, 20, or 60 Hz imposed on a broadband noise carrier (e.g., Viemeister, 1979). The just detectable modulation depth was described as 20log*m,* where *m* was the amount of modulation imposed on the carrier and ranged from 0–1 (0 being no modulation, 1 being fully modulated).

Modulation Detection Interference (MDI). This task was similar to modulation detection, but the carrier was a tone rather than noise. The just-detectable modulation depth was measured in the presence of a high-frequency tone, which when modulated, interfered with modulation detection of the low-frequency tone (e.g., Yost et al., 1989). Here, listeners detected the presence of 5, 10, or 20 Hz amplitude modulation (AM) imposed on a 400-Hz tone. This tone was presented with a 1,974-Hz tone that was either unmodulated (MDI unmod) or fully modulated (MDI mod) at the same rate as the 400-Hz tone, both with a different randomly selected starting phase. Thresholds were expressed as 20log*m*.

Informational Masking (IM). In this task, listeners detected a series of fixed-frequency tone bursts (either 500 or 1,000 Hz) embedded in a masker having similar temporal characteristics to the signal, but randomly selected frequency characteristics (e.g., Kidd et al., 1994). The signal contained eight 60-ms tone bursts with 10-ms rise/fall times. Maskers also consisted of eight bursts, but each burst contained two frequency components that were separated at least 1.5 ERBs from the signal frequency. In the burst-same condition (BS), the frequencies and phases of the masker bursts were held fixed across the eight bursts, and a new masker was generated for each interval. In the burst-different condition (BD), the frequencies and phases were randomly selected (the frequency selected without replacement) across bursts and across intervals. Thresholds for signal detection are reported in dB SPL.

Binaural Detection (i.e., Masking Level Difference, MLD). Listeners detected a pure tone added to broadband Gaussian noise, with the same noise presented to each ear. Signal frequencies were 250 and 500 Hz. In the N_0S_0 conditions, the tone was presented in phase across the ears. In the N_0S_π condition, the tone was presented 180° out of phase across the ears (e.g., Hirsh, 1948). Thresholds for signal detection were measured in dB SPL.

Anisochrony. In this task, listeners detect a lengthened inter-onset interval (IOI) embedded in an otherwise isochronous tone sequence. Tone sequences consisted of eight 50-ms tone bursts with 5-ms rise/fall times, separated by 100 ms. Listeners detected a temporal increase (Δt) in the IOI between one pair of tones. In the fixed/fixed (FF) condition, each tone in the sequence had a frequency of 1,000 Hz, and the increased IOI (Δt) always occurred between the 4th and 5th tones. In the variable/variable (VV) condition, the frequencies of the tones within the sequence randomly varied between 500 and 2,000 Hz (in logarithmic spacing) both within and across trials, and the position of the increased IOI was variable among the seven possible IOI positions. This task was patterned after the "rhythm discrimination" task in the Test of Basic Auditory Capabilities (TBAC; Kidd et al., 2007; Watson, 1987). Thresholds for the temporal increase are reported in milliseconds.

Harmonic Mistuning. Listeners detected a mistuned component from a 12-component, equal-amplitude 400-ms harmonic stimulus (e.g., Moore et al., 1985) with fundamental frequency of 100- and 200- Hz. The just noticeable increase in frequency Δf (in Hz) of the 3rd harmonic was measured.

Stream Segregation. Two tones and a harmonic complex were alternated and separated by quiet intervals to form a sequence of triplets: ABA_ABA_ABA_ABA … (Bregman & Campbell, 1971; van Noorden, 1977). A, B, and "_" (a silent interval) were fixed at 100 ms. Stimulus A was either a tone burst at 250 Hz or 1,000 Hz or was a 12-tone equal-amplitude harmonic complex with a 150-Hz fundamental frequency. When A was a pure tone, B was also a pure tone, and when A was a harmonic complex, so was B. B began at a frequency (or fundamental frequency) of 1.5 octaves above A. Each subsequent decreasing frequency (or fundamental frequency) of B (f_B) decreased with each subsequent presentation according to: $f_{Bn} = f^{(1/1.06)} \times B(n-1)$, where n is the triplet number. Listeners were told to press a button as soon as they heard a galloping sound. We note that Humes et al. (2013) used two streaming tasks, but only report one of them here, as subsequent analyses indicated the second streaming task produced less reliable results than the other psychoacoustic measures.

Cognitive Tests. In Humes et al. (2013) subjects completed two cognitive tasks—a set of WM tests (Lewandowsky et al., 2010) and the AQT (A quick test; e.g., Wiig et al., 2002). All cognitive measures used visual stimuli to preclude impact of the participant's hearing loss on performance. Visual acuity was not measured but the visibility of the stimuli and the comprehension of the tasks was confirmed through several initial practice trials on each task. Results from the WM tests are used here, as about 25% more subjects completed this set of tests than completed the AQT. The WM and AQT also loaded on a single component in a principal-components analysis (PCA) analysis that accounted for 72% of the variance. As such, by using only WM data, we can analyze data from more subjects without losing a large amount of information about the subjects' cognitive skills.

In the battery of WM tests, the first was a memory updating test: Subjects saw a sequence of 3–5 digits, each surrounded by a square marking its position on the screen. After the digits were presented, the squares remained and a sequence of 3–5 simple arithmetic operations (−7 to +7) appeared in each square, one at a time. Subjects were required to remember the initial digit in the square, complete the arithmetic operations, and report back the final resulting value. The second was a sentence span test in which subjects were presented with an alternating sequence of simple sentences (3–6 words in length) and single letters on the computer screen. Subjects judged whether each sentence was true or false and after four to eight sentence/letter presentations, subjects recalled the letters in the order they were presented. Finally, in the spatial short-term memory tests, subjects were asked to recall the location of dots (filled circles) in a 10×10 grid. A sequence of two to six dots, each displayed on the screen for 1 s and then removed before the next dot was displayed, were presented on each trial and subjects indicated the relative position of the dots by touching (or pointing and clicking with a computer mouse) the cells within the grid. For each of these tests, the percent correct scores were computed.

Results

Differences between Young and Older Adults

Data from all conditions from the seven psychoacoustic tasks are plotted in Figure 2, with data from young and older listeners plotted using black and gray filled bars, respectively.

Figure 2 illustrates group effects that appeared to be consistent across conditions within each psychoacoustic task. For example, for broadband modulation detection, thresholds for older listeners were lower than for the young listeners. The opposite tended to be true for MLD, where thresholds were higher for the older listeners than the young. With this in mind, before we analyzed the data statistically, we sought to determine whether it was possible to reduce the number of dependent variables available. Initially, as noted, there were performance measures available for a total of 24 conditions, many of which were different stimulus configurations for the same psychoacoustic task. For example, for modulation-detection interference (MDI), there were six stimulus conditions representing two different modulation conditions and three different modulation frequencies. This analysis addressed whether all six were needed or whether the number of MDI measures could be reduced based on correlations across the six conditions.

To explore this, performance for the set of multiple stimulus conditions for a given psychoacoustic task were subjected to principal components analysis (PCA); Gorsuch, 1988) using an extraction criterion of eigenvalue >1 and oblique rotation (Promax, $k = 4$) which would allow for correlation among the components identified for a given phenomenon. We used PCA for data reduction (SPSS v27, Dimension Reduction/Factor module), rather than just averaging across all conditions, because we were uncertain which conditions for a given task would be appropriate to average. In addition, because the PCA is based on correlations, we felt it would better preserve individual differences over averaging. Oblique rotation was also used because we were again uncertain how subsets of task conditions might be related and we did not want to assume that they were independent. As will be seen below, the choice of rotation, oblique or orthogonal, did not matter for 6 of the 7 psychoacoutic phenomena as only one component emerged.

Missing data were replaced by mean values for these analyses. Typically, missing values were scattered and accounted for 4–9% of the data for a particular measure, except for the masking-level difference measures for which 14.8% of the data were missing. The percentage of missing data is greater for these measures because we required the interaural difference in hearing thresholds at both test frequencies (250, 500 Hz) to be less than 10 dB. A single PC for each psychoacoustic ability under study emerged for 6 of the 7 cases with Kaiser-Meyer-Olkin (KMO) sampling adequacy ranging from 0.5 to 0.78, the percentage variance explained from 72.5 to 94.6%, and the communalities all >0.52 (except for 3 of the 24 measures, communalities were >0.70). In other words, for 6 of the 7 psychoacoustic tasks, a single component represented performance across the multiple stimulus conditions well. The 6 MDI measures required two PC for a good fit (one for MDI-unmod and one for MDI-mod) and the correlation between these two MDI components was $r = 0.37$. For the lone psychoacoustic measure with a relatively high percentage of missing data (masking-level difference, 14.8%), as noted above, the PCA and subsequent mixed-model analysis of variance (ANOVA), described below, were run with mean replacement and with deletion of subjects with missing data with no change in the results of the analyses.

An identical PCA was applied to the three measures of working-memory obtained from all participants. Here too a single component provided an excellent description of

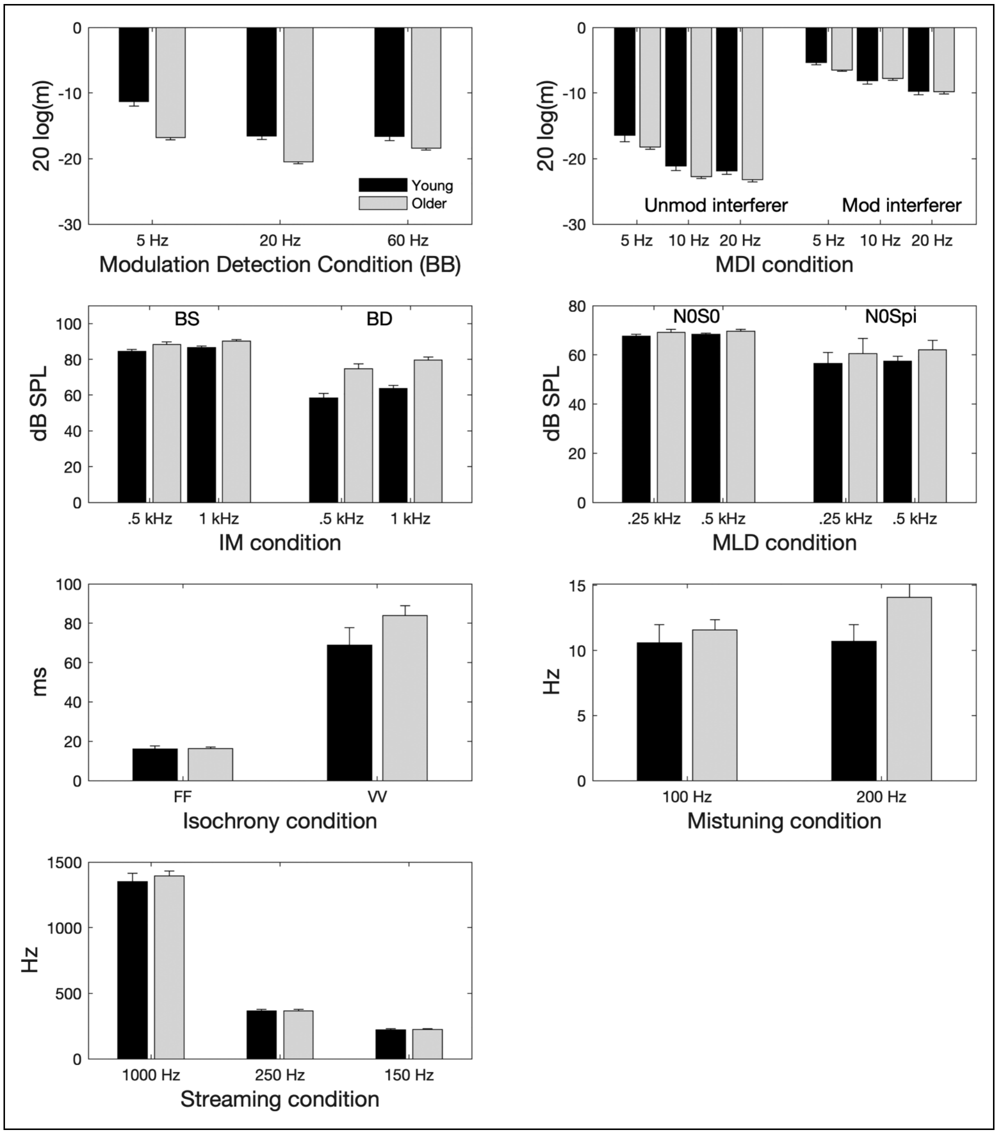

Figure 2. Average thresholds for the younger and older listeners are shown for 7 different psychoacoustic tasks. Error bars represent the standard errors of the mean.

performance on the set of working-memory measures (KMO = 0.66, % variance explained = 73.6%, communalities >0.64).

The two groups of adults included in this study differed significantly in PTA4 for the test ear (M young = 7.4 dB HL, SD = 3.1 dB; M older = 26.7 dB HL, SD = 6.2 dB) and on the working-memory PC [PCwm; M young = 1.13, SD = 0.45; M older = −0.32, SD = 0.87; $t(153) = -9.3$, $p < .001$]. Moreover, age was strongly and significantly ($p < .001$) correlated with PTA4 ($r = 0.70$) and PCwm ($r = -0.65$). As a result, after examining the effects of age group using the ANOVA for the psychoacoustic measures below, further analyses were conducted to assess the roles of hearing loss and WM on performance. The GLM-univariate ANOVA module of SPSS v27 was used for these analyses. With the inclusion of WM and hearing loss as covariates in these analyses this became an analysis of covariance (ANCOVA).

The top panel of Figure 3 plots the mean PC scores from the PCA for older (gray bars) and younger (black bars) listeners for each psychoacoustic task. Note that higher PC scores are associated with higher scores (thresholds) on the psychoacoustic tasks (poorer performance). Significant effects of age group (unadjusted $p < .05$) from the ANOVA are indicated with asterisks. We considered each of the eight dependent measures in Figure 3 to be an independent psychoacoustic phenomenon and did not correct the significance level for multiple dependent measures. The performance of older listeners differed from that of younger listeners on a variety of tasks: MDI unmod, MLD, IM, and

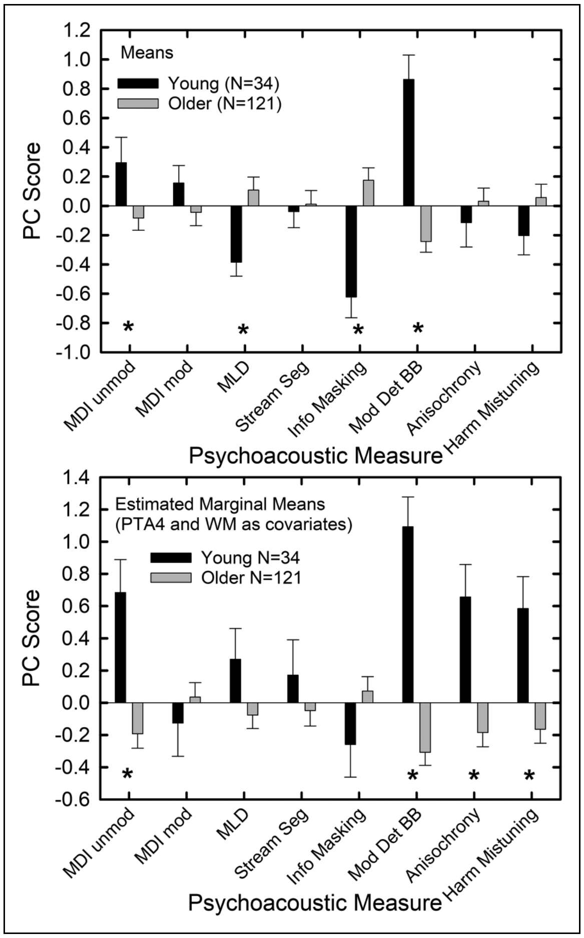

Figure 3. Principal component (PC) scores for younger and older listeners on the PC analyses for 8 psychoacoustic tasks. Average PCA values are plotted for young and older listeners as black and gray bars, respectively, with standard errors indicated. The top panel plots mean PC scores for the two groups, whereas the bottom panel plots estimated marginal means from a GLM treating PTA4 and WM as covariates. Significant effects at the $p <$ 0.05 level are indicated with asterisks.

broadband modulation detection. For the two temporal-processing tasks (MDI unmod and broadband modulation detection), the older listeners had lower scores than the younger listeners, consistent with better performance in those two tasks. For MLD and IM tasks, the older listeners had higher (poorer) scores than the younger listeners. These trends are also evident in the data in Figure 2.

The bottom panel of Figure 3 shows results from a similar analysis but, in this case, estimated marginal means from an ANCOVA treating PTA4 and PCwm as covariates. Significant differences between the groups remained for MDI unmod and broadband modulation detection. The adjusted means for MLD and IM were not significantly different between the two groups, but two additional tasks were now associated with significant differences between the groups—anisochrony and harmonic mistuning. For both anisochrony and harmonic mistuning, the estimated marginal means were better for the older listeners than the younger listeners. Thus, all four significant differences in performance between groups in the lower panel of Figure 3 indicate lower adjusted means for the older listeners than the younger listeners when controlling for cognition and hearing loss. For all four significant group differences, the partial Eta-squared effect size was either large ($\eta_p^2 = .21$; broadband modulation detection) or medium ($\eta_p^2 = 0.06$, 0.08, and 0.08, for harmonic mistuning, anisochrony, and MDI unmod, respectively).

We acknowledge that the difference in the group sizes and the collinearity between WM, PTA4, and age can complicate the interpretation of the results of the ANOVA and ANCOVA presented here. We evaluated the heterogeneity of variance assumption using Levene's test for Equality of Variances. This analysis indicated significant differences in variance for MDI-Mod and broadband modulation detection only ($p = 0.043$ and $p = 0.047$, respectively). We then tested for significant differences between the groups for these two tasks (t-tests) under an unequal-variance assumption. As in the original ANOVA and ANCOVA, no significant difference between groups was observed for the MDI-mod task ($p = 0.19$), but a significant difference between the groups for broadband modulation detection was evident ($p <$ 0.001). As such, our interpretation of the results from the ANOVA and ANCOVA remains

Next, because of the collinearity among the independent variables, we took another statistical approach to examine the roles of WM, age, and hearing loss on psychoacoustic performance. Here, rather than use age as a between-group factor, age was included, along with WM and hearing loss, in a series of linear-regression analyses for the entire sample of 155 adults. A potential advantage of this approach to the analyses was that the partial and part (or semi-partial) correlations could be generated and would help evaluate collinearity among the independent variables. The partial correlation examines the association between an independent variable and a dependent variable after controlling for the influence of other variables on both the independent and dependent variable. The part or semi-partial correlation examines the association between the independent and dependent variable after controlling for the effects of the other variables on just the independent variable. For example, for a psychoacoustic measure, such as the MLD, examining the partial and part correlations for age when WM and hearing loss have also been included as predictors will isolate the contributions of age to the MLD independent of WM and hearing loss.

Table 1 reports a summary of the linear-regression analyses for each of the 8 psychoacoustic phenomena. All analyses except that for stream segregation yielded significant linear-regression solutions. The standardized Beta coefficients and the significance of these coefficients (t, p values) are provided in three of the columns in Table 1. The three far-right

Table 1. Results of the Linear-Regression Analyses for Each Dependent-variable Principal-Component Score for the 155 Young and Older Adults.

Dep Var	F (3,151)	Ind Var	Std Beta	t	*p*	*r*	Partial *r*	Part *r*
MDI-unmod	8.22*	**PC WM**	**−0.447**	**−4.485**	**<.001**	**−0.156**	**−0.343**	**−0.338**
		zAge	**−0.468**	**−3.828**	**<.001**	**−0.156**	**−0.297**	**−0.289**
		zPTA4	0.029	0.269	.789	−0.082	0.022	0.020
MDI-mod	7.24*	PC WM	−0.191	−1.902	.059	−0.014	−0.153	−0.145
		zAge	0.050	0.404	.687	−0.127	0.033	0.031
		zPTA4	**−0.430**	**−4.013**	**<.001**	**−0.301**	**−0.310**	**−0.305**
MLD	11.23*	**PC WM**	**−0.279**	**−2.872**	**.005**	**−0.366**	**−0.228**	**−0.211**
		zAge	−0.081	−0.680	.497	0.302	−0.055	−0.050
		zPTA4	**0.286**	**2.765**	**.006**	**0.366**	**0.220**	**0.203**
Stream Seg	1.37	PC WM	−0.099	−0.937	.350	−0.064	−0.076	−0.075
		zAge	−0.201	−1.544	.125	0.002	−0.125	−0.124
		zPTA4	0.197	1.742	.084	0.104	0.140	0.140
IM	11.42*	**PC WM**	**−0.304**	**−3.126**	**.002**	**−0.411**	**−0.247**	**−0.230**
		zAge	0.181	1.522	.130	0.363	0.123	0.112
		zPTA4	−0.023	−0.220	.826	0.253	−0.018	−0.016
Mod Det BB	17.80*	**PC WM**	**−0.346**	**−3.739**	**<.001**	**0.089**	**−0.291**	**−0.262**
		zAge	**−0.617**	**−5.446**	**<.001**	**−0.438**	**−0.405**	**−0.381**
		zPTA4	−0.066	−0.669	.505	−0.331	−0.054	−0.047
Anisochrony	11.39*	**PC WM**	**−0.487**	**−5.009**	**<.001**	**−0.374**	**−0.377**	**−0.368**
		zAge	**−0.335**	**−2.810**	**.006**	**0.136**	**−0.223**	**−0.206**
		zPTA4	**0.217**	**2.100**	**.037**	**0.220**	**0.168**	**0.154**
Harm mistuning	10.60*	**PC WM**	**−0.343**	**−3.507**	**<.001**	**−0.345**	**−0.274**	**−0.259**
		zAge	**−0.244**	**−2.039**	**.043**	**0.211**	**−0.164**	**−0.151**
		zPTA4	**0.330**	**3.170**	**.002**	**0.326**	**0.250**	**0.234**

Bold font highlights those independent variables having significant ($p < .05$) standardized Beta coefficients in significant regression solution. Asterisks mark significant F values, $p < .01$, for the regression solution.

columns of Table 1 provide the zero-order, partial, and part correlations from each linear-regression analysis and for the entire sample of N = 155. The three independent variables entered in each regression analysis were the PCwm, z-transformed age, and z-transformed PTA4. The results here suggest a relatively complex influence of WM, age, and hearing loss for 7 of the 8 psychoacoustic abilities. Notice that age was a significant predictor in 4 of the 8 linear-regression analyses: MDI-unmod, broadband modulation detection, anischrony, and harmonic mistuning. In all of these cases, the part and partial correlations were negative indicating that increasing age was associated with lower (better) scores. Further, in these cases, WM alone (MDI-unmod, broadband modulation detection) or WM and hearing loss (anisochrony, harmonic mistuning) were significant predictors. The partial and part correlations for WM and hearing loss were of comparable magnitude to those for age in each case. All told, the picture that emerges from the review of the linear-regression analyses in Table 1 is entirely consistent with the group data in the bottom panel of Figure 3. Age significantly impacted performance on the same four tasks in both approaches to analysis and this was true even when controlling for working-memory and hearing loss. The direction of the effect, as shown in the bottom panel of Figure 3 and revealed by the negative partial and part correlations for age in Table 1, is the same: when controlling for WM and hearing loss, scores were better for older adults than the young adults.

Of the three remaining significant linear-regression solutions in Table 1 without a significant age effect, WM (IM), hearing loss (MDI-modulated), or both (MLD) were found to be significant predictors and the correlations support the independence of the observed effects. In summary, of the 7 significant linear-regression solutions in Table 1 (all but stream segregation), 6 found WM to make significant contributions, 4 found hearing loss to make significant contributions, and 4 found age to make significant contributions to psychoacoustic performance. Collectively, differences in performance between the two groups, nominally attributed to differences in chronological age, are due largely to age-related differences in hearing loss and cognition.

The ANCOVA and linear-regression analyses support the conclusion that age-group differences in performance on a number of psychoacoustic tasks are driven by more than the differences in chronological age. Underlying differences in WM and hearing loss may be important contributors to "age-group differences" reported for many psychoacoustic phenomena in the literature.

As a third approach to establishing the relative roles of age, hearing loss, and WM on these psychoacoustic performance, we conducted a relative weight analysis (RWA using the RWA-Web; Tonidandel & LeBreton, 2015) of the predictors (see also Johnson & LeBreton, 2004) for each PC. RWA is designed to establish the relative importance of predictors when some or all of the predictors are correlated. In RWA, the weights for each predictor sum to 100%. The statistical significance of each predictor, as well as the total variance explained (r^2) by the set of predictors, are also key parts of RWA. The significance of the predictors was based on bootstrapping with 10,000 iterations and $p < .05$. The results of the RWA are provided in Table 2. As can be seen by the entries marked with asterisks in that table, WM, age, and hearing loss were significant predictors for 7 of the 8 psychoacoustic measures with stream segregation being the lone measure without any significant predictors. For 5 of the 7 psychoacoustic measures with significant predictors, more than one predictor was significant. This supports the important role played by all three predictors, WM, age, and hearing loss, when accounting for individual differences in psychoacoustic performance for the 155 adults in this study. The relative weights in bold font in Table 2 show the predictor with the highest relative importance for each of the 7 psychoacoustic measures with significant predictors. The predominant predictor was WM for 5 of the 7 psychoacoustic measures with age or hearing loss being predominant of the other 2 psychoacoustic measures with significant predictors. In at least one case (MLD), the relative importance of WM (42%) barely exceed that of hearing loss (41%). The results of the RWA again support the conclusion that chronological age alone does not drive the observed differences in psychoacoustic performance on many psychoacoustic tasks.

Table 2. Results of Relative Weight Analyses for Each Psychoacoustic Principal Component Based on the Data from 155 Young and Older Adults.

Psychoacoustic measure	r^2	Working memory (%)	Age (%)	Hearing loss (%)
MDI unmodulated	0.14	**49***	42*	9
MDI modulated	0.13	11	14	**75***
MLD	0.18	**42***	17*	41*
Stream segregation	0.03	19	26	55
Informational masking	0.18	**55***	33*	12
Modulation detection	0.26	13*	**63***	24*
Anisochrony	0.18	**70***	12	18
Harmonic mistuning	0.17	**48***	11	41*

Bold font is used to show the predictor that had the highest relative weight for each dependent measure. Those marked with an asterisk were found to be significant predictors in the relative-weight analyses.

Individual Differences among the Older Adults

In addition to examination of age-group differences across a wide range of psychoacoustic measures, we were also interested in what factors were important contributors to the individual differences in psychoacoustic performance *among the older adults*. Recall that the 121 older adults in this report ranged in age from 60 to 88 years, a range that should be sufficient to examine the impact of aging on each psychoacoustic phenomenon *among older adults*.

Prior to performing these regression analyses, the thresholds for the entire set of 24 psychoacoustic measures was again subjected to PCA for data reduction for the older adults only. Here, a single analysis was performed for all 24 measures as the subject-to-variables ratio was more likely to be adequate given the larger sample of older adults. Using the same analysis parameters described previously for the entire dataset, six oblique PC emerged and accounted for 74.0% of the variance (KMO = 0.78). The communalities were all $\geq$ 0.55 except for the anisochrony VV measure which was 0.36. This measure was dropped and the PCA repeated, this time accounting for 75.9% of the variance, KMO = .78, and all communalities exceeded 0.54. The six principal-components were then saved as PC scores for the 121 older adults. Based on the pattern matrix of PC loadings, the six components were easily interpreted as: (1) IM; (2) masking-level differences; (3) stream segregation; (4) modulation detection-broadband; (5) MDI (for both the modulated and unmodulated conditions); and (6) harmonic mistuning. The lone anisochrony measure, FF, loaded moderately (weight = .53) and most strongly on the same component as harmonic mistuning. The pattern matrix of PC loadings from the final PCA is included in the Appendix as Table A1.

When oblique rotation is used in PCA, if multiple correlated components emerge, one can perform a second higher-order PC analysis of those correlated PC scores (c.f. Gorsuch, 1983; Humes et al., 2013; Schmid & Leiman, 1957). This may often be done iteratively until a single higher-order components emerges or those that emerge are no longer correlated. In these analyses, the six oblique components that emerged resulted in a total of 15 inter-component correlations and 6 of the 15 exceeded r values of 0.3 ($r = 0.34$, 0.39, 0.47, 0.47, 0.55, 0.59). As a result, a second-order PCA was performed on the six PC scores from the first-order analysis. Oblique rotation was used initially in case more than one higher-order component emerged. Two components emerged, but the inter- component correlation was just $r =$ .14. As a result, orthogonal rotation was used in the final higher-order PCA.

A good fit was obtained in the second-order PCA with 60.5% of the variance explained by the two orthogonal components, all communalities >0.48, and KMO sampling adequacy statistic = 0.73. Figure 4 provides a schematic illustration of the resulting two-level component structure with the component weights indicated adjacent to each arrow. For the first-order oblique solution, the weights shown are from the pattern matrix of PC loadings. Overall, the second-order analysis shows one component associated with the IM and stream-segregation PC scores and a second independent component associated with the remaining four PC scores (MLD, modulation detection, MDI, and harmonic mistuning).

The results of eight linear-regression analyses for the 121 older adults are summarized in Table 3. As in Table 1, Table 3 also includes the correlations, partial correlations and part correlations to assist in determining the relative independence of each predictor's contributions to the significant regression solution. For 6 of the 8 dependent measures in Table 3, significant regression solutions were obtained. The entries in Table 3 in bold font highlight the significant predictors for each of the six measures with significant regression solutions. Importantly, chronological age was not a significant predictor of psychoacoustic performance among this group of 121 older adults. On the other hand, WM was a significant predictor in 5 of 6 cases and hearing loss in 3 of the 6, with both WM and hearing loss identified as significant predictors in 2 of the 6 cases. The corresponding partial and part correlations support the interpretation of the relative independence of these significant effects from chronological age.

As for the full group of 155 adults, we also conducted relative weight analyses for this subset of 121 older adults alone. Results from the RWA for these 121 older adults are reported in Table 4. Significant predictors were identified

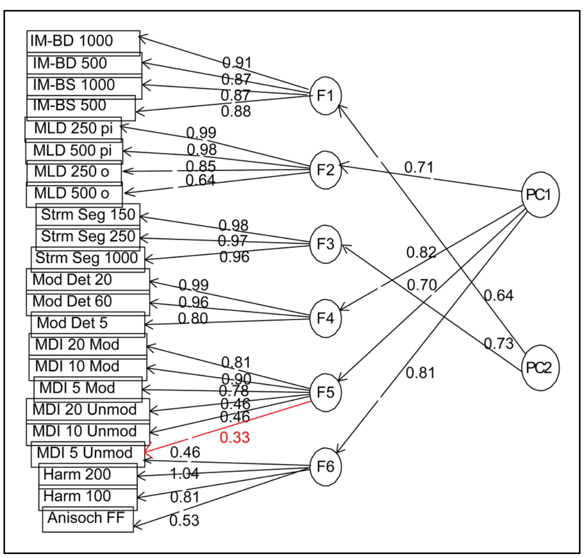

Figure 4. Schematic illustration of the results of the two-stage principal-component analyses for the data from the 121 older adults in this study. The numerical values adjacent to each arrow represent the component weights showing the loading of each measure on a given component. For the first stage of the analyses, oblique rotation was used and the numerical values were drawn from the pattern matrix of PC loadings for that solution.

for 5 of the 8 psychoacoustic measures in Table 4: MLD, broadband modulation detection, harmonic mistuning, and PC1 and PC2 of the second-order PCA. WM was the predominant component in the MLD (43%), broadband modulation detection (86%), harmonic mistuning (58%), and PC1 (89%). On the other hand, the relative weight for hearing loss (PTA4) was signifcant for the MLD (28%) and PC2 (62%). Chronological age was only a significant predictor for the MLD (29%).

In summary, performance of the older adults on several psychoacoustic tasks was influenced significantly by the cognitive status and degree of hearing loss for the older adults. Chronological age, per se, was seldom found to be a significant predictor of psychoacoustic performance among these 121 older adults.

Discussion

Performance on psychoacoustic tasks was influenced to varying degrees by aging, hearing loss, and cognitive status. Thus, there are a variety of means by which an older listener may experience difficulty with auditory perception. Each of these factors is discussed in turn.

Age-Group Effects

Once cognitive factors and hearing loss were taken into consideration, older listeners had significantly better PC scores than younger listeners for four of the seven psychoacoustic tasks: broadband modulation detection, MDI unmodulated, anisochrony and harmonic mistuning. Even so, for the two modulation-detection tasks, older listeners performed better than the young listeners before accounting for hearing loss and WM abilities. It is worth mentioning that while these performance differences were not apparent between groups for anisochrony and harmonic mistuning prior to that analysis, age positively impacted scores when controlling for WM and hearing loss in the regression analysis for these two psychoacoustic measures.

These tasks all involved the ability to follow temporal changes within a stimulus. Broadband modulation detection and MDI unmod were tasks in which good performance required the ability to detect the presence of AM, and the anisochrony task could only be accomplished by representing the temporal pattern in the stimulus. While harmonic mistuning could, in principle, have been accomplished using a spectral cue, the temporal cue is also very salient (e.g., Hartmann et al., 1990).

Although our data indicate better scores for older than younger listeners, age-related declines in temporal processing abilities, which are sometimes considered to be a consequence of changes to the neural representation of temporal cues, are more commonly observed in the literature (see Gordon-Salant & Fitzgibbons, 1999; Gordon-Salant et al., 2020 for reviews). Physiological data also have supported

Table 3. Results of the Linear-Regression Analyses for Each Dependent-variable Principal-Component Score for the 121 Older Adults.

Dep Var	F (3,120)	Ind Var	Std Beta	t	*p*	*r*	Partial *r*	Part *r*
IM	2.51	PC WM	−0.210	−2.190	.030	−0.234	−0.198	−0.196
		zAge	0.092	0.832	.407	0.145	0.077	0.075
		zPTA4	−0.039	−0.369	.713	0.052	−0.034	−0.033
MLD	8.62*	**PC WM**	**−0.246**	**−2.750**	**.007**	**−0.332**	**−0.246**	**−0.230**
		zAge	0.145	1.411	.161	0.323	0.129	0.118
		zPTA4	0.174	1.775	.079	0.300	0.162	0.148
Stream Seg	2.35	PC WM	−0.126	−1.308	.194	−0.090	−0.120	−0.117
		zAge	−0.230	−2.086	.039	−0.067	−0.189	−0.187
		zPTA4	0.228	2.158	.033	0.132	0.196	0.194
Mod Det	6.00*	**PC WM**	**−0.352**	**−3.825**	**<.001**	**−0.343**	**−0.333**	**−0.329**
		zAge	0.058	0.549	.584	0.107	0.051	0.047
		zPTA4	−0.145	−1.431	.155	−0.043	−0.131	−0.123
MDI	5.78*	**PC WM**	**−0.267**	**−2.898**	**.004**	**−0.168**	**−0.259**	**−0.250**
		zAge	−0.153	−1.440	.152	−0.177	−0.132	−0.124
		zPTA4	**−0.226**	**−2.236**	**.027**	**−0.252**	**−0.202**	**−0.193**
HARM anisoch	9.72*	**PC WM**	**−0.324**	**−3.658**	**<.001**	**−0.385**	**−0.320**	**−0.303**
		zAge	0.061	0.605	.547	0.279	0.056	0.050
		zPTA4	**0.197**	**2.024**	**.045**	**0.294**	**0.184**	**0.167**
PC1	7.12*	**PC WM**	**−0.375**	**−4.130**	**<.001**	**−0.389**	**−0.357**	**−0.351**
		zAge	0.065	0.618	.538	0.173	0.057	0.053
		zPTA4	−0.046	−0.459	.647	0.064	−0.042	−0.039
PC2	5.12**	PC WM	−0.160	−1.727	.087	−0.211	−0.158	−0.150
		zAge	−0.018	−0.165	.869	0.186	−0.015	−0.014
		zPTA4	**0.281**	**2.753**	**.007**	**0.304**	**0.247**	**0.239**

Bold font highlights those independent variables having significant ($p < .05$) standardized Beta coefficients for those psychoacoustic measures with significant regression solutions (*$p < .001$; **$p < .01$).

this interpretation, particularly those data based on the Frequency Following Response (FFR), with studies generally demonstrating widespread deficits in the way temporal envelope is represented in the auditory system of older listeners (e.g., Clinard & Tremblay, 2013; Roque et al., 2019).

Table 4. Results of Relative Weight Analyses for Each Lower-Order and Higher-Order Principal Component Based on the Data from 121 Older Adults.

Psychoacoustic measure	r^2	Working Memory (%)	Age (%)	Hearing Loss (%)
Informational masking	0.06	**77**	21	2
Masking level difference	0.18	**43***	29*	28*
Stream segregation	0.06	19	33	**48**
Modulation detection BB	0.13	**86***	7	7
Modulation detection interference	0.13	36	22	**42**
Harmonic mistuning	0.20	**58***	16	26
Higher-order PC1	0.15	**89***	10	1
Higher-order PC2	0.12	27	11	**62***

Bold font is used to show the predictor that had the highest relative weight for each dependent measure. Those marked with an asterisk were found to be significant predictors in the relative-weight analyses.

In an attempt to interpret this result, we first considered whether thresholds for these tasks were similar to those reported previously for the young listeners. Perhaps the older adults performed better because our sample of young adults performed worse than expected on these psychoacoustic tasks. In some cases, the younger listeners did in fact perform more poorly than expected. For broadband AM detection, Takahashi and Bacon (1992) reported thresholds for similar conditions around −24 dB (see also Viemeister, 1979), considerably better than the thresholds of roughly −16 dB reported here. Similarly, for the MDI unmod conditions, Bacon and Opie (2002), who used somewhat different carrier frequencies (984 and 3,952 Hz), found better thresholds (better than −17 dB for 8 of 9 young, normal-hearing subjects) than those reported here (∼−16.5 dB). As such, we cannot rule out poor performance of the young listeners as drivers of this finding for AM detection.

Importantly, however, previous work on AM detection is somewhat equivocal on whether older listeners demonstrate declines in temporal processing. For broadband AM detection, Takahashi and Bacon (1992) measured Temporal Modulation Transfer Functions (TMTFs) at 35 dB SPL spectrum level and found that older listeners with hearing loss performed more poorly than younger listeners with better hearing at a variety of modulation rates. In contrast, Schoof and Rosen (2014) also measured TMTFs using band-limited noise carriers presented at 70 dB SPL in older and younger listeners with relatively normal hearing, but they did not observe group differences in performance. Recent studies testing AM detection abilities using pure-tone carriers (usually 500 Hz) have selected older listeners with good hearing and used relatively low AM rates. Many have illustrated no group differences when AM detection was measured at 40 dB SL (equivalent to roughly 55–60 dB SPL for the groups with normal hearing) and a 5-Hz modulation rate (Paraouty et al., 2016), 60 dB SPL and 1 and 20- Hz modulation rates (Whiteford et al., 2017), and 75 dB SPL at a 5-Hz modulation rate (He et al., 2008). On the other hand, Wallaert et al. (2016) tested subjects at 40 dB SL with 2- and 20- Hz modulation rates but found that older listeners performed more poorly than younger listeners. A similar result was obtained by He et al. (2008) for two higher modulation rates (40 and 80 Hz).

When better performance of the older listeners on modulation detection tasks was observed, is has sometimes been attributed to cochlear damage (e.g., Wallaert et al., 2017). The argument is that loss of the cochlear nonlinearity leads to an enhanced representation of the stimulus envelope at the cochlear level. That said, we specifically selected a high stimulus level (85 dB SPL) to ensure audibility and to diminish the effects that recruitment due to hearing loss could have on the representation of the envelope. Our observation of better scores of the older group also stands even when hearing loss was a covariate in our analyses.

Overall, this data set does not provide convincing evidence for age-related declines in auditory temporal processing, but we also do not conclude that increased age is associated with better temporal processing for many of these tasks, particularly as it seems possible that the young listeners performed more poorly than in previous studies. Nevertheless, there is physiological evidence that compensatory mechanisms at the midbrain and auditory cortex might enhance the neural representation of the temporal envelope (c.f., Parthasarathy et al., 2019). The end result on behavior may therefore be relatively variable across individuals, as the degree of compensation could be modulated by individual factors, including degree of hearing loss (Cardin, 2016) and cognitive ability (Peelle & Wingfield, 2016).

Importantly, recent discussions in the literature have suggested that the FFR (a common tool to measure the encoding or temporal cues in humans) may not exclusively reflect brainstem activity (Coffey et al., 2017) and that it may be influenced by cognitive factors (Bidelman et al., 2017). Thus, as with psychophysical measurements, physiological measurements supporting age-related temporal processing declines in older listeners could be influenced by cognitive changes. As will be discussed in a later section, the impact of cognitive declines on temporal processing measures is not negligible and should be considered as a factor in future studies.

In contrast to the results on the temporal processing tasks, group effects were generally absent for the other tasks tested. To date, relatively few studies have evaluated the effects of aging on IM, with existing work examining IM within a speech context. These studies have supported an interpretation that aging negatively impacts IM release (Helfer & Freyman, 2008; Li et al., 2004). The only study we have found evaluating IM in older listeners using a similar paradigm is a dissertation by Poling (2009). Poling tested six older subjects (56–66 yo) and six younger subjects with a very similar procedure to that used here (BS/BD paradigm of Kidd et al., 1994). Poling noted that older listeners demonstrated a smaller difference in threshold between BD and BS conditions, consistent with our initial results that IM performance was poorer for older listeners when PTA4 and WM were not accounted for. We took a closer look at the data gathered here and conducted a repeated-measures ANCOVA treating group as a between-subject variable, BS/BD and frequency as within subjects' variables, but included PTA4 + PCwm as covariates. The main effect of age was not significant [$F(1,140) = 2.4$; $p = 0.12$)], but the interaction between BS/BD and age was significant [$F(1,140) = 9.0$; $p = 0.003$)] with a small effect size ($\eta^2 = 0.06$). Generally, the older listeners had poorer performance than the younger listeners in the BD conditions compared to the BS conditions.

Modulation detection interference is another task that is commonly used to measure the ability of listeners to group sounds based on similar patterns (in this case, modulation rate). To date, no study has measured MDI in older subjects, other than Humes et al. (2013) on which these more detailed analyses are based. Our analyses at the group level indicated that performance in MDI unmod conditions was better for older listeners than younger listeners, but performance was not influenced by age for MDI mod conditions. As such, the MDI (typically defined as the difference in thresholds between MDI mod and unmod conditions) was greater for the older listeners compared to the younger listeners. The larger MDI suggests that the binding of modulation patterns across frequency may have been stronger in older listeners and that once the interferer was modulated, older listeners could no longer outperform the younger listeners. Note that these effects were not observable for the analyses of older group alone as all MDI tasks loaded on the same PC in those analyses.

It is worth noting that the PC scores did not differ between groups for the MLD, after covarying cognition and hearing loss, or for streaming when analyzed at the group level. There were age-group differences for the MLD measures in this study, with the young adults having better performance than older adults, when no covariates were included in the analyses. Many binaural detection experiments illustrate higher thresholds for older than younger listeners in the dichotic N_0S_π conditions (c.f. Anderson et al., 2018; Eddins et al., 2018; Pichora-Fuller & Schneider, 1991).

However, even when we conducted a mixed-measures ANCOVA, similar to that for the IM task, age and the interaction between age and diotic/dichotic masking were not significant. This finding is consistent with the literature in which not all studies report age-related differences, particularly for conditions with broadband maskers presented at relatively high stimulus levels, like those adopted here (e.g., Dubno et al., 2008). Importantly, when controlling for age and hearing loss between the two age groups using ANCOVA and regression analyses, the difference between groups for the MLD task disappeared.

Streaming has yet to be widely tested in the aging population, but Alain et al. (1996) used similar methods to those used here. Their study concluded that while there were no differences in the parameters facilitating one or two streams in older listeners, older listeners may have experienced greater cognitive load or less reliability in accomplishing the task. These data also support a generally weak or nonexistent connection between age and auditory streaming ability. None of the analyses presented here indicate an effect of age on streaming ability.

Effects of Hearing Loss

Although the conditions tested in this study were designed to limit the effects of hearing loss (e.g., the signal frequencies tested were relatively low and levels relatively high), some of the psychoacoustic abilities were influenced by the presence of hearing loss. The group analysis indicated poorer thresholds associated with hearing loss for MLD, anisochrony, and harmonic mistuning but better thresholds for the MDI mod tasks. The analysis for the older listeners indicated effects of hearing loss for two PC: the MDI component and the harmonic mistuning/anisochrony component (Harm/anisoch), with hearing loss leading to better scores for MDI and poorer for the Harm/anisoch component. The effect of hearing loss on the MLD and pitch perception has been well-established, although we do note that the effect of hearing loss on harmonic mistuning has not been specifically addressed previously. Here we focus on a new finding: that hearing loss predicted performance in the MDI task.

For the MDI tasks, greater hearing loss was associated with better (lower) MDI thresholds in the MDI mod conditions when the full group data were analyzed. In this case, greater hearing loss would lead to a smaller MDI (i.e., because thresholds did not predict MDI unmod thresholds). Previous work on MDI has demonstrated no effect of hearing loss on the size of the MDI. However, while these previous studies used similar conditions, they also used much smaller groups. For example, Bacon and Opie (2002) tested four listeners with bilateral SNHL and Grose et al. (1994) tested 11 listeners with hearing loss. Although the stimulus parameters were not identical between the current and previous studies, it is possible that the effects of hearing loss on the MDI are relatively small and sufficiently large sample sizes would be needed to reveal the effects of hearing loss on the MDI.

Regarding the group differences, deficits to the across-frequency mechanism that is engaged in MDI tasks may lead to a smaller MDI, as observed here. Healy and Bacon (2002) determined that listeners with hearing loss experienced difficulty comparing and processing temporal speech information at different frequencies (see also Healy et al., 2005). Applying this logic to the MDI-modulated conditions, deficits in across-frequency processing may lead to a weaker ability to group sounds based on similar modulation rates, thereby improving thresholds in the MDI-mod conditions.

Effects of Cognition

This study is the first to comprehensively evaluate the role that cognition (i.e., WM) has on auditory perception, across a range of psychoacoustic tasks. To date, very few psychoacoustic experiments have measured the contribution of cognitive abilities on perception, although the scientific community has discussed the role of cognitive decline on auditory perceptual deficits (e.g., CHABA, 1988). The finding that WM predicts performance on a wide range of psychoacoustic tasks is extremely important regarding the interpretation of previous psychophysical findings from older adults and regarding the design of future experiments. Of particular relevance are studies on older listeners who may pass a dementia screening, such as the MMSE, but still experience cognitive deficits when compared to younger listeners.

In particular, performance on many of the psychoacoustic factors within the older group was influenced by WM. In all of these cases where an influence of WM was observed, poorer WM was associated with poorer psychoacoustic performance. A subset of these tasks tapped into temporal processing, consistent with a growing body of work suggesting a connection between WM deficits and temporal processing declines (e.g., Füllgrabe et al., 2015; Roque et al., 2019), although a considerable amount of this work has been applied to subjects with normal hearing (Troche & Rammsayer, 2009) or dyslexia (e.g., Banai & Ahissar, 2004; Fostick & Revah, 2018). Generally speaking, these experiments have measured temporal processing using psychophysical timing tasks, such as duration discrimination or temporal order judgment. In the only study we are aware of that measured temporal acuity, Füllgrabe et al. (2015) reported a relationship between performance on a test of everyday attention and modulation detection thresholds. The test of everyday attention required subjects to visually search maps and telephone directories, and likely taps into similar abilities as the WM tests used here. The work presented here implicates WM in a broad range of temporal processing tasks.

Yet, other tasks were also influenced by WM, such as IM and MLD. Both of these tasks required a listener to detect a tone added to a background sound, with each requiring different auditory mechanisms. Attentional factors have been linked to IM tasks (e.g., Freyman et al., 2004). Attentional mechanisms, such as selective attention, and WM are believed to be interrelated and may share, in part, a common top-down neural mechanism (Gazzaley & Nobre, 2012). Although it is perhaps not surprising to see WM abilities influencing performance on these two tasks, the results here strongly implicate the need to measure factors such as WM in order to adequately interpret deficits in these abilities.

As a final thought, psychoacoustic tasks often require listeners to store auditory information in memory and make decisions about that information, an ability that relies on WM. In fact, six of the seven tasks used here applied a standard/2-interval, 2-alternative forced-choice (2I-2AFC) procedure that required the sensory representation of a stimulus, the ability to hold percepts in memory, and decision making based on those percepts. As such, there was a cognitive load associated with each of these psychoacoustic tasks. Interestingly, the factors dependent on WM did not include streaming, which made use of a completely different paradigm (the method of adjustment), one without the same memory requirements. One might speculate then that the cognitive load associated with the experimental procedures influenced the results. Relevant to this idea, Jäkel and Wichmann (2006) have argued that 2IFC tasks can be difficult for naïve listeners. Such may also be true for older listeners who have less cognitive flexibility than younger listeners, and the contribution of WM deficits might negatively influence the ability to interpret differences in performance between groups with different cognitive abilities. While it is premature to make robust conclusions based on the type of data presented in this paper, the implications of measurement techniques on interpretations of data should be considered.

It is also noteworthy that the associations in older adults between cognitive function and psychoacoustic performance on several tasks was based on cognitive measures that used visual stimuli. As a result, the association is not likely due to a shared impact of hearing loss on both the cognitive measures and the psychoacoustic tasks.

Although a key finding from the present study was that "age effects" on several psychoacoustic measures disappeared when controlling for hearing loss, cognition, or both, it should be emphasized that these analyses were focused on understanding the possible mechanisms underlying the oft-observed "age effects." That is, the raw data (Figure 2) and PC scores from those raw data (top panel of Figure 3), show that older adults may perform differently than young adults on psychoacoustic tasks. The other analyses presented here attempted to discern what it is in particular about aging that leads to these performance differences. The ANCOVA and regression analyses applied to threshold data and PC scores suggest that it is often the age-related changes in cognition that underlie the observed age-group differences. This conclusion is also supported by the relative-weight analyses (Tables 2 and 4). Although age can be a useful independent variable or predictor, it is just a stand-in for a large class of variables that change with age. In the present study, age-related changes in auditory perception were found to be largely due to hearing loss and a decline in cognitive function.

Summary and Conclusions

There are a number of major themes evident in this evaluation of the effects of age-related factors on auditory perception. The results here indicate that older listeners experience difficulty on a variety of psychoacoustic tasks, with most performance differences explained by hearing loss or deficits in WM. Generally, we observed that older listeners experienced a broad range of deficits in auditory perception, with many of those deficits related to declines in WM. Collectively, many older adults would be expected to experience auditory perceptual deficits compared to young adults in everyday listening conditions as a result of hearing loss, cognitive skills, and other factors that are associated with aging. We did not find broad support for age-related central auditory changes using a psychoacoustical approach.

This study makes clear the need for considering cognitive factors when measuring auditory perception in older listeners. When controlling for differences in the amount of hearing loss and cognitive function, scores for older adults were seldom poorer than those of the young adults. If the auditory measures examined here are considered to be measures of "higher level auditory processing", then age-related factors other than hearing loss and cognition do not appear to impact such processing. Rather, consistent with the review of Humes et al. (2012), differences observed between age groups on such tasks are often attributable to underlying differences in peripheral hearing loss, cognition, or both.

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Supplemental Material

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