Do 'Auditory Processing' Tests Measure Auditory Processing in the Elderly?

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Objective: **To examine the associations between measures of auditory processing and measures of auditory or cognitive function in elderly listeners with impaired hearing.**

Design: **Multiple measures of auditory processing, auditory function, and cognitive function were obtained and linear, multiple-regression analyses were conducted to examine the relations between these sets of variables. In particular, four measures of auditory processing were obtained from each of 213 elderly participants. Measures of auditory processing included duration discrimination for a 1000-Hz pure tone, temporal-order discrimination for mid-frequency pure tones, dichotic syllable identification, and recognition of 45% time-compressed monosyllables. Each participant also completed additional measures of auditory function, including pure-tone thresholds, auditory brain stem responses for each ear and at two presentation rates (11.1 and 71.1 clicks per second), and performance-intensity functions for monosyllabic words (PI-PB rollover). Finally, three measures of cognitive function, all from the Wechsler Adult Intelligence Scale-Revised, were obtained from the 213 participants.**

Results: **For three of the four measures of auditory processing examined in this study (duration discrimination, temporal-order discrimination, and dichotic CV identification), a measure of cognitive function (IQ) and age were the two primary predictors of individual differences in performance. For these three measures of auditory processing, 11 to 14% of the total variance could be accounted for by the predictor variables. For the remaining measure of auditory processing (recognition of time-compressed monosyllables), 56% of the total variance could be accounted for by a set of four predictor variables, but most of this variance (54% of the total variance) was associated with individual differences in hearing loss. When hearing loss was removed as a predictor for this measure of auditory processing, 14% of the total variance was explained by four variables: age, IQ, and two measures derived from auditory brain stem response wave-V latency.**

Conclusions: **Performance on the battery of auditory processing measures by elderly hearing-impaired listeners was systematically related to individual differences in cognitive function rather than auditory function, especially for stimuli not affected by peripheral hearing loss. However, much of the variance in auditory processing performance remained unaccounted for by any of the predictor variables examined in this study.**

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There are a variety of schema that can be used to conceptualize age-related changes in auditory perception, including speech understanding (e.g., Pichora-Fuller, 1997), but one that we have used previously (Humes, 1996) and is fairly commonplace, partitions the processing of auditory information into peripheral, central auditory, and cognitive components. This approach is largely based on underlying anatomy and physiology and was originally articulated in the context of age-related declines in speech understanding by a working group of the National Research Council's Committee on Hearing and Bioacoustics and Biomechanics (CHABA, 1988). Within this framework, there is a fair amount of overlap between the "central auditory" and "cognitive" components (Jerger et al., 1991).

Although some have suggested that there are modality-specific age-related declines in the processing of auditory information, including speech (e.g., Jerger, Chmiel, Allen, & Wilson, 1994; Jerger, Jerger, Oliver, & Pirozzolo, 1989; Stach et al., 1990), others have argued that these declines may represent more global amodal cognitive deficits (e.g., Hallgren, Larsby, Lyxell & Arlinger, 2001; Humes, 1996; Humes, Christopherson & Cokely, 1992; van Rooij & Plomp, 1990, 1992; van Rooij, Plomp & Orlebeke, 1989). Basically, the argument is that these general cognitive deficits manifest themselves as "auditory processing" deficits because audiologists and hearing scientists typically use sound as the stimulus on such tasks. Parallel testing in the visual modality, for example, would help to determine how much of the deficit is modality specific (Humes et al., 1992). The debate with regard to the existence of modality-specific auditory processing disorders versus general cognitive deficits is probably even more contentious when school-age children have been studied (e.g., Cacace & McFarland, 1995, 1998; Domitz & Schow, 2000; McFarland & Cacace, 1995, 2002; Schow, Seikel, Chermak, Berent & Domitz-Vieira, 2002).

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In addition to parallel testing in nonauditory modalities, another approach to disentangling modality-specific auditory processing deficits from more global cognitive declines is to examine correlations of “auditory processing” measures with other measures of auditory performance and cognitive function. Though cause and effect can never be discerned from correlational analyses, stronger correlations of “auditory processing” measures to general cognitive measures than to other measures of auditory performance would imply that there is more shared variance with cognitive function than modality-specific auditory function.

In this report, we present data from 213 elderly hearing-impaired listeners who had completed an extensive battery of auditory and cognitive measures as a part of a larger project focused on hearing-aid outcome measures (Humes, 2002, 2003; Humes, Garner, Wilson & Barlow, 2001). The measures of auditory processing were selected on the basis of prior work with two test batteries in our laboratory: the Test of Basic Auditory Capabilities (TBAC) (Christopherson & Humes, 1992; Humes, Watson, Christensen, Cokely, Halling & Lee, 1994; Watson, 1987) and the Veterans Administration’s compact disc (VACD) entitled, *Tonal and Speech Materials for Auditory Perceptual Assessment* (Humes, Coughlin & Talley, 1996; Noffsinger, Wilson & Musiek, 1994). Based on prior evaluations of reliability and underlying factor structure for each of these test batteries, six tests were selected for use in this study, three tests from each battery. However, the results from two of the six measures obtained in this study were ultimately discarded due primarily to floor (syllable-sequence task of the TBAC) and ceiling (pitch-pattern task of the VACD) effects in the data.

The remaining four measures of auditory processing included the duration-discrimination and tonal temporal-order-discrimination tasks of the TBAC and the dichotic consonant-vowel (CV) identification and 45%-time-compressed word-recognition tasks of the VACD. The duration-discrimination task of the TBAC makes use of a 1000-Hz tone. Performance on this task was found to be closely associated with an intensity-discrimination task for the same stimulus and both tasks could be interpreted as ones in which the listener makes use of differences in stimulus energy or the associated differences in perceived loudness (Humes et al., 1994). The tonal temporal-order discrimination task of the TBAC, on the other hand, was strongly associated with individual differences in the discrimination of differences in a single component of a 10-tone sequence, differences in the rhythm of a series of tone pulses, and differences in frequency for a 1000-Hz pure-tone standard. Thus, individual differences in the tonal temporal-order discrimination task were believed to be representative of individual differences on a variety of complex, timing-based tasks (Humes et al., 1994). For the two tasks from the VACD included in this study, one (dichotic CV identification with 90-msec lag between the ears) was representative of a larger set of dichotic measures, including those making use of either the same CV stimuli or digits with 0-msec interaural time lag, and the other (45% time-compressed word recognition) was representative of processing of degraded speech stimuli, including other rates of time compression (65%) and filtering (Humes et al., 1996). Thus, although just four measures of auditory processing were examined in this study, they were selected as tasks that were established previously to be representative of a broader set of tests associated with various auditory processing abilities in elderly hearing-impaired listeners. Further, three of the four behavioral tests of auditory processing recommended by the American Academy of Audiology (Jerger & Musiek, 2000) have been included in this study. It is noteworthy, however, that all four tests included in this study involve temporal aspects of auditory processing; an aspect of auditory processing that has received much attention in studies of elderly listeners in recent years (e.g., Gordon-Salant & Fitzgibbons, 1999, 2001; Schneider & Pichora-Fuller, 2001).

In addition to these measures of auditory processing, the following measures of auditory function were obtained. All participants completed an audiological evaluation that included pure-tone and speech audiometry, immittance measurements, and the measurement of auditory brain stem responses (ABRs) for typical (11.1 clicks per second) and accelerated (71.1 clicks per second) presentation rates, with the difference between the wave-V latencies at each rate providing a measure of neural adaptation [See Hall (1992), pp. 137–141, for review]. In addition, performance-intensity functions were measured in each ear using monosyllabic words (PI-PB functions), and a measure of PI-PB rollover was computed (Bess, Josey & Humes, 1979; Jerger & Jerger, 1971). All of these measures of auditory function were included to evaluate the integrity of the auditory neural pathways from the VIIIth nerve through the upper brain stem. In addition, given the focus on temporal aspects of auditory processing in the behavioral measures included in this study, a physiological measure sensitive to temporal processing, such as ABR adaptation, was included as another measure of auditory function.

Finally, all subjects completed the Wechsler Adult Intelligence Scale-Revised (WAIS-R) (Wechsler, 1981) as a general measure of cognitive function (verbal, nonverbal, and total IQ values). These measures tap a wide range of cognitive abilities, including several aspects of memory, knowledge, and reasoning.

With this extensive set of measures available from a large sample of elderly listeners evaluated under identical conditions, the basic approach was to examine associations between the measures of auditory processing (TBAC and VACD) and the measures of auditory and cognitive function using linear multiple regression analysis. Additional procedural details are provided in the next section.

METHOD

Participants

The participants in this study were recruited via newspaper ads, flyers posted in the community, printed announcements in church/synagogue bulletins, and word of mouth. All participants enrolled in the study met the following selection criteria: (1) age between 60 and 89 years; (2) hearing loss that was flat or gently sloping (from 250 to 4000 Hz, no interoctave change in hearing thresholds of more than 20 dB); (3) hearing loss that was of sensorineural origin (normal tympanometry and air-bone gaps no greater than 10 dB at three or more frequencies); (4) hearing loss that was bilaterally symmetrical (interaural difference within 30 dB at all octave and half-octave intervals from 250 to 4000 Hz); (5) pure-tone thresholds within the following ranges at frequencies of 250, 500, 1000, 1500, 2000, 3000, 4000, and 6000 Hz, respectively: 5 to 85, 5 to 85, 10 to 90, 20 to 95, 25 to 95, 30 to 120, 30 to 120, and 30 to 120 dB HL (ANSI, 1996); (6) no known medical or surgically treatable ear-related condition; (7) no known fluctuating or rapidly progressing hearing loss; (8) no cognitive, medical, or language-based conditions that may have limited the participant's ability to complete the procedures of this study; (9) no use of medications that could affect hearing or cognition; and (10) completion of a signed medical clearance form, or waiver of such by the participant, and a signed informed consent form.

After completion of a detailed case history, a comprehensive audiological evaluation was conducted for all participants in this study and comprised several of the measures of auditory function in this study. All audiologic measurements were obtained using ER-3A insert earphones, and all equipment was calibrated in accordance with ANSI S3.6–1996. This evaluation included: (1) air-conduction pure-tone audiometry at 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz, with additional threshold measurements at 750 and 1500 Hz, whenever thresholds at the adjacent octave test frequencies differed by 20 dB or more; (2) bone-conduction pure-tone audiometry at octave intervals from 250 to 6000 Hz; (3) immittance measurements, including tympanometry, acoustic reflex thresholds, and acoustic reflex decay; (4) speech-recognition threshold (SRT) for CID W-1 spondaic words presented via monitored live voice; (5) 50-item word-recognition scores (Auditec recordings of NU-6 materials; Tillman and Carhart, 1966) at either 40 dB SL or maximum audiometer output, whichever corresponded to a lower sound pressure level, in quiet and in white noise at a +12 dB signal-to-noise ratio; and (6) loudness discomfort level measurements using the scaling categories and instructions described by Hawkins, Walden, Montgomery and Prosek (1987), an ascending approach with 5-dB step size, and pure-tone frequencies of 500, 1000, 2000, 3000, and 4000 Hz.

The 213 elderly subjects ranged in age from 60 to 88 years (mean = 73.2 years; SD = 6.6 years), and 75 (35.2%) were female. A total of 73 individuals (34.3%) were hearing-aid users before enrolling in this study. Figure 1 presents the means and standard deviations for the air-conduction pure-tone thresholds (circles) and loudness discomfort levels (inverted triangles) for the right (top panel) and left (bottom panel) ears. For the air-conduction pure-tone thresholds, measures of average hearing loss were also calculated. These included the pure-tone average (PTA) based on thresholds at 500, 1000, and 2000 Hz and the high-frequency pure-tone average (HFPTA) based on thresholds at 1000, 2000, and 4000 Hz. Mean SRT values were 32.0 (SD = 12.4 dB) and 32.5 (SD = 12.7 dB) dB HL for the right and left ears, respectively. Mean word-recognition scores in quiet were 88% (SD = 14.2%) and 86% (SD = 14.4%) for the right and left ears, respectively, whereas they were 49% (SD = 20.9%) and 46% (SD = 21.2%) in white noise for the right and left ears, respectively.

Test Materials and Procedures

Additional Measures of Auditory Function • Tests included in this session were: (1) ABRs measured for each ear, using a Bio-Logic Model 54 system, for 2000 rarefaction click stimuli presented at a level of 90 dB nHL and at a rate of 11.1 clicks per second, with wave-V latency from two repeatable responses recorded; (2) same as the preceding ABR measurements, but for a stimulus presentation rate of 71.1 clicks per second; and (3) performance-intensity functions for each ear for NU-6 words with 25 monosyllabic words presented at several levels, beginning 40 dB above SRT and progressing, in 10 dB steps to a maximum of 100 dB HL, with the maximum score (PB-max) and

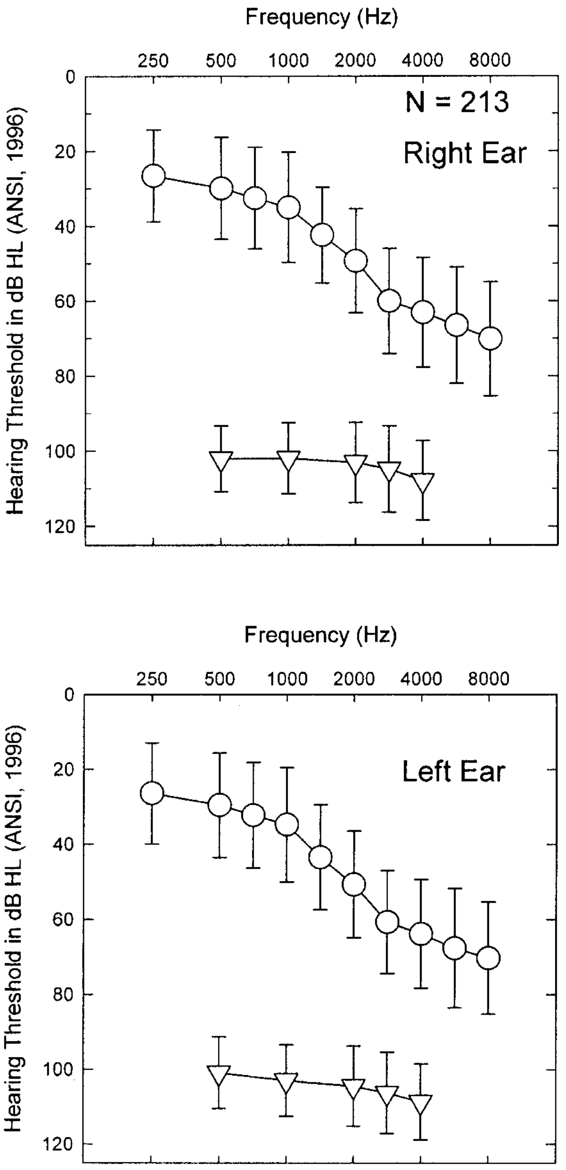

Fig. 1. Mean air conduction thresholds (circles) and loudness discomfort levels (inverted triangles) for the right ear (top) and left ear (bottom) of the 213 elderly hearing-impaired participants. Error bars represent ±1 standard deviation about the mean.

the score at the maximum possible presentation level (PB-maxHL) recorded. A measure of PI-PB rollover was calculated by subtracting PB-maxHL from PB-max and dividing it by the PB-max score (Bess et al., 1979; Jerger & Jerger, 1971).

Auditory Processing • Auditory processing capability at high sound levels represented another area assessed in each participant. As noted in the introduction, there were two primary tools used to assess auditory processing capabilities and in both cases the stimulus presentation level was 90 dB SPL. The first was the TBAC developed by Watson and et al. (Watson, 1987). This battery of auditory discrimination tests has been demonstrated to be reasonably reliable in a small sample of elderly hearing-impaired listeners tested at moderate presentation levels (Christopherson & Humes, 1992) and has been used previously with elderly hearing-impaired listeners (Christopherson & Humes, 1992; Humes & Christopherson, 1991; Humes et al., 1994). All tasks from the TBAC used in this study made use of a standard two-comparison trial structure in which the subject must select which of two subsequent comparison stimuli differs from the standard stimulus on each trial. Percent correct scores based on 72 trials are calculated for each test and should range from 50% (chance) to 100%. The studies with hearing-impaired listeners have found that the TBAC provides measures of auditory discrimination ability that are unaffected by the presence of peripheral hearing loss when administered at sensation levels greater than 30 dB (Christopherson & Humes, 1992). In the present project, the TBAC was administered at a level of 90 dB SPL, which, given the tests selected, was typically at least 30 dB above threshold. As noted previously, based on prior principal component analyses of the application of the TBAC to hearing-impaired listeners (Humes et al., 1994), the following three tests were administered sequentially: (1) duration discrimination for a 1000-Hz pure tone; (2) temporal order for tones, which is a temporal order discrimination task for a four-tone sequence spectrally centered at 1000 Hz; and (3) syllable sequence test, which measures temporal order discrimination performance for consonant-vowel syllables (/fa,ta,ka,pa/) as a function of syllable duration. All TBAC tests were administered diotically. Floor effects were observed in the current data for the syllable-sequence test and research conducted subsequent to the initiation of this study (Humes, Wilson & Humes, 2003) indicated that this task had poorer test-retest reliability than had been observed previously with a smaller study sample. As a result, the TBAC results for the syllable-sequence task were discarded and are not discussed further in this paper.

In addition, three tests of auditory perceptual processing were selected from the Veterans Administration compact disc for auditory perceptual assessment (VACD) (Noffsinger, Wilson and Musiek, 1994). This test battery had been evaluated previously for use with a similar group of 38 elderly hearing-impaired participants (Humes et al., 1996). Based on the findings of Humes et al. (1996), the following three measures were selected for use in this study: (1) dichotic consonant-vowel syllable identification for syllables delivered with 90-msec interaural onset disparity (Noffsinger, Martinez &

Wilson, 1994) with the score based on 30 dichotic presentations (60 syllables) and administered in a free-report mode; (2) the pitch-pattern test, which involves verbal reproduction of the temporal order of stimuli comprising three-tone sequences (Musiek, 1994), with the score based on 60 trials to the left ear; and (3) recognition of NU-6 monosyllabic words that have been 45% time-compressed (Wilson, Preece, Salmon, Sperry & Bornstein, 1994), with each score based on 50 words presented to the right ear. The presence of ceiling effects in the data from the pitch-pattern test resulted in scores that were not normally distributed and inappropriate for use in subsequent linear multiple regression analyses. As a result, these scores were also discarded and are not considered further in this paper. The dichotic-CV identification task is a closed-set identification task in which the subject must select the two CV syllables presented from among the six alternatives provided. Possible percent correct scores range from 16.7% (chance) to 100%. The time-compressed NU-6 test, on the other hand, is an open-set word-recognition task and scores can range from 0 to 100% as a result.

For all the measures of auditory processing, stimuli were presented from either a digital audiotape (TBAC) or CD (VACD), through an attenuator and amplifier, to ER-3A insert earphones. All sound pressure levels specified for stimulus presentation level are referenced to an HA-2 2-cm^3 coupler (Frank & Richards, 1991).

Measures of Cognitive Function • Participants in this study completed the WAIS-R (Wechsler, 1981). Measures of verbal IQ, nonverbal IQ, and total IQ were generated from the WAIS-R. Testing was performed by a graduate student in educational psychology with experience in test administration and scoring. In addition, a hardwired assistive listening device was made available for use during WAIS testing in the event any of the participants had trouble hearing or understanding the instructions and explanations provided for various measures by the examiner due to the subject's hearing loss.

The foregoing auditory function, auditory processing, and cognitive measures were completed in four separate sessions over a period of 2 to 4 weeks. Each session required 90 to 120 minutes for completion.

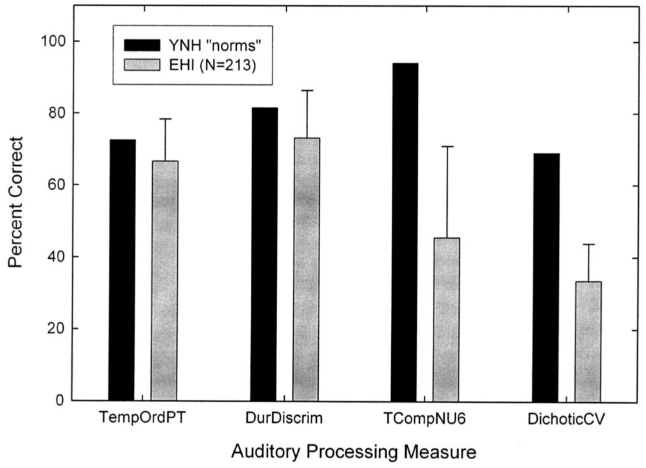

Fig. 2. Means (gray bars) and standard deviations (error bars) for the 213 elderly hearing-impaired participants in this study on each of the measures of auditory processing. The two measures on the left are from the Test of Basic Auditory Capabilities (TBAC) and the two on the right are from the Veterans Administration Compact Disk (VACD). The black vertical bars represent "norms" available for each test from young normal-hearing adults tested under similar or identical listening conditions. TempOrdPT = temporal order discrimination for pure tones; DurDiscrim = duration discrimination; TCompNU6 = recognition of time-compressed NU-6 words; DichoticCV = identification of dichotic consonant-vowel syllables.

Results

Figure 2 presents the means (gray bars) and standard deviations (error bars) for the two auditory processing measures from the TBAC (left half) and the two measures from the VACD (right half). Less than 2% of the data were missing for any of the six measures of auditory processing. For reference, the black vertical bars in Figure 2 provide the mean data for young normal-hearing listeners obtained under similar ($N = 9$; TBAC at 85 dB SPL; Christopherson & Humes, 1992) or identical ($N = 40$; VACD at 90 dB SPL; Humes et al., 1996) listening conditions. Although the purpose of this report is not to examine age-related differences in performance, it is apparent from the data in Figure 2 that the average elderly hearing-impaired listener in this study performed poorer than the average normal-hearing young adult from the prior studies, especially for the two auditory processing tasks using speech stimuli (time-compressed NU-6 words and dichotic CV syllables). In addition, mean scores for the elderly hearing-impaired listeners from this study are similar to those from the elderly hearing-impaired listeners in the studies by Humes et al. (1996) for the VACD and by Christopherson & Humes (1992) and Humes (1996) for the TBAC.

As noted, the pool of predictor variables included each participant's age, as well as various measures of auditory function, including hearing loss (binaural average PTA and HFPTA; binPTA and binHFPTA, respectively), ABR wave-V latency, ABR adaptation (difference in wave-V latency for 11.1 and

TABLE 1. Means and standard deviations for 213 elderly participants on the measures of auditory and cognitive function

Measure	Mean	Standard deviation	Missing *n*
Age (yr)	73.2	6.7	3
Auditory function			
binPTA (dB HL)	38.2	10.7	0
binHFPTA (dB HL)	49.5	10.5	0
ABR wave-V latency RE (msec)	6.0	0.3	0
ABR wave-V latency LE (msec)	6.0	0.4	0
ABR adaptation RE (msec)	0.08	0.04	18
ABR adaptation LE (msec)	0.08	0.03	23
PI-PB rollover RE	0.06	0.01	6
PI-PB rollover LE	0.04	0.01	4
Cognitive function (WAIS-R)			
Verbal IQ	110.9	11.1	4
Nonverbal IQ	110.9	12.8	4
Total IQ	112.0	11.7	4

71.1 clicks per second), and PI-PB rollover. The means and standard deviations for each of these measures of auditory function appear in the upper portion of Table 1. In addition, the number of participants having missing values for each variable is also indicated in the far right column of this table. With the exception of the ABR adaptation measure, values were missing in less than 3% of the cases. Even for the ABR adaptation measures, however, only approximately 10% of the data were missing. In all cases of missing data, mean values were used to replace the missing values. The mean values in Table 1 for ABR wave-V latency, ABR adaptation, and PI-PB rollover are representative of those values obtained previously from similar groups of participants (Hall, 1992; Jerger & Jerger, 1971; Jerger & Johnson, 1988).

In addition to these measures of auditory function, the lower portion of Table 1 presents the means and standard deviations for the performance of the elderly hearing-impaired participants on the WAIS-R. Performance on each of the three measures of IQ are presented. As indicated in the far right column, less than 2% of the data were missing for the WAIS-R.

Before conducting the series of linear multiple -regression analyses between each of the four measures of auditory processing (Figure 2) and the set of predictor variables (Table 1), all percent correct data were arcsine-transformed, and the distributions of all the variables were examined. Kolmogorov-Smirnov tests indicated that none of the distributions for the four dependent variables differed significantly ($p > .05$) from the normal distribution. With regard to the set of predictor variables, only the measure of PI-PB rollover differed significantly from a normal distribution (Kolmogorov-Smirnov $Z = 4.2$ for each ear, $p < 0.01$), and this remained true for a variety of variations in the calculation of rollover. The distributions of an arcsine-transformed version of the rollover measures from each ear are illustrated in Figure 3. All other versions of the rollover measure examined were similarly skewed toward values of 0, indicating that the majority of subjects in this study had little measurable rollover.

The final step in the analyses was to examine the relation between individual differences in auditory processing for each of the dependent variables (Figure 1) and the set of predictor variables (Table 1). The results of the stepwise linear regression analyses for each of the auditory processing variables are summarized in Table 2 [using the default stopping criterion of only including significant ($p < .05$) standardized coefficients (β values)]. For the first three auditory processing measures in Table 2, a similar pattern of results was obtained. Specifically, the multiple correlation was low ($R = 0.35$ to 0.38), accounting for 12 to 14% of the total variance (based on adjusted R^2 values), and a measure of IQ accounted for the majority of the systematic variance, with age as the second significant predictor variable. The only exception to this pattern for the top three measures of auditory processing in Table 2 was observed for tonal measures of temporal order discrimination from the TBAC. For this dependent variable, ABR adaptation also emerged as a significant predictor, accounting for 3% of the systematic variance for this measure. Moreover, for these same three measures of auditory processing, the standardized β coefficients in the best-fitting regression equation are of similar magnitude and direction, indicating that performance on the auditory processing tasks improved as IQ increased and age decreased. In addition, for the temporal order discrimination task, smaller amounts of ABR adaptation resulted in higher performance. The direction of all of these associations is consistent and logical, which

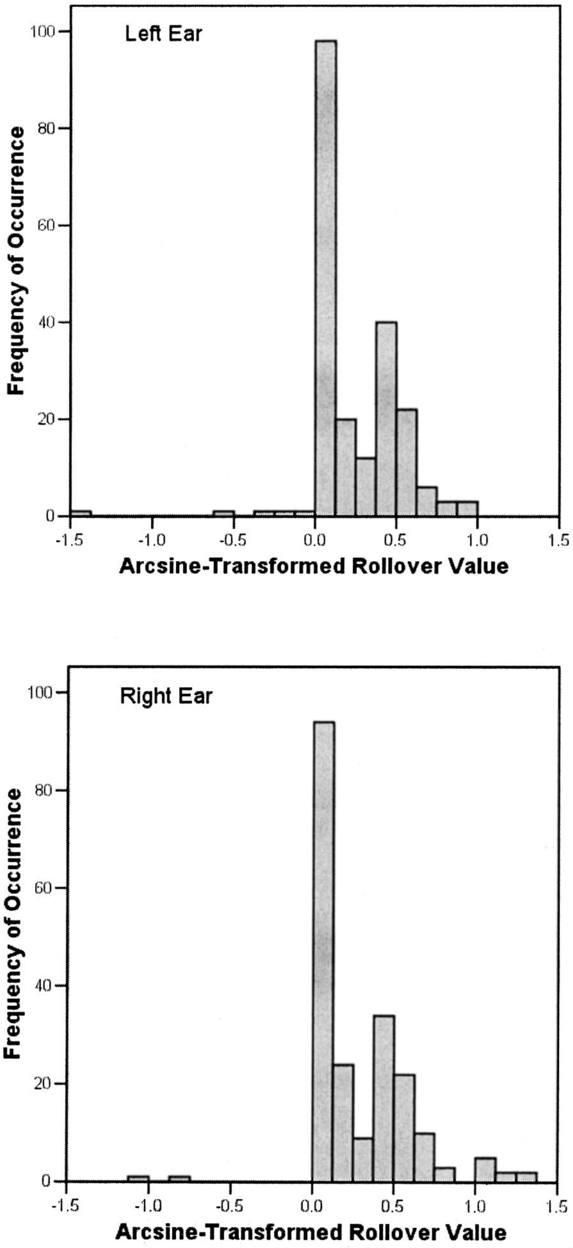

Fig. 3. Distribution of rollover scores for left (top) and right (bottom) ears. The rollover metric shown here was the difference between the arcsine-transformed percent-correct value corresponding to PB-max and that obtained at the highest presentation level. Similar distributions were obtained for rollover metrics involving proportional differences (i.e., difference divided by the score at PB-max) with both transformed and non-transformed percent-correct values.

reinforces the validity of the resulting regression solutions.

The remaining measure of auditory processing appearing in Table 2, recognition of time-compressed NU-6 words, revealed a completely different set of predictor variables from the other measures of auditory processing. The primary differences for this auditory processing measure were that the average high-frequency hearing loss (binHFPTA) played a significant role in the regression solution and the solution accounted for much more of the total variance. Specifically, 56% of the total variance could be explained by four predictor variables, with 54% of the total variance associated with binHFPTA alone.

This is not too surprising because high-frequency hearing loss has been found frequently to be the best predictor of the recognition of nonsense syllables, words and sentences, without time compression being involved and even at high presentation levels (e.g., Humes et al., 1994; Humes, 2002, 2003). Although use of high presentation levels (90 dB SPL) improves the audibility of the speech stimulus, the high-frequency portion of the speech signal is still often inaudible for many listeners with moderate or severe amounts of high-frequency hearing loss.

To determine the role played by other variables in the recognition of time-compressed speech, partial correlations were calculated for each of the other predictor variables while controlling for binHFPTA. When doing so, age, ABR wave-V latency (left ear), nonverbal IQ, total IQ, and ABR adaptation (left ear) were significantly ($p < 0.05$) correlated with the recognition of time-compressed NU-6 words, although all of the correlations were weak ($0.14 < r < 0.19$). As a result, a second step-wise linear multiple-regression analysis was conducted for the recognition of time-compressed NU-6 words without measures of hearing loss (binPTA, binHFPTA) included. Table 3 presents the results from this analysis. Four predictor variables account for 14% of the variance with each of the variables accounting for 3 to 4% of the variance. Once again, the standardized β coefficients reveal logical associations between each predictor variable and the dependent variable. Specifically, among these 213 elderly hearing-impaired listeners, increases in age, ABR adaptation, and ABR wave-V latency and decreases in total IQ are associated with decreases in the recognition of time-compressed NU-6 words.

The foregoing regression analyses indicate that individual differences in performance on several measures of auditory processing in elderly hearing-impaired listeners are associated primarily with individual differences in cognitive function and age. Thus, for this sample of 213 elderly hearing-impaired listeners, performance on the battery of "auditory processing" tests included in this study is more closely related to individual differences in cognitive function than to auditory function. It should be noted, however, that although this was the common pattern that emerged repeatedly and the details of the resulting regression equations appeared to be logical with regard to the nature of

TABLE 2. Stepwise linear regression results for each of the measures of auditory processing (arcsine-transformed percent correct scores)

Dependent variable	Predictor variable	*R*	Adj. R^2	β	*F*(*df*)*
Duration	Verbal IQ	0.31	0.10	0.30	23.1 (1, 211)
Discrimination	Age	0.35	0.11	−0.15	14.3 (2, 210)
Temporal order	Total IQ	0.28	0.07	0.24	17.7 (1, 211)
Discrimination	Age	0.35	0.11	−0.22	14.5 (2, 210)
	ABR adaptation LE	0.38	0.14	−0.16	11.9 (3, 209)
Dichotic CV	Nonverbal IQ	0.35	0.11	0.33	29.8 (1, 211)
Identification	Age	0.38	0.14	−0.13	17.1 (2, 210)
Time-compressed	binHFPTA	0.73	0.54	−0.71	245.5 (1, 211)
NU-6 words	Nonverbal IQ	0.75	0.55	0.10	130.8 (2, 210)
	ABR adaptation LE	0.75	0.56	−0.10	90.0 (3, 209)
	Age	0.76	0.56	−0.10	69.5 (4, 208)

R represents the multiple correlation coefficient; β is the standardized regression coefficient.
* $p < 0.01$.

the associations between the predictor and dependent variables, most often only a small amount of the total variance (11 to 14%) could be accounted by the variables included in this study. Thus, it is possible that other variables not included in this study may yet be identified that are even better predictors of performance on these measures of auditory processing in the elderly.

Support for the observation that there is some commonality underlying the four measures of auditory processing can also be found in the correlations among these four measures. Performance on the dichotic CV-identification task, for example, was correlated significantly ($p < 0.01$) with the three other measures of auditory processing, with *r* values ranging from 0.33 to 0.36. Moreover, performance on temporal order discrimination was also significantly correlated with performance on the duration-discrimination task ($r = 0.60$, $p < 0.01$). The only nonsignificant correlations ($p > 0.01$) were between scores for the recognition of time-compressed words and the two tonal discrimination tasks (duration discrimination and temporal order discrimination) with *r* values of 0.13 and 0.17. Thus, this pattern of correlations among the four measures of auditory processing is consistent with the results of the regression analyses summarized previously in Table 2. Specifically, some common factors, accounting for about 11 to 14% of the variance (cognitive function and age) appear to underlie individual differences in performance on the measures of duration discrimination, temporal order discrimination, and dichotic CV-syllable identification, but other factors (primarily hearing loss) underlie individual differences in performance in the recognition of time-compressed monosyllables.

There were some hints that cognitive function might be related to performance on these auditory processing tasks in prior studies. For example, with young, college-age adults, Watson (1991) had observed a positive association ($r = 0.55$ to 0.59) between total TBAC scores and general cognitive abilities (Math and Verbal Scholastic Aptitude Test scores). In addition, Humes (1996) reported that previously observed differences in performance between "young-old" (65 to 74 years of age) and "old-old" (75 to 84 years of age) groups of listeners on various tests from the TBAC (Humes & Christopherson, 1991) disappeared once the two groups were matched for cognitive function (IQ and digit-span scores). In addition, using tests other than those comprising the TBAC, Jerger et al. (1989) reported that 54% of those elderly diagnosed with central auditory processing disorder also were diag-

TABLE 3. Stepwise linear regression results for the recognition of time-compressed NU-6 words (arcsine-transformed percent-correct scores) after measures of hearing loss were omitted from the set of predictor variables

Dependent variable	Predictor variable	*R*	Adj. R^2	β	*F*(*df*)*
Time-compressed	Age	0.21	0.04	−0.21	10.1 (1, 211)
NU-6 words	ABR adaptation (L)	0.28	0.07	−0.21	8.8 (2, 210)
	Wave-V (L)	0.35	0.11	−0.24	9.7 (3, 209)
	IQ total	0.39	0.14	0.18	9.4 (4, 208)

R represents the multiple correlation coefficient; β is the standardized regression coefficient.
* $p < 0.01$.

nosed as having abnormal cognitive status. Finally, Hallgren et al. (2001) had obtained several measures of dichotic speech identification from elderly hearing-impaired listeners, including the identification of CV nonsense syllables under free recall conditions (conditions equivalent to those used here), and observed strong correlations to cognitive function. In that study, the cognitive test battery was comprised of measures of working memory, processing speed for verbal information, and phonologic processing. The present results, therefore, support these previous indications of a link between individual differences in cognitive function and individual differences in "auditory processing."

It is important to note, however, that all four of the measures of auditory processing involved manipulations of temporal aspects of the auditory stimuli. Although this has been a focal point for many measures of (central) auditory processing applied to the elderly, certainly other measures of auditory processing not involving temporal manipulations (i.e., filtered speech, speech in noise, and so forth) are available and could have been used in this study. It is certainly possible that the associations of cognitive function and age with performance on the particular measures of auditory processing from this study, and the lack of correlation with measures of auditory function, could be due to the temporal nature of the tasks evaluated in this study. Aging has long been shown to have a negative impact on the speed of information processing (e.g., Salthouse, 1996), regardless of modality, and such a cognitive decline could underlie the associations observed in this study between the measures of auditory processing, IQ, and age. This is, in fact, one of the central arguments of this paper. Specifically, deficits observed on measures of "auditory processing" in the elderly may, in fact, reflect amodal deficits in cognitive function associated with aging. Whether this applies to an even broader set of measures of "central auditory processing," including several with no manipulation of the temporal aspects of the stimuli, remains to be seen.

Regarding the measures of auditory function, the focus in this study was placed on measures of the integrity of the auditory nerve and brain stem pathways, including PI-PB rollover, ABR wave-V latency, and ABR wave-V adaptation. The latter measure, moreover, was included because of its emphasis on stimulus presentation rate and the potential importance of this stimulus manipulation to several of the temporally based measures of auditory processing. For example, in the temporal order discrimination task for tones of the TBAC (as well as the syllable-sequence task of the TBAC that was eliminated), stimulus difficulty is manipulated by shortening the duration of the stimuli in a four-stimulus sequence and increasing the rate of presentation in the process. Similarly, time-compressed speech, one of the tests included from the VACD, involves an increase in the rate of presentation of monosyllabic words. Nonetheless, it is possible that some other measures of auditory function, not included in the present study, might be more strongly correlated with the measures of auditory processing than those included here.

It is of theoretical interest to know whether what is being measured is truly a modality-specific processing disorder or a general cognitive processing disorder measured with acoustic stimuli. The results of these analyses indicate that many measures of auditory processing in the elderly may reflect individual differences in cognitive function, presumably independent of the sensory modality involved in the peripheral encoding of the stimulus. This speculation, however, requires direct confirmation via the assessment of elderly hearing-impaired listeners on parallel tasks conducted in different sensory modalities, as has been suggested previously for elderly adults (Humes et al., 1992) and young school-age children (McFarland & Cacace, 1995).

Finally, it has been observed previously that older adults identified as having auditory processing disorders rate themselves as being more handicapped than those without such processing disorders (Jerger, Oliver & Pirozzolo, 1990). Similarly, elderly hearing-aid wearers with auditory processing deficits have exhibited less benefit from amplification (Chmiel & Jerger, 1996). Assuming that the measures of "auditory processing" used were reliable, something that should not always be taken for granted (Humes et al., 1992), the findings of the present study do not negate the observations of Jerger and colleagues in these two studies. It is not unlikely, for instance, that older listeners with equivalent amounts of hearing loss, but differing degrees of cognitive processing deficits, would perceive their handicap or the benefit provided by amplification differently and, most likely, in a manner related to the superimposed cognitive processing problems. In other words, the practical consequences of having a "processing disorder" may be the same whether the disorder is truly a centrally located auditory processing disorder or a centrally located cognitive processing disorder. In a recent study from our laboratory (Humes, Wilson & Humes, 2003), however, three groups of elderly hearing-impaired individuals, matched for gender, age, hearing loss, and prior hearing aid experience, but differing in the degree of hearing-aid success (never tried hearing aids, tried hearing aids but rejected them, or tried hearing aids and retained them), were not found to differ significantly on any of the measures of auditory processing from the TBAC and VACD used here. Thus, the link between "processing disorders" in the elderly and practical consequences, as measured by hearing-aid success or hearing handicap, requires further investigation.

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