Measures of Working Memory, Sequence Learning, and Speech Recognition in the Elderly

Larry E. Humes
Shari S. Floyd
Indiana University,
Bloomington

This study describes the measurement of 2 cognitive functions, working-memory capacity and sequence learning, in 2 groups of listeners: young adults with normal hearing and elderly adults with impaired hearing. The measurement of these 2 cognitive abilities with a unique, nonverbal technique capable of auditory, visual, and auditory-visual stimulation, patterned after the Simon memory game, is described. The use of simple, easily understood items in the test sequences enabled the measurement of these cognitive abilities in older listeners with no apparent impact of age-related hearing loss on the cognitive measures. Age-related cognitive deficits were observed for all 3 modes of stimulation and in both working-memory capacity and sequence-learning ability. The age-related deficits appeared to be greatest, however, for the sequence-learning task. Although it was hypothesized that there might be an association between an individual's performance on these cognitive tasks and his or her performance on various measures of speech recognition, such an association generally was not observed.

KEY WORDS: aging, memory, hearing loss, learning

As people age, there is a decline in the ability to understand speech (Committee on Hearing and Bioacoustics and Biomechanics, 1988; Weinstein, 2000). This age-related decline in speech-recognition performance has been attributed previously to mechanisms, working either in isolation or in combination, that are categorized as auditory-peripheral, central-auditory, or cognitive (Committee on Hearing and Bioacoustics and Biomechanics, 1988; Humes, 1996; Pichora-Fuller, 1997). Several studies have suggested that the age-related decline in unaided speech recognition is primarily determined by peripheral auditory factors, with secondary contributions from cognitive factors (Divenyi & Haupt, 1997a, 1997b, 1997c; Humes et al., 1994; van Rooij & Plomp, 1990, 1992; van Rooij, Plomp, & Orlebeke, 1989). More recently, Humes (2002) demonstrated that the primary importance of peripheral hearing loss was evident even in the *aided* speech-recognition performance of elderly listeners ($N = 171$), although the relative importance of cognitive factors was greater than has generally been observed previously for unaided listening.

Aging is known to affect a number of cognitive processes negatively (Salthouse, 1985). Working-memory capacity is a cognitive process that has been positively associated with speech-communication abilities in recent years. Pisoni and colleagues (Cleary, Pisoni, & Geers, 2001; Pisoni, 2000; Pisoni & Cleary, 2003; Pisoni, Cleary, Geers, & Tobey, 2000; Pisoni

& Geers, 2000), working with the other end of the age continuum (children who had received cochlear implants), have demonstrated positive correlations between measures of working-memory capacity and a number of speech-communication measures, including "aided" speech-recognition performance. Recently, Pisoni and Cleary (2004) also have observed significant positive associations between a measure of sequence learning and speech-communication abilities in children using cochlear implants.

To measure working-memory capacity and sequence learning in this population, Pisoni and colleagues implemented a research version of the Simon memory game. The Simon-based measures they developed enabled stimulation using auditory, visual, and auditory-visual stimuli and a limited set of highly distinguishable items comprising the test sequences used. The test items are comprised of four color names (red, yellow, green, and blue), each of which is easily distinguishable from the others, even in the presence of significant hearing loss. Nonverbal responses were also incorporated. Some of these same features make the Simon-based measures particularly suitable for use with elderly individuals. For example, Humes, Nelson, Pisoni, and Lively (1993) were able to obtain measures of working memory for strings of monosyllabic words from elderly individuals with normal hearing, but these measures proved to be impossible to complete in elderly individuals with hearing impairment. The presence of typical, age-related hearing loss precluded a clear interpretation of the elderly participants' recall errors as errors attributable to faulty memory rather than poor initial encoding due to the presence of peripheral hearing loss. The Simon-based measures of working memory and sequence learning should circumvent this difficulty. The fact that these measures make use of a nonverbal (button-press) response would also make them suitable for use as cognitive measures in older adults incapable of verbal responses (e.g., following a stroke or tracheotomy).

It is not unreasonable to assume that working-memory capacity might play a role in the speech-recognition performance of elderly hearing impaired (EHI) listeners. Consider, for example, the use of a sentence test to measure speech recognition, such as the Connected Speech Test (CST; Cox, Alexander, Gilmore, & Pusakulich, 1988). Most often, such measures of speech recognition require the listener to repeat the sentence to the experimenter, who scores the number of key words repeated correctly. To perform this task successfully, the listener must correctly encode the acoustic pattern of speech sounds, identify them as words, and then retain the string of words in memory until the sentence is completed and can be repeated to the experimenter. In an information-processing context, allocation of additional resources to the encoding process might be needed to compensate for peripheral distortions of the input associated with age-related hearing loss. In finite-capacity information-processing models, moreover, such allocation results in fewer resources available for rehearsal processes required for the retention of items in working memory. This may also result in fewer resources being available for the retrieval of information from working memory during the recall process. As a result, one might expect sentence-based scores of speech recognition in EHI listeners to be related to individual differences in working-memory capacity.

However, such a linkage between speech-recognition performance and working-memory capacity may not be confined to sentence-based measures of speech recognition. Consider, for example, a closed-set nonsense-syllable test involving several response alternatives. The CUNY Nonsense Syllable Test (NST; Levitt & Resnick, 1978), which involves seven to nine alternatives for a given speech token, is a common example. In this case, after the listener hears the speech stimulus, this item must be retained in memory (through rehearsal) while the listener scans the list of alternatives to select the appropriate response. Again, if more resources are allocated to the more peripheral encoding processes, then fewer will remain for rehearsal and retrieval processes. As a result, individual differences in various aspects of working-memory capacity can result in individual differences in speech-recognition performance when measured with such nonsense-syllable tasks. Of course, similar arguments can be made for any closed-set speech-recognition task, including those using words. Most tests using monosyllabic words, however, typically have fewer response alternatives (four to six) to scan.

Another attractive feature of the Simon memory paradigm for the current application is the capability of administering the test using auditory, visual, or audiovisual stimuli. Comparison of performance across modalities might assist in establishing the allocation of additional resources to peripheral encoding of the stimuli. For example, whereas the presence of age-related hearing loss might require the use of additional resources for the encoding of auditory stimuli, such would not be the case for the encoding of visual stimuli (the lighting of the red, yellow, green, or blue panels on the Simon apparatus). Further, the availability of multiple modalities for stimulus input may allow one to determine whether the observed age-related deficits in performance, if any, are due to underlying cognitive or modality-specific auditory-processing deficits (Humes, Christopherson, & Cokely, 1992). If age-related deficits are observed in the auditory modality only, then this might suggest the presence of a modality-specific central auditory-processing impairment, especially because the impact of peripheral hearing loss on these same auditory stimuli has been minimized through the use of a small and highly intelligible stimulus set.

Finally, the Simon apparatus used to measure working-memory capacity can be adapted easily to measure sequence-learning capacity. Typically, in measures of working-memory capacity, the length of the sequence of stimuli to be recalled is increased one item at a time. The resulting subsequent sequence of $N + 1$ items is a new random sequence, unrelated to those shorter sequences presented previously. In sequence learning, on the other hand, the first N items of the new sequence of $N + 1$ items are identical to those of the prior sequence. Thus, each new sequence adds one new item to the sequence developed from all prior sequences. As a result, through repeated presentations and rehearsal, a progressively longer sequence is "learned." Karpicke and Pisoni (2004) have argued that because the participant is neither instructed to learn nor trained in how to learn the sequence, this may be a special case of "implicit learning" (e.g., Reber, Walkenfeld, & Hernstadt, 1991) using a working-memory task. Several studies of implicit learning in the elderly have suggested that there are no effects of aging on this cognitive ability (e.g., Cherry & Stadler, 1995; Curran, 1997), although this conclusion has more recently been called into question (Salthouse, McGuthry, & Hambrick, 1999). However, because there may be some debate as to whether the Simon-learning task is, in fact, a memory-based measure of implicit learning, we will refer to this task simply as a sequence-learning task throughout the remainder of this paper.

In the present study, we used the Simon-memory and Simon-learning paradigms described by Pisoni and Cleary (2004) to measure working-memory capacity and sequence learning in a group of 24 EHI listeners. Examination of the use of this device for the measurement of these two cognitive processes in EHI listeners represented the central focus of this study. A variety of other measures, including aided and unaided measures of speech-recognition performance, also were available from another study (Humes, 2002) for most (n = 22) of these same elderly individuals. Measures of speech recognition included a closed-set nonsense-syllable identification task (the CUNY NST) and an open-set sentence-recognition task (the CST), both obtained at conversational levels in a background of noise. Because the norms for both Simon-based measures from young normal-hearing (YNH) adults were still under development at the time this study was initiated and because we made a slight procedural change for the Simon-learning task, we also tested a separate group of 12 YNH adults in this study.

Method

Participants

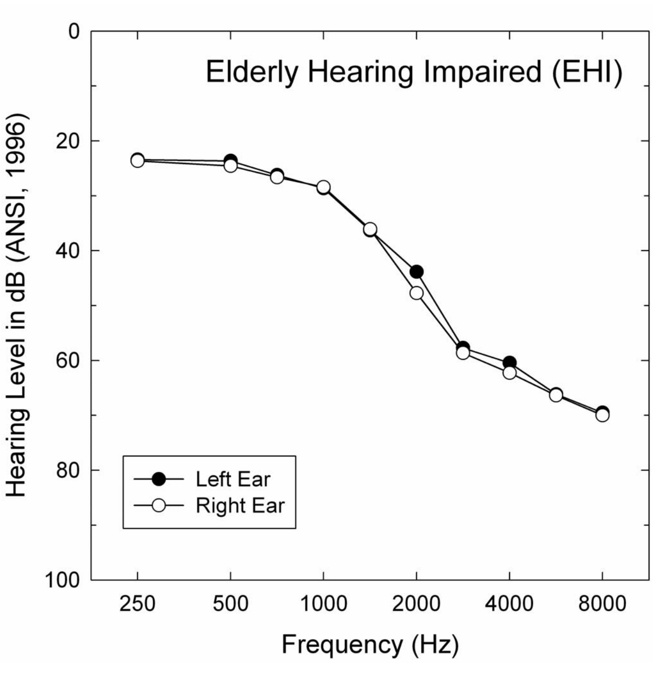
Two groups of participants took part in this study. One group consisted of 24 EHI individuals (14 female and 10 male), ranging in age from 62–86 years (M = 75.6). The other group consisted of 12 YNH adults (10 female and 2 male), ranging in age from 21–22 years (M = 21.5). All YNH adults passed a hearing screening at 500, 1000, 2000, and 4000 Hz at 20 dB HL (American National Standards Institute, 1996). The mean air-conduction audiograms for the right and left ears of the EHI participants are shown in Figure 1. Participants had mild to moderate, sloping sensorineural hearing loss in both ears. The hearing screening for the YNH participants and the threshold measurements for the EHI participants were completed in a double-walled sound-treated room.

Only one session was required to complete the Simon tasks, which took approximately 1 hr. Each participant was paid $10 for his or her participation. All hearing impaired participants with hearing aids were asked to remove their hearing aids following instruction and before beginning the Simon-based tasks.

Materials

Measures of speech-recognition performance were obtained from the EHI listeners in a prior study (Humes,

Figure 1. Mean air-conduction pure-tone thresholds for the left and right ears of the 24 EHI participants.



2002). Measures were obtained in both unaided and aided listening conditions in the sound field using a speech presentation level of 65 dB SPL. The CUNY NST was used as one measure of speech recognition, and the competition was composed of the multitalker babble from the Speech Perception in Noise test (Kalikow, Stevens, & Elliott, 1977). The other measure of speech recognition made use of two passages, each with 25 key words, from the CST (Cox et al., 1988). The competition was the multitalker babble developed for use with the CST. For both the NST and the CST, the speech-to-babble ratio was +8 dB. Additional procedural details regarding the speech-recognition measures can be found in Humes (2002).

The Simon device was used to obtain the measures of working-memory capacity and sequence learning. This device is circular, about 10 in. in diameter, and made of plastic. Four back-lit colored (red, yellow, green, and blue) panels or buttons are arranged on top of the Simon device in a circular arrangement. The Simon device was connected to a computer, which controlled the device and was the means of all data collection. In addition to the Simon device, an amplified loudspeaker was connected to the output of the computer's sound card. This speaker was used to deliver the auditory stimuli for the auditory and auditory-visual test conditions in the Simon-memory and Simon-learning measurements. The computer and loudspeaker were positioned in a quiet area of the laboratory outside the sound booth. This replicated conditions under which the norms for both tasks had been obtained previously (Pisoni & Cleary, 2004). Sound level measures of the ambient noise, taken at the location of the participant's head, were 62 dBC and 45 dBA. Using the method of substitution to establish presentation levels for the Simon auditory stimuli, auditory signals from the Simon device were presented at approximately 70 dBA through the loudspeaker. This was about 25 dB above the environmental background noise. The loudspeaker was placed on a table approximately 30 in. from the center of the participant's head at 30° azimuth and about –10° elevation.

Procedure

Participants were tested individually, closely following the procedures used by Pisoni and Cleary (2004). A general consent form was presented to and signed by each participant before the Simon tasks began. Then, a brief description of the experiment was provided. The next step in each session was to have the participant complete a simple stimulus identification task, pointing to the four colors (red, yellow, green, and blue) on the Simon device as each was presented in isolation acoustically. This task was included to ensure that there were no discrepancies between color names and the corresponding colored buttons, as well as to confirm that the listener could hear and recognize the stimuli in isolation. The Simon device was maintained at a consistent orientation to each participant throughout. As a result, visual spatial cues were redundant with the visual color cues for the visual and auditory-visual stimulus presentations. The experimenter then completed a demonstration of five sequences to clarify the task prior to both the memory and the learning tasks. After the introduction, participants were given the opportunity to practice a set of 10 trials to demonstrate that they had full understanding of the task and could respond in the appropriate manner.

The testing procedure consisted of the two tasks, Simon-memory and Simon-learning. In both tasks and all stimulus modalities, an interstimulus interval of 100 ms was incorporated and the durations for the visual stimuli (in either the visual or auditory-visual stimulus presentations) were matched to the durations of the auditory stimuli. In combination, the stimulus durations and the interstimulus interval together resulted in a stimulus presentation rate of about two items per second. In Simon-memory, each new string was a random sequence of stimuli, whereas in Simon-learning each new string involved the addition or deletion of one item at the end of the person's previous pattern. Each task consisted of 20 trials during which a sequence was presented. Consistent with the protocol employed by Pisoni and Cleary (2004), the Simon-learning task began with a sequence of three stimuli, and the Simon-memory task began with only one stimulus. Adaptive tracking procedures (Levitt, 1971) were used for both tasks. For both the Simon-learning and Simon-memory tasks, each incorrect response resulted in the subsequent string of stimuli being shortened by one item. For every correct response in Simon-learning, the string was increased by one item; for every two correct responses in Simon-memory, the string was increased by one item. These task-specific adaptive rules were patterned after those used by Pisoni and Cleary (2004) to collect normative data for each task. Failure to initiate or continue a response for a period of 5 s marked the end of the response, and the length of the next sequence was adjusted as dictated by the task-specific adaptive rule.

For each Simon task, three modalities were tested. The three modalities were auditory only (A), in which only the color names were presented through a loudspeaker; visual only (V), in which only the colored buttons on the Simon device were activated; and auditory-visual (AV), in which the color names were presented through a loudspeaker and the corresponding colored button activated simultaneously. The orders of the two tasks and the three modality-presentation conditions were counterbalanced across participants to minimize order effects. Each participant was allowed a break after each set of 20 trials, and directions were presented before each new set of 20 trials began.

Results

The proportions of each group, YNH participants and EHI participants, attempting lists of various lengths for the Simon-memory and Simon-learning tasks are shown in Figures 2 and 3, respectively, for the three presentation modalities. For the Simon-memory task (Figure 2), 100% of the EHI group attempted sequence lengths ranging from one to four items in each modality. Progressively fewer elderly adults attempted sequence lengths exceeding four items, with fewer than about 10% of the group attempting list lengths of seven items or more. For the most part, the YNH participants showed a similar trend, but with the functions shifted to the longer lists by about 1.5 items.

For the Simon-learning task (Figure 3), there were larger differences between the YNH and EHI participants in the proportion of each group attempting lists of various length than were observed previously for the Simon-memory task. For example, whereas 100% of the EHI participants attempted sequence lengths from 1–4 items, only about 60% of the group got enough correct in each modality to attempt a sequence length of 7 items. In contrast, 100% of the YNH participants attempted sequence lengths of 7 items for each modality. In addition, whereas not a single EHI participant was successful enough in the sequence-learning task to attempt a sequence of 17 items presented in any modality, 25% of the YNH participants attempted sequences of this length in both the auditory and visual modalities.

In summary, it appears from the data presented in Figures 2 and 3 that the combination of starting list length, number of sequences presented in a track, and the adaptive tracking rules used in each Simon task produced sequences that were neither too easy nor too difficult for each group of participants. Clearly, in both tasks, the YNH participants performed better than the EHI participants, and as a result more YNH participants experienced longer stimulus sequences.

Figures 4 and 5 show the proportion of incorrect responses for each list length for the Simon-memory and Simon-learning tasks, respectively. These are group psychometric functions in which the proportion of incorrect trials out of those attempted, for the entire group, is plotted as a function of sequence length. A 50% “threshold” value is represented by the dotted horizontal line in each figure. This point displays the number of items that yield 50% incorrect (or 50% correct) for each group in each modality. Four-parameter (Simon-memory task) and five-parameter (Simon-learning task) sigmoidal functions were fit to each group psychometric function, and the best-fitting functions (R^2 > .98) appear as the solid, dotted, and dashed lines in Figures 4 and 5. The equations for each best-fitting sigmoidal function were used to determine the sequence length corresponding to the 50% point on the group psychometric function. These values are organized and presented in Table 1 according to task, group, and modality.

In Figure 4 (Simon-memory task), the EHI participants show very similar performance across modalities.

Figure 2. The proportion of each group attempting various sequence lengths for the Simon-memory task. YNH = young normal-hearing.

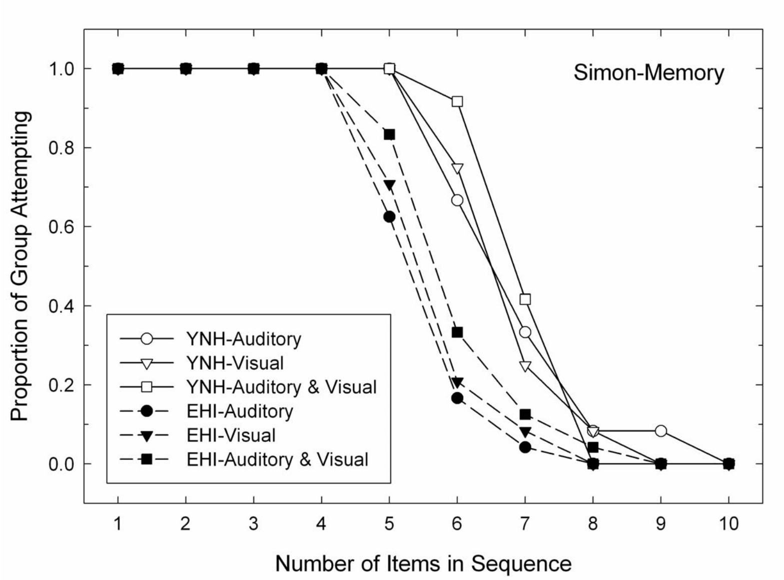
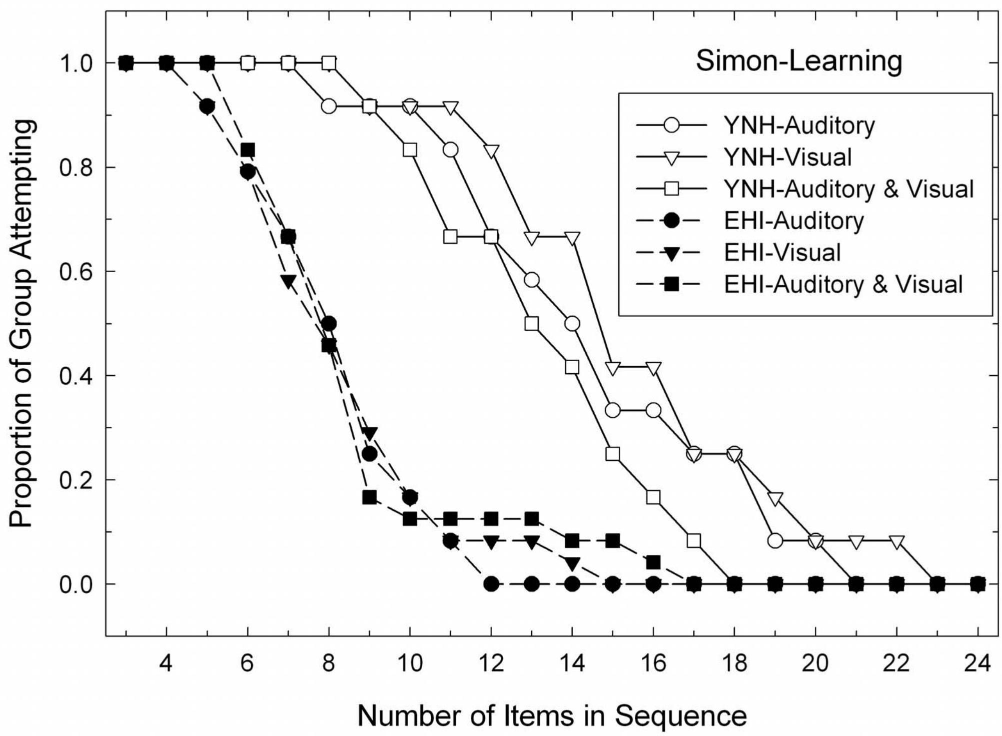


Figure 3. The proportion of each group attempting various sequence lengths for the Simon-learning task.



However, they performed the best when presented with AV stimuli. The YNH participants also performed similarly across modalities on this task. The group psychometric functions for these participants show no difference in performance between A or V presentations. The YNH participants also performed the best when presented with AV stimulus sequences. The YNH participants also performed slightly better overall, compared to the EHI participants, across modalities. Both groups show synergistic effects across modalities with a similar relative improvement in performance for the AV stimuli compared to either modality alone.

The group psychometric functions for the Simon-learning task shown in Figure 5 reveal larger differences in performance between the YNH and EHI groups. The YNH participants performed considerably better across all modalities compared to the EHI participants. In addition, whereas the EHI participants performed similarly for all three presentation modes, the YNH participants showed greater differences in performance across modalities, performing best with the V stimuli. They showed the lowest performance when stimuli were presented in the AV mode.

Pisoni and Cleary (2004) calculate a score, referred to as a weighted score, by simply summing the proportion correct across all sequence lengths for each participant. The higher the weighted score, the longer the sequence the participant was able to recall in each task. Weighted scores were calculated for all 36 participants, and the group means and standard errors for the YNH and EHI participants are presented in Figure 6. The trends apparent in the weighted scores in this figure are generally consistent with the patterns apparent in the group psychometric functions and the thresholds derived from them (Table 1). For comparison, the norms established for 48 YNH adults, using very similar (but not identical) conditions from Pisoni and Cleary (2004), are also provided in Figure 6. Whereas the present results for the Simon-memory task are in excellent agreement with these norms, the weighted scores for the Simon-learning task for the YNH participants in the present study consistently

Table 1. Number of items calculated from the 50% point of the best-fitting sigmoidal functions for the group psychometric functions for the Simon-memory (Figure 4) and Simon-learning (Figure 5) tasks.

Task	Group	Auditory	Visual	Auditory-visual
Memory	YNH	5.57	5.64	6.13
	EHI	4.65	4.66	4.93
Learning	YNH	11.33	12.60	10.43
	EHI	5.84	5.54	5.99

Note. YNH = young normal-hearing; EHI = elderly hearing impaired.

Figure 4. Group psychometric functions for the EHI participants (filled symbols) and the YNH participants (unfilled symbols) for the Simon-memory task. Circles = auditory stimuli; inverted triangles = visual stimuli; squares = auditory-visual stimuli. Sloping solid, dashed, and dotted lines represent the best-fitting four-parameter sigmoidal function for each data set. The horizontal dotted line represents 50% correct, and the sequence lengths corresponding to this performance level are listed in Table 1.

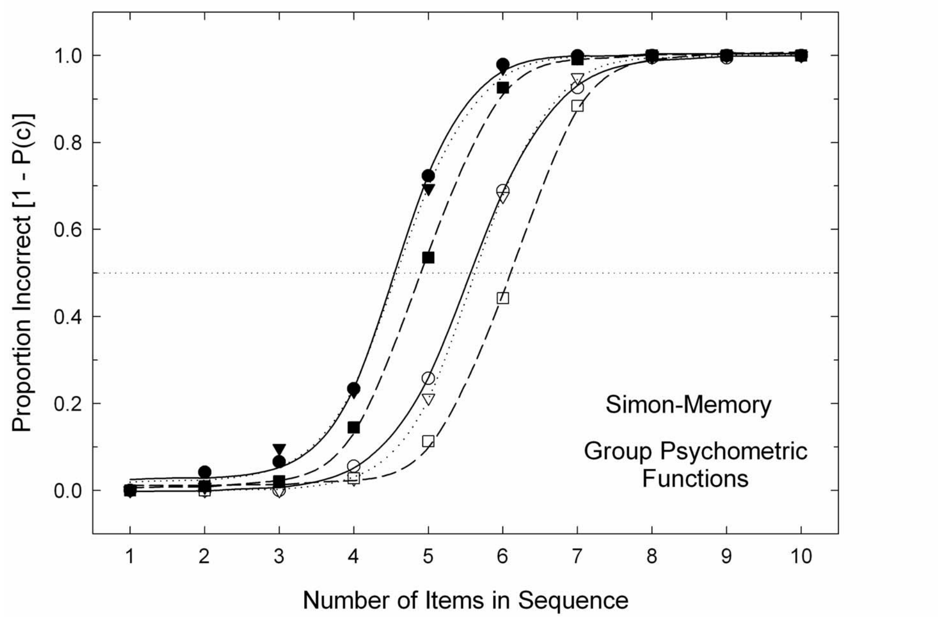
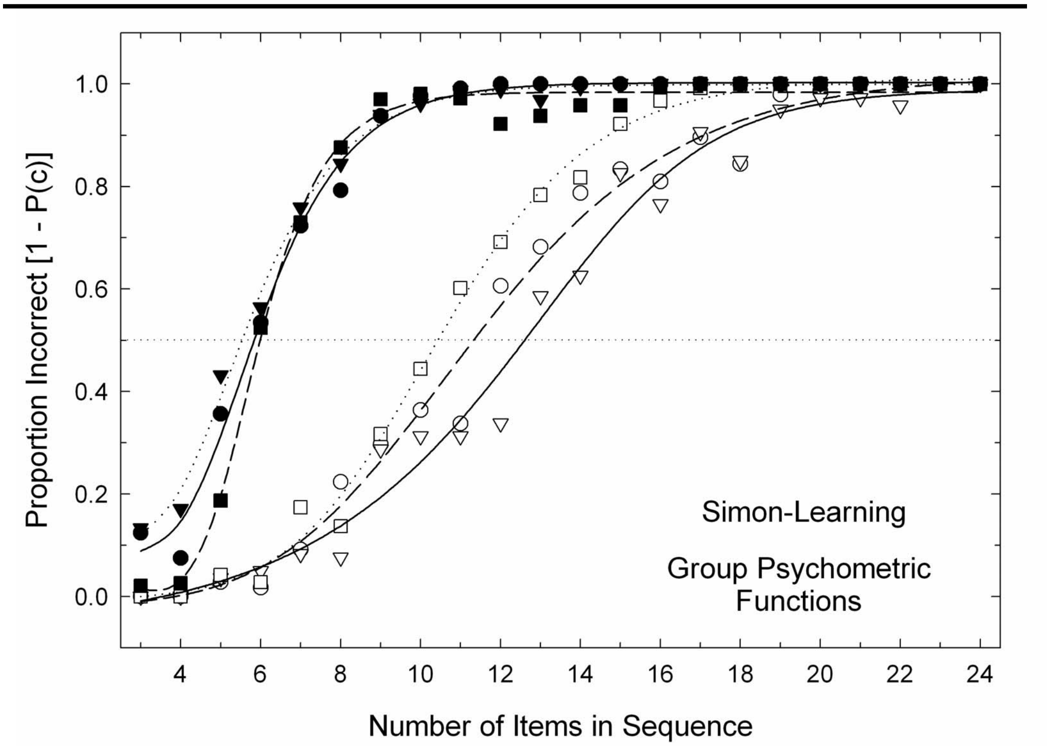


Figure 5. Group psychometric functions for the EHI participants (filled symbols) and the YNH participants (unfilled symbols) for the Simon-learning task. Circles = auditory stimuli; inverted triangles = visual stimuli; squares = auditory-visual stimuli. Sloping solid, dashed, and dotted lines represent the best-fitting five-parameter sigmoidal function for each data set. The horizontal dotted line represents 50% correct, and the sequence lengths corresponding to this performance level are listed in Table 1.



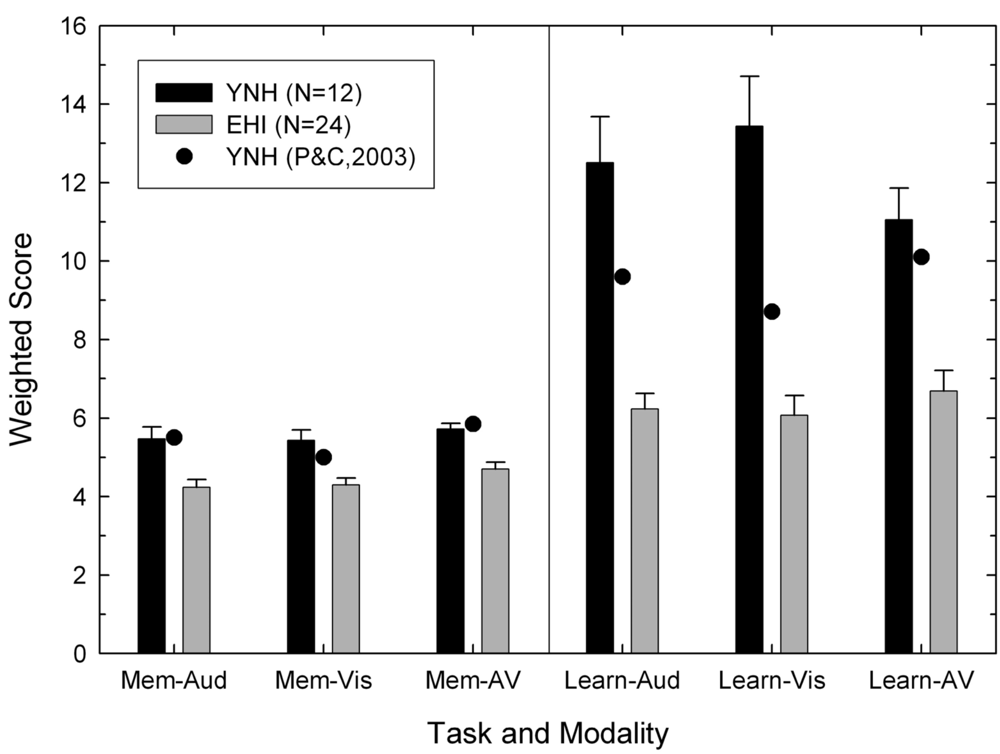
exceed those reported by Pisoni and Cleary (2004). A key difference between studies, though, was that the maximum sequence length was limited to 15 items in the prior study, whereas a maximum sequence length of 23 items was used in this study. The implications of this procedural difference are described in greater detail below.

The weighted scores from Figure 6 were analyzed using the general linear model (SPSS, Version 11). A 2 (subject group) × 2 (Simon task) × 3 (stimulus modality) mixed factorial model was examined initially. Significant main effects of subject group, $F(1, 34) = 53.16$, $p < .01$, and Simon task, $F(1, 34) = 127.8$, $p < .01$, were observed, but the effect of stimulus modality failed to achieve statistical significance. However, 2 of the 3 two-way interactions and the lone three-way interaction were significant, $p < .05$, which negated any simple interpretation of the main effects noted. As a result, a series of post hoc t tests were performed to examine the effects of each of the independent variables on the weighted Simon scores. First, a series of six independent-sample t tests were computed to compare the mean performance of the EHI and YNH groups for each task and stimulus modality. When the significance level of $p < .01$ was adjusted for multiple comparisons, all t tests revealed that the weighted Simon scores of the YNH participants, for both memory and learning and for all three stimulus presentation conditions, were significantly greater than those of the EHI participants.

Next, several sets of paired-sample t tests were computed for each group. For the YNH participants, the weighted scores for the A, V, and AV presentations of the Simon-learning task were each significantly greater than the weighted scores for the corresponding Simon-memory task, $p < .01$, adjusted for multiple comparisons. Finally, within each task, comparison of mean weighted scores for all possible paired comparisons of the A, V, and AV presentation conditions revealed no significant effects of modality for the YNH participants.

An identical set of paired-sample t tests were then conducted for the EHI participants. Again, mean performance on the Simon-learning task was significantly higher than that on the Simon-memory task for all three modalities. For a given task, however, examination of all possible paired comparisons for each modality revealed only one significant difference, adjusted $p < .01$; namely, the weighted score for the EHI participants on the Simon-memory task was significantly greater for the AV presentation mode than for the A presentation mode.

Figure 6. Mean weighted scores for YNH and EHI participants on the Simon-memory (Mem, left panel) and Simon-learning (Learn, right panel) tasks. Aud = auditory; Vis = visual; AV = auditory-visual stimuli. For comparison purposes, mean data from 48 YNH adults reported in Pisoni and Cleary (2003) obtained under similar (but not identical) conditions are shown as filled circles.



Discussion

To recap the primary findings: (a) YNH participants were generally superior to the EHI participants on all measures of working-memory capacity and sequential learning; (b) both groups demonstrated significantly higher weighted scores on the Simon-learning task compared to the Simon-memory task, although the gain from the memory to the learning task appears to be much greater for the YNH participants; and (c) with one exception, there were no significant effects of stimulus modality for either task in either group. As noted previously, the data for the YNH participants on the Simon-memory task compare favorably with similar data obtained from a larger group ($N = 48$) of YNH participants by Pisoni and Cleary (2004). Despite the similarity between these two sets of weighted scores for the Simon-memory task (Figure 6), Pisoni and Cleary reported significant effects of modality in their YNH participants on this task, whereas no such effects were observed here. At least part of this difference in results can be attributed to the use of p values that were not adjusted for multiple comparisons in their study but were in our study. Regardless, the differences between modalities *in both studies* are much smaller than the differences between normal-hearing and hearing-impaired groups in each study or between the Simon-memory and Simon-learning tasks in each study. That is, the modality effects are small in both studies when compared to the effects of subject group or Simon task.

With regard to performance of the YNH participants on the Simon-learning task, we noted previously that our group of YNH adults performed considerably higher than those described in Pisoni and Cleary (2004). Procedural differences between studies in the number of trials used and the upper limit for list length used in the Simon-learning task most likely account for this difference in results for the YNH adults. Whereas the data reported by Pisoni and Cleary (2004) made use of 12 trials and an upper limit of 15 items in the sequence, the present study made use of 20 trials per weighted score and a maximum list length of 23 items. Examination of the data in Figure 3 reveals that 30–40% of the YNH participants in this study attempted list lengths exceeding 15 items, and this higher upper limit clearly had an impact on the measured weighted scores in this study. These procedural differences for the Simon-learning task between studies most likely underlie the observed differences in weighted scores across studies for the YNH adults on this task.

As noted, the differences in weighted scores between the YNH and EHI groups were significant for both tasks and all three stimulus-presentation conditions, a total of six between-group comparisons. The group differences also were much larger for the sequence-learning task than for the memory-capacity task (Figure 6). Whereas the weighted scores for the YNH group were about 1.2 to 1.3 times greater than those of the EHI group on the Simon-memory task, they were closer to twice that of the EHI participants on the Simon-learning task. Thus, aging seems to have a greater impact on sequence learning than on memory capacity itself. We feel fairly confident in attributing this difference between groups to aging because the same trends were observed for the visual stimuli that could not have been degraded perceptually by the presence of age-related hearing loss. Thus, although the two groups in this study differed in both age and hearing impairment, it appears that the former is impacting performance more than the latter. This is due in no small measure to the easily identified "vocabulary" items constituting the lists involved in the Simon measures. In fact, there were no significant correlations between the binaural high-frequency pure-tone average (average hearing thresholds in both ears at 1000, 2000, and 4000 Hz) and any of the six Simon-based measures of memory capacity or sequence learning. Age, on the other hand, was negatively correlated with each of the six Simon-based measures for the EHI participants, with correlation coefficients ranging from –.23 to –.59, half of which were statistically significant, $p < .05$. (Aging and high-frequency pure-tone average were not significantly correlated, $r = .12$.)

Wechsler Adult Intelligence Scale—Revised (WAIS–R; Wechsler, 1981) digit-span scores, a more broadly used measure of working-memory capacity in adults, were also available for 22 of the 24 EHI participants in this study. Correlations between WAIS–R digit-span scores and each of the six Simon-based measures for these 22 EHI listeners revealed weak to moderate positive correlations, ranging from .22 to .52, with three of the six correlations being statistically significant, $p < .05$. More specifically, the correlations between digit-span scores and the Simon-memory task were .32 (A), .49 (V), and .50 (AV), with the latter two correlations being statistically significant, $p < .05$. These moderately strong and positive correlations further validate the use of the Simon-memory task as a measure of working-memory capacity.

Clearly, one of the most noticeable differences between the YNH and EHI participants in this study was the gain or benefit associated with repetition of the same stimulus sequence (Simon-learning task) relative to recall of a new random sequence on each trial (Simon-memory task). This group difference is apparent in the group psychometric functions in Figures 4 and 5, as well as the weighted scores in Figure 6. This learning-versus-memory performance differential was evaluated within each modality and within each group as both a simple arithmetic difference (weighted score for the Simon-learning task minus weighted score for the Simon-memory task) and a ratio (weighted score for the

Simon-learning task divided by weighted score for the Simon-memory task). The means and standard deviations for these learning "gain" values, computed both ways, appear in Table 2. Whereas the weighted scores for YNH participants increased 5.3 to 8.0 items or 1.9 to 2.5 times in length when going from the Simon-memory task to the Simon-learning task, the corresponding values for the EHI participants increased 1.8 to 2.0 items or 1.4 to 1.5 times in length. The learning gain values for the YNH participants were significantly greater, adjusted $p < .01$, than those of the EHI participants for all six between-group comparisons in Table 2. Thus, whether the relative improvement in performance from the memory task to the learning task (i.e., the learning-gain value) is described as an arithmetic difference or a multiplicative factor, YNH participants benefited more from the repetition of the same sequence than the EHI participants did. That is, the YNH participants were better able to *learn* the repeated sequence than the EHI participants were. Again, given that this was true even for the vision-only stimulus conditions, this difference between groups is most likely attributable to differences that exist between the groups in age rather than in hearing.

There were no effects of stimulus modality on either task in the EHI listeners. Thus, the equivalent performances for auditory and nonauditory modalities by the EHI adults suggest that the age-related deficits in working memory and sequence learning obtained with the Simon device were not affected by the presence of peripheral hearing loss. The results also suggest that this deficit is a general cognitive decline, not a modality-specific auditory-processing decline. These data, however, are neutral with regard to whether there is a link between the presence of impaired hearing and cognitive decline in the elderly. It has been argued recently (e.g., Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994) that sensory decline precedes, and may be causally related to, cognitive decline. Thus, it is possible that the EHI participants in this study have a general amodal cognitive decline due to the presence of the long-standing peripheral hearing loss and the diminished sensory input that results. Our prior work with elderly *normal-hearing* participants (Humes et al., 1993) supports this conclusion as well in that there were no significant differences observed in that study between the younger and older normal-hearing adults on serial-recall tasks.

Although we have discussed performance on the Simon-memory and Simon-learning tasks as separate tasks measured with somewhat different paradigms, this should not be interpreted to imply that these measures are unrelated. One might expect, for example, those with poor working-memory capacity also to have poor sequence-learning ability. This is in fact borne out by the correlation matrix presented in Table 3. The correlations between weighted scores for Simon-memory and Simon-learning tasks are shown for each modality, with those for the EHI participants only ($n = 24$) shown in the upper portion of the matrix and those for both groups combined ($N = 36$) in the lower portion of the matrix. All but two of the correlations are moderate and statistically significant, $p < .05$, indicating a moderate and positive association among measures of working memory and sequence learning. In fact, if one considers the various stimulus modalities employed to be essentially "alternate forms" of the same measure, then the correlations among alternate forms of the same measure (e.g., working memory) are essentially the same as those between measures (sequence learning and working memory). Moreover, these correlations are of the same magnitude as those reported previously between the WAIS–R digit-span measures and the Simon-memory measures for these same participants. Thus, it may well be that the age-related decline in sequence learning is due primarily to corresponding age-related declines in working-memory capacity. This is not too surprising in that many of the same cognitive processes, such as encoding, storage, rehearsal, retrieval, and recall, underlie both measures. Sequence learning may just involve *more* of some of the same processes underlying working-memory capacity, such as rehearsal, but not necessarily separate or independent processes.

Finally, as noted previously, measures of unaided and aided speech-recognition performance were available from 22 of the 24 EHI participants from another

Table 2. Means and standard deviations of learning "gain" computed as difference between the weighted scores for the Simon-learning and Simon-memory tasks or the ratio between these two weighted scores.

		Auditory		Visual		Auditory-visual	
Task	Group	*M*	*SD*	*M*	*SD*	*M*	*SD*
Difference	YNH	7.0	4.2	8.0	4.3	5.3	2.5
	EHI	2.0	1.6	1.8	2.0	2.0	2.5
Ratio	YNH	2.4	0.8	2.5	0.8	1.9	0.4
	EHI	1.5	0.4	1.4	0.4	1.4	0.5

Note. Difference = learning – memory; ratio = learning/memory.

Table 3. Correlations among various weighted scores for the Simon-memory (Mem) and Simon-learning (Learn) tasks.

	Mem(A)	Mem(V)	Mem(AV)	Learn(A)	Learn(V)	Learn(AV)
Mem(A)	—	.33	.73*	.55*	.46*	.50*
Mem(V)	.52*	—	.47*	.44*	.55*	.47*
Mem(AV)	.67*	.62*	—	.53*	.51*	.26
Learn(A)	.53*	.54*	.58*	—	.55*	.50*
Learn(V)	.52*	.60*	.67*	.78*	—	.64*
Learn(AV)	.45*	.51*	.54*	.67*	.82*	—

Note. Values for 24 EHI participants only are shown above the diagonal, and values for the entire group of 36 participants (YNH and EHI) are shown below the diagonal. A = auditory; V = visual; AV = auditory-visual.
*Significant correlations ($p < .05$).

study (Humes, 2002). When correlations were computed between the six measures of working-memory capacity and sequence learning from this study and each of four measures of speech recognition, only one of the six sets of four correlation coefficients had any significance, $p < .05$. Specifically, the correlations between the weighted scores for auditory stimuli on the Simon-learning task and speech-recognition performance were .47, .31, .46, and .46 for the unaided NST, aided NST, unaided CST, and aided CST measures, respectively. Only the lowest correlation was not significant statistically. To further evaluate the possible association between performance on the Simon-memory and Simon-learning tasks and speech-recognition performance, the six Simon-based measures were subjected to a principal-components factor analysis that resulted in the identification of a single factor accounting for 58.3% of the variance (and communalities ranging from .49 to .66). This result reinforces the strong overlap between the Simon-memory and Simon-learning tasks noted previously (Table 3) and suggests that performance on both tasks *for the EHI participants* may be mediated by a common underlying mechanism. The correlations between this Simon-task factor score and each of the measures of speech-recognition performance in the EHI participants were .34, .21, .52 ($p < .05$), and .41 ($p = .058$) for the unaided NST, aided NST, unaided CST, and aided CST measures, respectively. Thus, there may be some association between the cognitive measures examined here and aided and unaided measures of speech-recognition performance in the elderly. This association is most evident for the sentence-based CST, albeit not particularly strong. Additional data with a larger sample of participants are needed to examine the relations among these measures. It appears, however, that the Simon-based measures of working-memory capacity and sequence learning offer two valid and reasonably reliable measures of cognitive function that are unaffected by age-related hearing loss. These measures, therefore, may be useful in future investigations involving EHI participants.

Acknowledgments

This work was supported in part by National Institutes of Health Grant R01 AG08293 to Larry E. Humes. The authors would like to thank Professor David Pisoni for making the Simon apparatus and software available for use in this study and Luis Hernandez for his technical assistance.

References

American National Standards Institute. (1996). *American National Standard S3.6: Specifications for audiometers.* New York: Author.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: A new window to the study of cognitive aging. *Psychology and Aging, 12,* 12–21.

Cherry, K. E., & Stadler, M. A. (1995). Implicit learning of a nonverbal sequence in younger and older adults. *Psychology and Aging, 10,* 379–394.

Cleary, M., Pisoni, D. B., & Geers, A. E. (2001). Some measures of verbal and spatial working memory in eight- and nine-year-old hearing-impaired children with cochlear implants. *Ear & Hearing, 22,* 395–411.

Committee on Hearing and Bioacoustics and Biomechanics. (1988). Speech understanding and aging. *Journal of the Acoustical Society of America, 83,* 859–895.

Cox, R. M., Alexander, G. C., Gilmore, C. G., & Pusakulich, K. M. (1988). Use of the Connected Speech Test (CST) with hearing-impaired listeners. *Ear & Hearing, 9,* 198–207.

Curran, T. (1997). Effects of aging on implicit sequence learning: Accounting for sequence structure and explicit knowledge. *Psychological Research, 60,* 24–41.

Divenyi, P. L., & Haupt, K. M. (1997a). Audiological correlates of speech understanding under non-optimal conditions in elderly listeners with mild-to-moderate hearing loss. I. Age and laterality effects. *Ear & Hearing, 18,* 42–61.

Divenyi, P. L., & Haupt, K. M. (1997b). Audiological correlates of speech understanding under non-optimal conditions in elderly listeners with mild-to-moderate hearing loss. II. Correlational analysis. *Ear & Hearing, 18,* 100–113.

Divenyi, P. L., & Haupt, K. M. (1997c). Audiological correlates of speech understanding under non-optimal conditions in elderly listeners with mild-to-moderate hearing loss. III. Factor representation. *Ear & Hearing, 18,* 189–201.

Humes, L. E. (1996). Speech understanding in the elderly. *Journal of the American Academy of Audiology, 7,* 161–167.

Humes, L. E. (2002). Factors underlying the speech-recognition performance of elderly hearing-aid wearers. *Journal of the Acoustical Society of America, 112,* 1112–1132.

Humes, L. E., Christopherson, L. A., & Cokely, C. G. (1992). Central auditory processing disorders in the elderly: Fact or fiction? In J. Katz, N. Stecker, & D. Henderson (Eds.), *Central auditory processing: A transdisciplinary view* (pp. 141–149). Philadelphia: B.C. Decker.

Humes, L. E., Nelson, K. J., Pisoni, D. B., & Lively, S. E. (1993). Effects of age on serial recall of natural and synthetic speech. *Journal of Speech and Hearing Research, 36,* 634–639.

Humes, L. E., Watson, B. U., Christensen, L. A., Cokely, C. A., Halling, D. A., & Lee, L. W. (1994). Factors associated with individual differences in clinical measures of speech recognition among the elderly. *Journal of Speech and Hearing Research, 37,* 465–474.

Kalikow, D. N., Stevens, K. N., & Elliott, L. L. (1977). Development of a test of speech intelligibility in noise using sentence materials with controlled word predictability. *Journal of the Acoustical Society of America, 61,* 1337–1351.

Karpicke, J. D., & Pisoni, D. B. (2004). Using immediate memory span to measure implicit learning. *Memory & Cognition, 32,* 956–964.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49,* 467–477.

Levitt, H., & Resnick, S. B. (1978). Speech reception by the hearing impaired: Methods of testing and development of materials. *Scandinavian Audiology Supplement, 6,* 107–129.

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: A powerful connection. *Psychology and Aging, 9,* 339–355.

Pichora-Fuller, M. K. (1997). Language comprehension in older listeners. *Journal of Speech-Language Pathology and Audiology, 21,* 125–142.

Pisoni, D. B. (2000). Cognitive factors and cochlear implants: Some thoughts on perception, learning, and memory in speech perception. *Ear & Hearing, 21,* 70–78.

Pisoni, D. B., & Cleary, M. (2003). Measures of working memory span and verbal rehearsal speed in deaf children after cochlear implantation. *Ear & Hearing, 24*(Suppl. 1), 106S–120S.

Pisoni, D. B., & Cleary, M. (2004). Learning, memory, and cognitive processes in deaf children following cochlear implantation. In F. G. Zeng, A. N. Popper, & R. R. Fay (Eds.), *Springer handbook of auditory research: Vol. 20. Cochlear implants: Auditory prostheses & electric hearing*. New York: Springer-Verlag.

Pisoni, D. B., Cleary, M., Geers, A. E., & Tobey, E. A. (2000). Individual differences in effectiveness of cochlear implants in children who are prelingually deaf: New process measures of performance. *Volta Review, 101,* 111–164.

Pisoni, D. B., & Geers, A. (2000). Working memory in deaf children with cochlear implants: Correlations between digit span and measures of spoken language processing. *Annals of Otology, Rhinology and Laryngology, 109*(Suppl.), 92–93.

Reber, A. S., Walkenfeld, F. F., & Hernstadt, R. (1991). Implicit and explicit learning: Individual differences and IQ. *Journal of Experimental Psychology: Learning, Memory and Cognition, 17,* 888–896.

Salthouse, T. A. (1985). *A theory of cognitive aging*. New York: Elsevier.

Salthouse, T. A., McGuthry, K. E., & Hambrick, D. Z. (1999). A framework for analyzing and interpreting differential aging patterns: Application to three measures of implicit learning. *Aging, Neuropsychology, and Cognition, 6,* 1–18.

van Rooij, J. C. G. M., & Plomp, R. (1990). Auditive and cognitive factors in speech perception by elderly listeners: II. Multivariate analyses. *Journal of the Acoustical Society of America, 88,* 2611–2624.

van Rooij, J. C. G. M., & Plomp, R. (1992). Auditive and cognitive factors in speech perception by elderly listeners: III. Additional data and final discussion. *Journal of the Acoustical Society of America, 91,* 1028–1033.

van Rooij, J. C. G. M., Plomp, R., & Orlebeke, J. F. (1989). Auditive and cognitive factors in speech perception by elderly listeners: I. Development of test battery. *Journal of the Acoustical Society of America, 86,* 1294–1309.

Wechsler, D. (1981). *The Wechsler Adult Intelligence Scale—Revised*. New York: The Psychological Corporation.

Weinstein, B. E. (2000). *Geriatric audiology.* New York: Thieme.

Received September 4, 2003

Accepted May 19, 2004

DOI: 10.1044/1092-4388(2005/016)

Contact author: Larry E. Humes, Department of Speech & Hearing Sciences, Indiana University, Bloomington, IN 47405-7002. E-mail: humes@indiana.edu