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The Contributions of Audibility and Cognitive Factors to the Benefit Provided by Amplified Speech to Older Adults

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Abstract

In this review of recent studies from our laboratory at Indiana University, it is argued that audibility is the primary contributor to the speech-understanding difficulties of older adults in unaided listening, but that other factors, especially cognitive factors, emerge when the role of audibility has been minimized. The advantages and disadvantages of three basic approaches used in our laboratory to minimize the role of audibility are examined. The first of these made use of clinical fits of personal amplification devices, but generally failed to make the aided speech stimuli sufficiently audible for the listeners. As a result, hearing loss remained the predominant predictor of performance. The second approach made use of raised and spectrally shaped stimuli with identical shaping applied for all listeners. The third approach used spectrally shaped speech that ensured audibility (at least 10 dB sensation level) of the stimuli up to at least 4000 Hz for each individual listener. With few exceptions, the importance of cognitive factors was revealed once the speech stimuli were made sufficiently audible.

Sumario

En esta revisión de estudios recientes de nuestro laboratorio en la Universidad de Indiana, se argumenta que la audibilidad es el factor primario que contribuye en las dificultades para el entendimiento del lenguaje en adultos mayores, bajo condiciones no amplificadas de escucha, pero que existen otros factores, especialmente cognitivos, que emergen cuando el papel de la audibilidad ha sido minimizado. Se examinan las ventajas y desventajas de los tres enfoques básicos utilizados en nuestro laboratorio para minimizar el papel de la audibilidad. El primero de estos hace uso de los ajustes clínicos en dispositivos personales de amplificación, pero que fallaron en convertir los estímulos amplificados de lenguaje en algo suficientemente audible para el sujeto. Como resultado, la hipoacusia continuó siendo el factor de predicción predominante en el desempeño. El segundo enfoque hizo uso de estímulos aumentados y moldeados espectralmente, con un moldeado idéntico para todos los sujetos. El tercer enfoque utilizó lenguaje moldeado espectralmente que aseguraba la audibilidad del estímulo (al menos a 10 dB de nivel de sensación) hasta al menos 4000 Hz para cada sujeto individual. Con pocas excepciones, la importancia de los factores cognitivos se reveló una vez que los estímulos de lenguaje habían sido hechos suficientemente audibles.

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For the past 20 years, the Audiology Research Laboratory (ARL) at Indiana University has been interested in the effects of peripheral sensorineural hearing loss and aging on speech communication. It is well known that, as people age, they typically lose their sensitivity to high-frequency sounds and may also experience age-related changes in central auditory processing and cognition (e.g., Committee on Hearing and Bioacoustics and Biomechanics [CHABA], 1988; Humes, 1996; Schneider and Pichora-Fuller, 2000). Work from the ARL over the past two decades has emphasized the primacy of the negative effect of the peripheral sensorineural hearing loss on the speech-understanding performance of older adults (e.g., Humes and Roberts, 1990; Humes and Christopherson, 1991; Humes et al., 1994; Humes, 1991, 1996, 2002, 2005). In general, these reports have indicated that, when listening to unamplified speech over a range of speech levels from 60 to 90 dB SPL, 65-90% of the variance in various measures of speech understanding can be accounted for by individual differences in high-frequency hearing loss (usually, the high-frequency pure-tone average for 1000, 2000 and 4000 Hz). The ARL is by no means alone in this observation (e.g., van Rooij et al, 1989; van Rooij and Plomp, 1990, 1992; Jerger et al, 1989; Jerger et al, 1991; Gordon-Salant and Fitzgibbons, 1993; Divenyi and Haupt, 1997a, 1997b, 1997c; Dubno and Schaefer, 1992, 1995; Dubno and Ahlstrom, 1995a, 1995b; Dubno and Dirks, 1993).

This article begins by briefly reviewing why high-frequency hearing loss has been the predominant contributor to the speech-understanding performance of older adults, even when high presentation levels have been used. The primary focus, however, is placed on the identification of the factors impacting speech-understanding performance once audibility has been restored. Recent studies completed in the ARL have made use of three different approaches to audibility restoration. The pros and cons of each approach and the data obtained using each approach are reviewed next and represent the primary focus of this article.

IMPORTANCE OF AUDIBILITY

Figure 1A illustrates why high-frequency hearing loss plays such a prominent role in the recognition of unamplified speech by older adults. The lowest solid line in this figure represents the average hearing thresholds of normal-hearing young adults plotted as level per cycle or dB SPL/Hz. The dashed lines in Figure 1A show median hearing thresholds for males at ages of 60, 70 and 80 years. This progressive loss of high frequency hearing with age, in both men and women, is so well established that it forms the basis of an international standard (ISO 7029:2000; International Standards Organization [ISO], 2000), which was the source for the median thresholds in this panel. The three parallel solid lines in Figure 1A, labeled 60, 75 and 90 dB SPL, depict the corresponding root-mean-square (rms) long-term-average speech levels. The 60-dB curve was derived from the conversational speech spectrum in ANSI S3.5-1997, the national standard for the Speech Intelligibility Index (SII), and the remaining curves were generated by adding 15 and 30 dB, respectively, to these values. This approach was taken, rather than using the long-term spectra for speech generated by raised or shouted vocal efforts from the SII standard, because it represents the approach used almost universally by researchers and clinicians when assessing speech recognition. That is, the level of the speech is raised uniformly in most research laboratories and clinics when presenting speech at levels exceeding conversational speech and the spectrum is not shifted to higher frequencies as in naturally produced speech using raised or shouted vocal efforts.

Consider first the case of conversational speech level, represented by the lower curve labeled 60 dB SPL. If one uses the intersection of the lower solid line and the three dashed lines as an indication for the upper end of the audible bandwidth for the listener, then the median hearing thresholds for 60-, 70- and 80-year-old males progressively decrease the audible bandwidth from about 4000 Hz for the youngest group to about 2000 Hz for the oldest group. Using the points of intersection between the dashed lines and the lower solid line in Figure 1A, however, results in a gross overestimate of the true audible bandwidth. It is well known, for instance, that the rms amplitudes of the long-term speech spectrum must be at least 12-15 dB above threshold to be fully useful to the listener (e.g., French and Steinberg, 1947; Fletcher and Galt, 1950; ANSI, 1997). Taking this into account results in upper cutoff frequencies for the audible bandwidth of conversational (60 dB SPL) speech that are about an octave below those noted previously. Regardless of the details, it is apparent that, for typical older adults, as they age, progressive amounts of high-frequency speech energy are rendered inaudible. This results in progressively lower speech-recognition scores for the same fixed speech level of 60 dB SPL. If instead of fixing the speech and noise levels to measure percent-correct performance, one fixes the target performance level at 50%, or SRT, as with the Hearing in Noise Test (HINT; Nilsson et al., 1994), then this progressive decrease in high-frequency bandwidth results in the need for progressively higher-than-normal speech-to-noise ratios (Plomp,

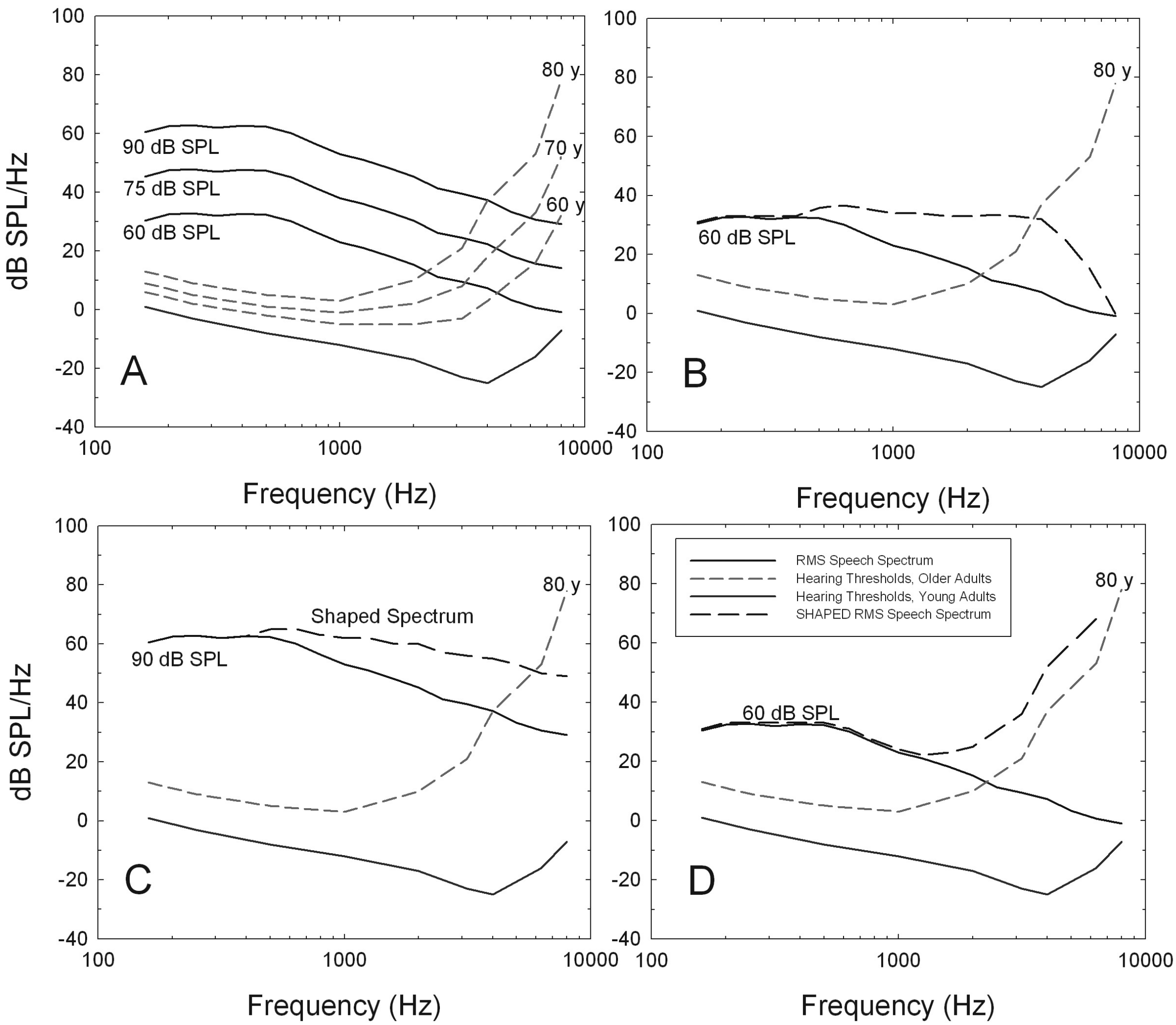

Figure 1. Illustration of four approaches to minimizing the contributions of audibility to speech understanding in older adults. In each panel, the lowest solid line represents median thresholds for young normal-hearing adults in dB SPL/Hz from ANSI (1997); the solid lines with dB-SPL values adjacent to them represent the long-term average speech spectrum; the short-dashed lines labeled in years represent median thresholds for males of various age groups from ISO 7029 (ISO, 2000); and the medium-dashed lines in panels B-D show various approaches to the spectral shaping of the speech spectrum. Panel A illustrates the approach which simply uses high presentations levels for the speech (and competing) stimuli. Panel B illustrates an approach using clinically fit linear hearing aids matched to common prescriptive targets for such devices. Panel C illustrates an approach that both raises the overall level, as in Panel A, but also applies additional spectral shaping (dashed line) in the high frequencies. Panel D illustrates an approach which spectrally shapes the speech (and competing) stimuli so that the long-term speech spectrum at conversational levels (60 dB SPL) is 15 dB above threshold through at least 4000 Hz.

1986; Van Tasell and Yanz, 1987; Humes et al, 1988; Lee and Humes, 1993; Nilsson et al., 1994).

Another noteworthy feature from the schematic illustration in Figure 1A has to do with the impact of presentation level on the audibility of high frequencies. Notice that, even when using a high presentation level of 90 dB SPL, levels that likely would be 40-50 dB above even the 80-year-olds' corresponding speech reception thresholds (SRTs), much of the high-frequency speech energy is still not audible. Use of a high presentation level alone, therefore, does not eliminate the problem of the inaudibility of many high-frequency speech sounds in older adults.

Finally, with regard to Figure 1A, the reader should keep in mind that the dashed lines represent idealized median values for each age group. For each age group, by definition, 50% of the individual hearing thresholds will lie above the median and 50% below the median. For example, ISO 7029:2000 (ISO, 2000), the international standard for age-related hearing loss, indicates that there is about a 25-30 dB variation from the 10th to the 90th percentiles in the high-frequency hearing thresholds for individuals 80 years of age. Thus, the dashed line representing the medians of the 60-year-olds approximates the hearing of the most sensitive decile of 80-year-olds with the least sensitive decile of the 80-year-olds having severe to profound hearing loss from 3000 to 8000 Hz. As a result, even among a group of adults of the same age, such as 80-year-olds, variations in the amount of high-frequency hearing loss will result in corresponding variations in audible bandwidth.

Not surprisingly, individual variations in audible bandwidth, as reflected by the amount of high-frequency hearing loss, can have significant impact on speech-recognition performance even for high presentation levels. Our most recent demonstration of this impact involved the presentation of time-compressed monosyllabic words to a large group (N=213) of individuals between the ages of 60 and 89 years (Humes, 2005). The Pearson-r correlation between word-recognition score and high-frequency PTA was 0.73, accounting for about 54% of the variance in scores. Even for 78 of the 213 older adults whose SRTs were less than 30 dB HL, performance at the 90 dB SPL presentation level was still moderately correlated with the amount of high-frequency hearing loss (r = -0.62).

Audibility or Cochlear Pathology?

The inaudibility of the high-frequency portion of the speech spectrum (Figure 1A) provides a viable explanation for such a finding, but this explanation is not the only possibility. Another possibility is that the hearing thresholds in sensorineural hearing loss could serve essentially as a "marker" for underlying cochlear pathology. The greater the hair cell loss in the base of the human cochlea, the greater the high-frequency hearing loss (e.g., Bredberg, 1968). Thus, the strong correlation between speech-understanding scores and high-frequency hearing loss, even at high speech levels, could be due to audibility restrictions from the hearing loss or due to the increasing amounts of cochlear pathology reflected by the hearing loss.

There are at least two broad approaches to disentangling the covariation of audibility and underlying cochlear pathology. One approach is to take individuals without underlying cochlear pathology and restrict audibility in a manner similar to that experienced by the hearing-impaired listeners, either via noise masking or filtering. There is a long history of the use of this approach and the results suggest that young normal-hearing listeners listening to filtered or noise-masked speech yield error rates and patterns similar to those measured in listeners with equivalent sensorineural hearing loss (e.g., Owens et al, 1972; Sher and Owens, 1974; Bilger and Wang, 1976; Wang et al, 1978; Fabry and Van Tasell, 1986; Humes et al, 1987; Zurek and Delhorne, 1987; Dubno and Dirks, 1993; Dubno and Schaefer, 1995). The findings from these and other similar studies support the suggestion that it is the loss of audibility, or loss of audibility plus reduced dynamic range in the case of noise-masked simulations, that reduces speech-recognition performance and not the presence of cochlear (or other) pathology per se.

AUDIBILITY RESTORATION

Another broad approach to evaluating the impact of audibility restrictions on speech recognition is to make the normally inaudible portions of the speech spectrum audible in listeners with existing cochlear pathology. This approach, referred to here as "audibility restoration," has been pursued much less often, in part, because it is more difficult to realize than the "simulated hearing loss" approach. On the other hand, this approach is much more germane to our understanding of *aided* speech understanding in older adults. The advantages and disadvantages of variations of the audibility-restoration approach, as well as the results from studies using these variations, are the focus of the remainder of this paper.

Audibility Restoration by Hearing Aids

Clearly, simply raising the level of the speech stimulus to very high levels (e.g., 90 dB SPL) does not accomplish this objective (Figure 1A). What about the use of conventional clinical amplification to compensate for the loss of high-frequency audibility in older adults? This approach is illustrated schematically in Figure 1B. Here, the dashed line merging with the long-term rms speech spectrum at 60 dB SPL (solid line) at the lower frequencies approximates the gain that would be provided in a conventional hearing aid fit using a common clinical prescriptive procedure for hearing aids, such as NAL-R (Byrne and Dillon, 1986).

Humes (2002) reported results from this approach to minimizing audibility that were obtained from 171 older adults fit with hearing aids matched to NAL-R prescriptive targets. The correlation between average high-frequency hearing loss and a weighted compilation of various aided speech-recognition scores, including sentences in quiet and noise at low to moderate levels (50-65 dB SPL) and nonsense syllables in noise at 65 dB SPL, was moderately strong and statistically significant ($r = -0.71$). Interestingly, however, speech-recognition performance in this study was also significantly correlated with age ($r = -0.38$), and the correlation between age and hearing loss was not significant ($r = 0.16$). When the data for 87 of the 171 older adults with milder amounts of hearing loss (high-frequency PTA < 50 dB HL) were examined separately, the correlations with hearing loss were much lower, accounting only for 14% of the variance, and more of the variance was explained by cognitive factors such as IQ. Once audibility restrictions have been overcome, then other factors, possibly cognitive in nature, might emerge as predictors of individual differences in performance. Thus, the approach outlined in Figure 1B was promising, but often the use of hearing aids could not fully compensate for the restricted audible bandwidth, at least using the technology and fitting approaches available at the time of these studies.

Audibility Restoration via Raised Level Plus Spectral Shaping

To better compensate for loss of audibility through at least 4000 Hz, subsequent research in the ARL has pursued the approach illustrated in panel C of Figure 1. The approach in Figure 1C, referred to here as "raised level plus shaped spectrum," is a variation of raised-level approach in Figure 1A. High presentation levels (e.g., 90 dB SPL) are used for the speech and competing signals, but additional spectral shaping (dashed line) is applied to the stimuli in the high frequencies to ensure sufficient audibility through at least 4000 Hz. Used in this way, the approach depicted in Figure 1C has the advantage of efficiency in the preparation of stimulus materials and the testing of listeners in that the desired spectral shaping is applied only once and to all materials. It also has the possible advantage of having less extreme variations in stimulus spectra across frequency, to the extent that such spectral imbalance might have a negative impact on speech perception (e.g., Skinner, 1980). Typically, subjects are then selected so that the shaped spectra are never less than 10-15 dB above the hearing thresholds of the listeners at any frequency from 250 through 4000 Hz.

Although this approach can ensure that the stimuli are sufficiently audible through 4000 Hz for all listeners, it does not ensure that they are equally audible for all listeners. Consider the case of fixing the presentation level at 90 dB SPL. For some listeners with more severe hearing loss, the stimuli will just be 10 or 15 dB above threshold whereas, for other listeners with milder amounts of hearing loss, especially in the high frequencies, the stimuli may be more than 30 dB above threshold. Thus, this method does not ensure *equivalent* audibility for all subjects, just *sufficient* audibility at all frequencies and for all subjects; at least as based on SII-like notions of sufficient audibility. Finally, this approach often results in much more than sufficient audibility *for all listeners* at the lower frequencies. In Figure 1C, for example, notice that the lower frequencies, in no need of amplification beyond conversational levels (60 dB SPL) due to the mild hearing loss at these frequencies, are actually increased 30 dB for the high-intensity (90 dB SPL) spectrally shaped speech. This may be an issue of even greater importance when both the target speech stimuli and competing stimuli, either noise or other speech, undergo similarly excessive increases in level in the low frequencies which may lead to unnecessary increases in the upward spread of masking in the mid- and high-frequency regions (e.g., Stelmachowicz et al., 1990; Dubno and Ahlstrom, 1995a).

Three recent studies from our laboratory made use of the approach illustrated schematically in Figure 1C: the raised level plus spectral shaping approach. It was hypothesized that correlations with hearing loss would be minimized under such conditions, if elevated high-frequency hearing thresholds primarily represented audibility restrictions rather than markers for the severity of the underlying cochlear (or other) pathology.

Shrivastav et al (2006) used the raised-level-plus-spectral-shaping approach and included 20 older adults with varying degrees of high-frequency hearing loss as participants. This study found that percent-correct scores on the CUNY nonsense syllable test (Levitt and Resnick, 1978), when spectrally shaped and presented in quiet at an overall level of 86 dB SPL, were not correlated ($r = -0.15$) with average high-frequency hearing loss. Although these listeners were not tested without spectral shaping of the speech materials (this was not the central focus of this study), we have established strong negative correlations of -0.7 to -0.9 between performance on the unshaped CUNY NST and average high-frequency hearing loss in similar groups of participants in several other studies, including some using high presentation levels of 90 dB SPL (e.g., Humes and Roberts, 1990; Humes et al., 1994; Halling and Humes, 2000).

The central focus for the study by Shrivastav et al. (2006) was the relationship between individual differences in spectral-shape discrimination abilities and speech-identification performance in older adults. The data indicated that there was a significant correlation ($r = -0.60$) between these two measures, such that those older adults with better (lower) spectral-shape discrimination thresholds had higher speech-identification scores on the CUNY NST. It is conjectured here that, if the stimuli were not made sufficiently audible so as to eliminate the strong correlation between speech-identification performance and average high-frequency hearing loss, such a correlation with spectral-shape discrimination thresholds would not have emerged. Basically, the strong association between hearing loss and speech-identification performance that would have existed for unshaped speech materials would have accounted for a very large proportion (50-80%) of the variance, allowing few other factors to emerge. It should be noted that spectral-shape discrimination is considered by many to be a higher-level centrally mediated process in which relative amplitude patterns across frequency are compared (Green, 1988). Thus, when sufficient audibility has been provided for the speech (and /f/ vs. /s/ spectral-shape) stimuli, other central or cognitive factors emerged which helped explain individual differences in speech-identification performance.

In another recent study that made use of the audibility-restoration approach outlined in Figure 1C, Humes et al (2006) observed a pattern of results similar to that of Shrivastav et al. (2006). In this case, however, the speech-understanding measures were obtained in the presence of competing speech. The speech stimuli were from the Coordinate Response Measure (CRM; Bolia et al., 2000), which is a sentence-length, closed-set speech-identification test. The competition was another item from the same stimulus materials, but spoken by a different talker. Either before (selective attention) or after (divided attention) both sentences were presented to the listener, a cue word was flashed on the computer monitor indicating which talker (male or female) was the target talker to which the listener should attend. Performance in the divided-attention task generally was worse than that in the corresponding selective-attention task. More importantly, there were individual differences in performance among the older adults and these individual differences were not related to the amount of high-frequency hearing loss. Thus, the identification of speech spoken by one talker in the presence of very similar competing speech spoken by a talker of the opposite gender was not related to hearing loss once sufficient spectral shaping had been applied to the high-intensity (90 dB SPL, unshaped) speech stimuli. In this study, direct verification of "sufficient" audibility for the CRM was obtained by measuring the performance of each listener for the target talker alone; that is, without a simultaneous competing talker. In all of the older listeners (N = 13), performance without competition was at least 96% correct for the raised and spectrally shaped CRM materials. Finally, correlational analyses not only failed to find significant correlations with average high-frequency hearing loss, but also observed significant and moderate ($r = 0.58$ to 0.76) positive correlations between measures of digit span and CRM scores. Once again, although these older hearing-impaired listeners never received unshaped materials, based on prior work, it is very likely that correlations with high-frequency hearing loss would have been observed and would most likely account for so much variance that the correlations with cognitive measures, such as digit span, would not have emerged.

Figure 2 shows the final set of data obtained using the general approach of Figure 1C (raised level plus spectral shaping). In this study (Humes et al, 2007), the revised Speech Perception in Noise (SPIN) test (Bilger et al., 1984) was one of the tests used in the assessment of 26 older adults. This test makes use of both predictability-low (PL) and predictability-high (PH) sentences administered in the presence of a multi-talker babble spectrally matched to the sentences. The data shown are for one representative listening condition in which the rms level of the speech was 3 dB greater than the rms level of the babble. In this case, using raised and spectrally shaped stimuli, the approach to audibility restoration illustrated previously in Figure 1C, performance was correlated negatively with average high-frequency hearing loss. In particular, correlations between average high-frequency hearing loss and speech-recognition performance for the PL and PH items were $r = -0.75$ and $r = -0.56$, respectively. Both correlations were statistically significant ($p < .01$). Visual inspection of the data in Figure 2, however, suggests that there is little or no dependence of speech-recognition performance on hearing loss for average hearing loss ≤30 dB HL, followed by a sharper dependence on average hearing loss above 30 dB HL. This was confirmed statistically by computing separate correlations for those having average high-frequency hearing loss ≤30 dB HL versus >30 dB HL. For the subgroup with little or no high-frequency hearing loss (N = 12), correlations were $r = 0.08$ and 0.15 ($p > 0.1$) for the PL and PH items, respectively. For the subgroup with greater than 30 dB HL average high-frequency hearing loss (N = 14), the correlations were essentially identical to those noted above for the entire group.

It is unclear why the results for the SPIN test from the subgroup of 14 older adults with average high-frequency hearing loss >30 dB HL from this study differ from those of the other two studies reviewed previously using a similar approach to audibility restoration. In all three studies reviewed, there were no significant correlations between age and average high-frequency hearing loss, so the correlations observed in Figure 2 are not a secondary manifestation of an effect of age. Since the materials used for the speech and background stimuli differed across all of the studies in our laboratory that have used this approach to audibility restoration, it is possible that what is "sufficient" audibility for one set of materials may not be sufficient for other speech materials. We did not obtain SPIN-PL and SPIN-PH scores in quiet for these same 26 listeners to verify that the speech items were, in fact, sufficiently audible. However, we did obtain scores for monosyllabic words (NU-6; VA recording) in quiet that had been subjected to the same spectral shaping approach outlined in Figure 1C. These scores, when obtained from the subgroup with milder high-frequency hearing loss, did not differ from those obtained from a group of 13 young normal-hearing listeners tested under identical conditions. The subgroup of older adults with average high-frequency hearing loss exceeding 30 dB HL, however, did perform significantly worse than both the young and older groups with normal or near-normal hearing when listening to the spectrally shaped monosyllables in quiet. Moreover, across all 26 older adults, there was a strong, significant and negative correlation ($r = -0.72$, $p < 0.01$) between NU-6 performance in quiet and average high-frequency hearing loss, consistent with that observed for the SPIN-PL scores (obtained in a background of multi-talker babble) in Figure 2. Thus, the association between speech-recognition performance and average high-frequency hearing loss observed in this study is not specific to the recognition of high- or low-context sentences in babble since the same basic relationship exists for the recognition of monosyllables in quiet for these same listeners.

The foregoing discussion of the data in Figure 2 from Humes et al. (2007), however, should not be taken to imply that high-frequency hearing loss was the *only* variable associated with performance on the PL and PH sentences of the SPIN test. An interesting feature of this study was the use of a visual text-recognition task that paralleled the auditory speech-recognition task. This approach was patterned after that pursued in vision alone by Speranza et al. (2000). Basically, the subjects not only heard the SPIN sentences in babble, but also read text versions of the SPIN sentences in visual noise on the computer monitor in a separate measurement of performance. When the auditory SPIN-PL scores of Figure 2 served as the dependent measure in a linear-regression analysis with age, average high-frequency hearing loss, IQ, and visual SPIN-PL score as the predictor variables, two predictors emerged. Average hearing loss accounted for 53% of the variance, and performance on the visual SPIN task accounted for an additional 11% of the variance. For an identical analysis of the high-context auditory SPIN-PH scores (with visual SPIN-PH score used as a predictor, along with age, hearing loss, and IQ), two significant predictors were again identified. Average high-frequency hearing loss accounted for 25% of the variance, and 19% additional variance was accounted for by performance on the visual SPIN task. Thus, even in this study, when significant negative correlations remained between average high-frequency hearing loss and auditory speech-recognition performance, despite efforts to restore audibility, other non-auditory measures emerged as predictors of substantial portions of additional variance not accounted for by hearing loss. The correlations with the corresponding visual version of the SPIN task were interpreted as reflecting a general cognitive ability to reconstruct the whole from its degraded parts or fragments, whether those degraded fragments are delivered to the

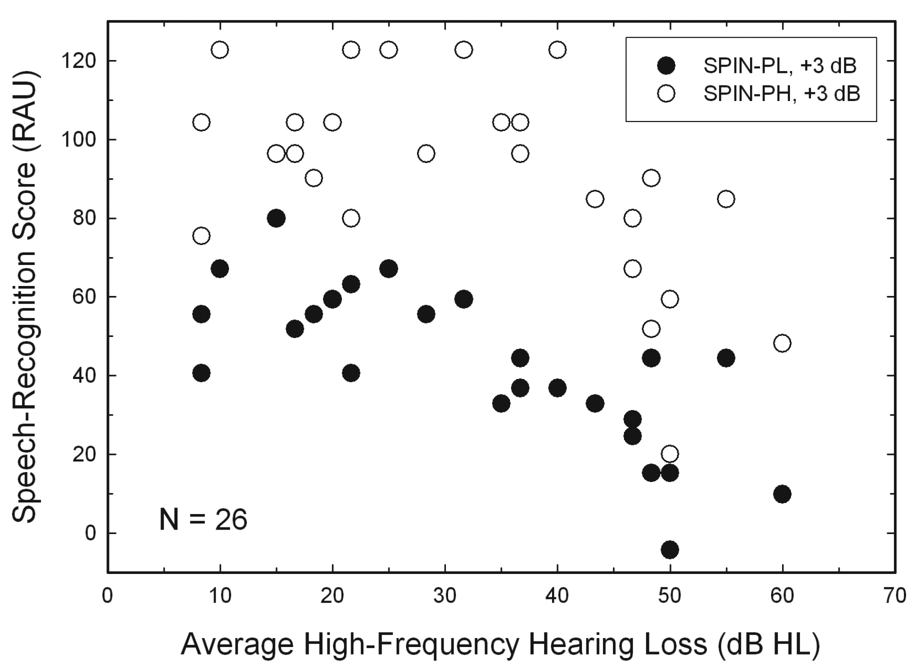

Figure 2. Scatterplots of RAU-transformed (Studebaker, 1985) percent-correct scores for the low-predictability (PL; filled circles) and high-predictability (PH; unfilled circles) items of the Speech Perception in Noise (SPIN) test versus average high-frequency hearing loss for 26 older adults from Humes et al (2007). Data shown were obtained at a + 3dB speech-to-babble ratio.

brain through the auditory system or the visual system.

To recap, three studies from the ARL have used raised plus spectrally shaped stimuli, the approach illustrated schematically in Figure 1C, in groups of older adults with varying degrees of high-frequency hearing loss in an attempt to minimize the contributions of audibility to speech-recognition performance. In two of the three studies, no dependence of speech-recognition performance on average high-frequency hearing loss was observed. In one study (Figure 2), however, speech-recognition performance was found to depend on average high-frequency hearing loss, especially when the average hearing loss in the high frequencies exceeded 30 dB HL. Even here, however, substantial portions of variance were explained by additional cognitive variables.

Audibility Restoration via Spectrally Shaped Speech

The final approach reviewed here, and used in several recent studies in our laboratory, is illustrated schematically in Figure 1D. The objective again is to make the speech (and background) stimuli "sufficiently" audible from 250 through at least 4000 Hz. The difference between approaches illustrated in Figure 1C and 1D is that, if conversational level speech (60-65 dB SPL) is sufficiently audible in a particular frequency region, typically the lower frequencies, then no amplification is provided using the spectral shaping approach. "Sufficiently audible" has been defined as the rms spectrum of the target speech stimulus being 10-15 dB above hearing threshold in that same frequency region. This approach is akin to realizing the theoretical objective of the Desired Sensation Level (DSL; Seewald, 1996) with hearing aids. The variation in amplitude across frequency is greater with this approach than that of Figure 1C, but the likelihood of increased upward spread of masking from unnecessarily high low-frequency amplitudes has been decreased with this approach compared to that of Figure 1C. Most often, the audibility-restoration approach described in Figure 1D was applied in our laboratory on an individual basis, as would be the case with hearing aids. Four recent studies in the ARL made use of this approach and are reviewed here.

Amos and Humes (2007) pursued an approach that was most similar to that illustrated in Figure 1D, but shared some features with the approach in Figure 1C as well. In that study, a total of 36 older adults with varying degrees of high-frequency hearing loss were studied. The speech and noise stimuli used to measure speech recognition were shaped so that the amplitude at any frequency (through 6000 Hz) was at least 15 dB higher than the greatest amount of hearing loss observed in *any* of the 36 listeners at that same frequency. Thus, only for those individuals approaching the maximum hearing loss of the group at each frequency would the shaped spectrum be just 15 dB above threshold. For all other participants with milder amounts of hearing loss, the stimulus level would be greater than 15 dB above threshold. Rather than individually shaping the spectrum for each listener, however, all 36 older adults received the same shaped spectrum. This met or exceeded the 15-dB criterion at each frequency for "sufficient" audibility of the speech stimulus and resulted in less low-frequency amplitude than the approach in Figure 1C, while still enabling the use of a single shaped spectrum for all participants.

Amos and Humes (2007) obtained word-recognition scores for the AB word lists (Boothroyd, 1995) in quiet and in noise (spectrally matched noise) at a +5 dB signal-to-noise ratio. The top panel of Figure 3 illustrates the dependence of the word-recognition score for unshaped speech at conversational level (65 dB SPL) on the average high-frequency hearing loss of the listener for 24 of the 36 subjects for whom these measures were obtained. The significant ($p < .01$) and negative correlations were $r = -0.82$ and $r = -0.88$ for quiet (filled circles) and noise (unfilled circles) conditions, respectively. When these materials were spectrally shaped, as described, and presented to all 36 participants in quiet and noise, the correlations were weak and nonsignificant ($r = -0.11$ and -0.22), as shown in the lower panel of Figure 3. For these 36 older adults, spectral shaping enabled previously inaudible speech energy to be heard and, when this was accomplished, the amount of high-frequency hearing loss no longer impacted word-recognition performance in quiet or in noise.

Further, just as in some of the prior studies that had used raised and spectrally shaped speech (the approach in Figure 1C), regression analyses performed on the data for spectrally shaped speech in quiet and noise for these 36 older adults identified various central or cognitive factors underlying individual differences in speech-recognition performance (Amos, 2001). For the quiet condition, for example, measures of speechreading, cognitive function (WAIS-R, arithmetic subscale), auditory temporal-order discrimination, and hearing loss at 1000 Hz accounted for 61% of variance in speech-recognition performance. Likewise, for speech in noise, 51% of the variance was accounted for by measures of speechreading, cognitive function (WAIS-R similarities and object-assembly subscales) and the hearing threshold at 250 Hz. Note that high-frequency thresholds did not account for significant amounts of variance for either speech

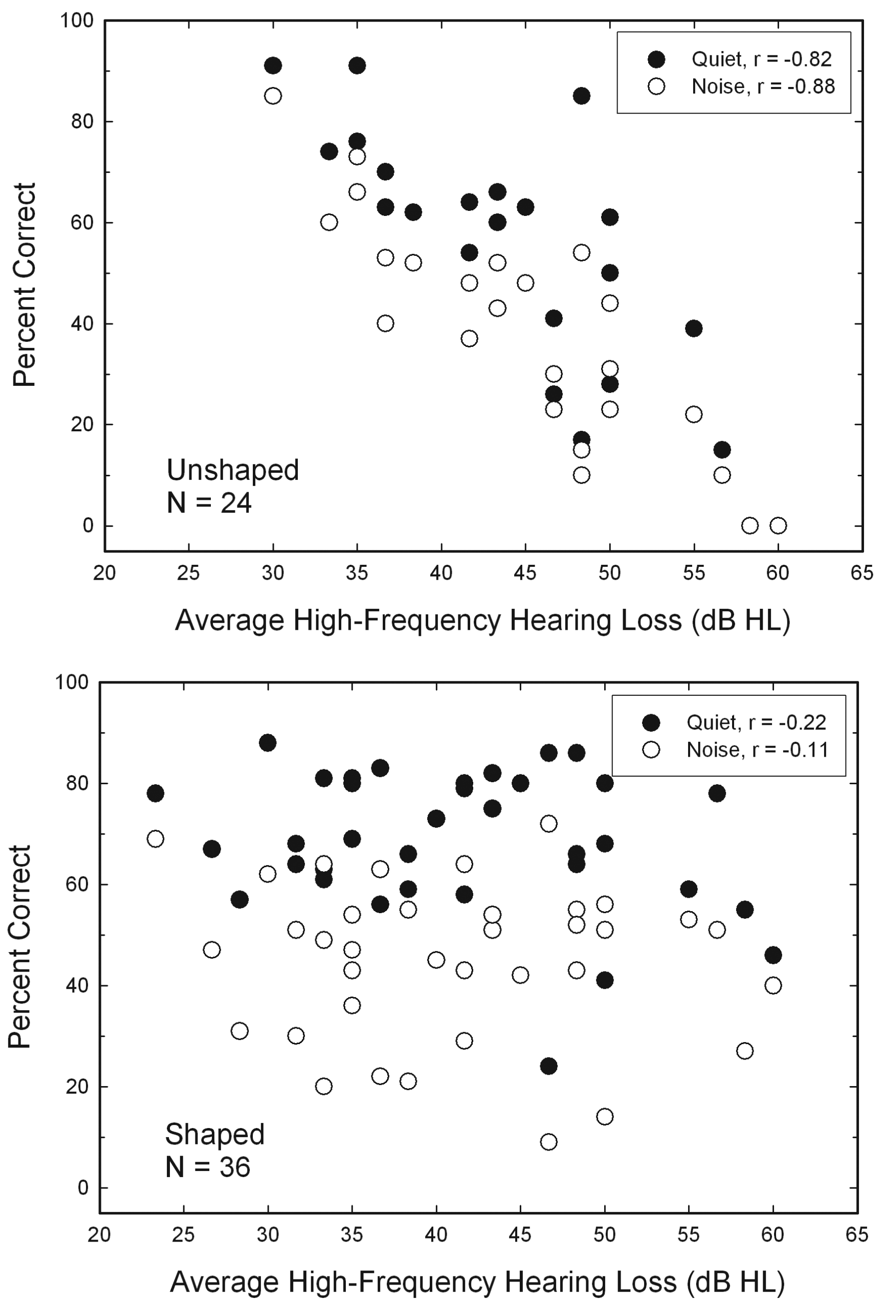

Figure 3. Scatterplots of the data from Amos and Humes (2007) for quiet (filled circles) and noise (unfilled circles) when speech and competition were either unshaped (top panel) or spectrally shaped (bottom panel). Correlations (r) are shown in each panel. Data for the unshaped condition were obtained for only 24 of the 36 older subjects.

recognition in quiet or in noise. On the other hand, central or cognitive variables, such as the various subtests of the WAIS-R, played a significant role in accounting for individual differences among older adults listening to spectrally shaped speech in quiet and noise. This was also reflected by the entry of various speechreading measures into each regression equation, assuming the process of speechreading can be considered generally to be an ability to reconstruct the whole from fragments, whether the fragments are auditory, visual, or both (e.g., Watson et al., 1996).

We have also employed the spectral shaping approach to audibility restoration illustrated in Figure 1D in two studies of word-based training programs. In both cases, the speech and competing noise stimuli used were shaped individually to provide sufficient audibility. In the first of these two studies (Burk et al, 2006), the same AB words lists and spectrally matched competing noise used by Amos and Humes (2007) were employed both before and after training. Weak, nonsignificant correlations of $r = -0.26$ (pre-training) and $r = -0.27$ (post-training) were observed between word-recognition scores and average high-frequency hearing loss in seven older listeners for these spectrally shaped stimuli. Three of four possible correlations between word-recognition performance and average high-frequency hearing loss were not significant. Thus, the data from older listeners in these two training studies, in which speech and noise stimuli were individually spectrally shaped to levels 15-20 dB above threshold from 250 through 4000 Hz, suggest that such spectral shaping minimizes or eliminates the dependence of word-recognition performance on the amount of high-frequency hearing loss.

In the final study making use of the approach illustrated by Figure 1D, Coughlin (2004) obtained sentence-identification scores using the CRM, described previously, in eight different conditions; all were essentially selective-attention conditions. For the 19 older listeners in this study, performance on the CRM was not correlated significantly with hearing loss, but was negatively correlated with age ($r = -0.51$). The correlation between age and average high-frequency hearing loss was 0.28 and not significant ($p > 0.10$). When linear regression analyses were performed for these 19 older listeners, 49% of the variance in CRM performance was accounted for by two variables: years of education and age. The greater the number of years of education and the younger the listener, the better the performance on the CRM task across the eight test conditions. As important, average high-frequency hearing loss did not enter the step-wise regression solution. Thus, once again, when the speech stimuli have been spectrally shaped in the high frequencies, strong associations between speech- identification performance and high-frequency hearing loss disappear, or are at least muted, and associations with other variables, typically cognitive or central in nature, emerge.

To recap, four recent studies in the ARL have made use of the spectral shaping approach similar to that illustrated in Figure 1D. The majority of the data obtained using this approach to minimize the contributions of inaudibility to speech-recognition performance have successfully negated the impact of the high-frequency hearing loss on performance. When doing so, other variables have often emerged to account for individual differences in performance among the elderly, and these have frequently been central or cognitive in nature.

CONCLUSION

This article has reviewed several recent studies of speech understanding in older adults from our laboratory which have made use of various approaches to restoring audibility. When considered together with prior work from our laboratory and others, across studies and approaches, a pattern emerges. Specifically, without spectral shaping to compensate for the loss of audibility in the high frequencies, older adults with impaired hearing exhibit poorer speech-recognition performance than young adults. This is true even for relatively high speech presentation levels. Among the group of older adults, in most studies, individual differences in speech-understanding performance for unshaped speech are largely determined by individual differences in average high-frequency hearing loss. When audibility is restored (to varying degrees) through at least 4000 Hz via spectral shaping, however, individual differences in performance among the older listeners can no longer be attributed to hearing thresholds. Instead, other factors, typically age or various cognitive measures, emerge as correlates with speech-understanding performance once audibility has been restored. These variables, alone or in combination, often accounted for 30-50% of the variance in the speech-understanding performance of older adults for spectrally shaped speech.

Finally, it is important to note that minimizing the impact of high-frequency hearing loss through spectral shaping does not mean that the older adults in these studies are performing equivalently to young normal-hearing adults. To the contrary, if a fixed signal-to-noise ratio was employed in a particular study, then the older adults typically performed worse than the younger adults. If the signal-to-noise ratio was adjusted to equate performance levels in some reference condition, then older adults typically required a better signal-to-noise ratio than young normal-hearing adults to achieve this performance criterion. When such a pattern of results has been observed for spectrally shaped speech, knowing that the impact of inaudibility of the high frequencies has been minimized or eliminated enables one to rule out such inaudibility as an explanation of any residual differences in performance between younger and older adults.

As noted, spectrally shaped speech, especially when generated following the approach illustrated in Figure 1D, closely resembles the situation existing for well-fit hearing aids. Assuming that clinically fit hearing aids provide "sufficient audibility" of the speech (and background) stimuli through at least 4000 Hz, then it is likely that individual differences in the speech-understanding benefit experienced by older adults will be determined by aging, cognitive, or central factors. These residual factors appear to underlie the need for a better-than-normal signal-to-noise ratio in *some* older adults when listening to spectrally shaped speech and noise.

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