Speech Recognition in Adults with Hearing Loss: Effects of Age, Amplification, and Noise

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Abstract
This study focused on three factors: age, noise modulation, and linear versus wide-dynamic compression amplification. Three audio metrically matched groups of adults with hearing loss were tested to determine at what age performance declined relative to that expected on the basis of audibility. Recognition fell below predicted scores by greater amounts as age increased. Scores were higher for steady versus amplitude-modulated noise. Scores for WDRC-amplified speech were slightly lower than for linearly amplified speech across all groups and noise conditions. We found no interaction between age and type of noise. The small reduction in scores for amplitude-modulated compared to steady noise and lack of age interaction suggests that the substantial deficit seen with age in multitalker babble for previous studies was due to some effect not elicited here, such as informational masking.

This hypothesis is consistent with recent data that audibility also over-predicted adults performance in interrupted speech spectrum noise (Dubno et al, 2002). Second, the multitalker babble was comprised of speech that could have been cognitively meaningful (i.e., informational masking). Given that cognitive processing ability declines with age (e.g., Jerger and Chmiel, 1996; Humes and Floyd, 2005), use of meaningful background noise may have degraded performance more for older than for younger listeners. For example, Souza and Turner (1994) found speech recognition of older listeners with hearing loss to be 20% poorer, on average, in a background of multitalker babble versus a speech-spectrum noise with the same temporal characteristics. Today, appropriately fit amplification usually means WDRC processing (e.g., Ross, 2001). We do not know what the relationship between audibility and recognition will be when speech in noise is WDRC amplified. Although the long-term average speech levels incorporated in traditional audibility indices can predict WDRC-amplified speech recognition in quiet (Souza and Turner, 1999), audibility of WDRC-amplified speech in noise probably depends on many time-varying factors, including the signal-to-noise ratio, modulation rate and modulation depth of the noise, duration of the noise “dips,” and time constants of the compressor (e.g., Stone et al, 1997; Verschuure et al, 1998; Moore et al, 1999). On one hand, WDRC amplification can improve audibility of brief, low-intensity speech components (Stelmachowicz et al, 1995; Jenstad and Souza, 2005). To the extent that these brief improvements in audibility are related to better speech recognition, we might expect recognition of WDRC-amplified speech in noise to be better than linearly amplified speech at a given audibility index value. On the other hand, WDRC amplification can decrease the signal-to-noise ratio by increasing low-level noise during speech pauses, at least when the spectra of the speech and noise are similar and with a small number of compression channels et al, 2006), which might reduce recognition. Recognition scores were slightly lower (about 2%, on average) for WDRC-amplified speech in noise than for linearly amplified speech in noise. Audibility was roughly controlled for by matching group mean audiograms for the younger and older listeners and by maintaining the same long term average speech input level across amplification conditions, but speech audibility at the output of the amplifier was not determined, nor was audibility assessed for individual listeners. An alternative approach (applied in the present study) is to quantify audibility then compare performance according to age and background noise types. In addition to these factors, the specific age of the listener may also have played a role.

METHOD

Subjects

Participants included 35 listeners with bilateral hearing loss, divided into three Audio metrically matched age groups (Table 1). Significant air-bone gap (>10 dB) and static admittance and tympana metric peak pressure exceeding normal limits in the test ear (Roup et al, 1998) excluded listeners from participation. All listeners had symmetrical loss except for four listeners who had a conductive component in the non test ear and one listener who had a profound loss in the non test ear. Except for those five listeners, one ear was randomly selected for testing. Mean audiometric thresholds for the test ear are shown in Figure 1.

Table 1. Number of Participants and Age for the Groups with Hearing Loss

Group	n	Age Range (years)	Mean Age (years)	Gender
1	10	50–65	58.2	6 female 4 male
2	12	67–75	71.6	9 female 3 male
3	13	77–82	80.2	10 female 3 male

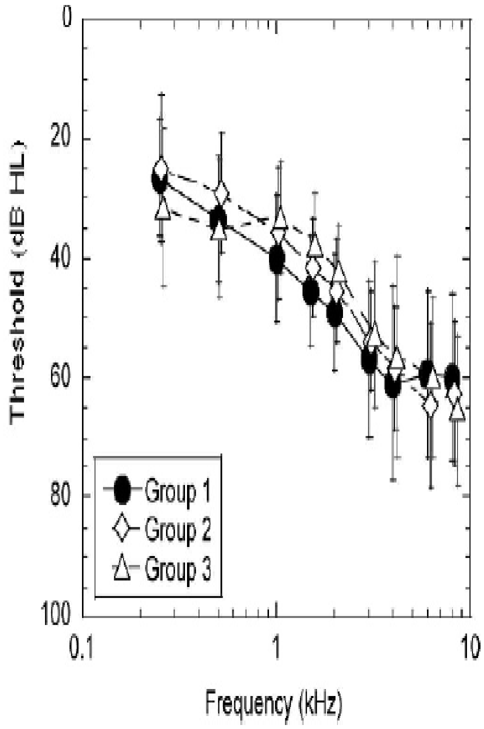

figure 1. Mean audiometric thresholds for the three groups with hearing loss. Error bars show plus or minus one standard deviation about the mean. Symbols have been offset slightly for ease of viewing.

Statistically, there was no significant difference between groups at any frequency (p = .807). A control group of ten listeners with normal hearing (mean age 23.5 years, range 20—27 years) was also tested. All of the listeners with normal hearing had audiometric thresholds of 20 dB HL or better at .25, .5, 1, 2, 3, 4, 6, and 8 kHz bilaterally and were also tested in one randomly selected ear. All participants were screened for cognitive deficits using the Mini-Mental State Examination (MMSE; Folstein et al, 1975). The minimum MMSE score required for study participation was 26 out of 30, and no prospective subject was excluded on this basis. Short-term memory was assessed using the auditory forward and backward digit span tests from the WAIS-III (Wechsler, 1997). The general health of the participants was self-assessed utilizing a scale ranging from 1 (poor) to 7 (excellent). MMSE, forward and backward digit spans, and general health scores for each group are shown in Table 2. The digit span results were consistent with those reported for similar age groups (Bopp and Verhaeghen, 2005).1 Using one-way analyses of variance (ANOVA), there were no significant differences across the four groups for MMSE (p = .189), forward digit span (p = .659), backward digit span (p = .631), or general health (p = .695).

Materials

The Connected Speech Test (CST; Cox et al, 1987) was used to measure speech recognition. Each test passage consisted of nine or ten sentences (25 key words) on a single topic. The passages were taken from a compact disc recording (Cox, 1994) and digitally transferred onto the hard drive of a computer.
Two different noises were used. The steady noise was taken from the CST recording and had the same long-term spectrum as the CST sentences. The noise was digitally transferred onto the hard drive of a computer. The amplitude-modulated noise was created using the 12-talker babble from the CST recording, digitally transferred onto the hard drive of a computer. The envelope of the babble was obtained by digitally rectifying and low-pass filtering the waveform with a cutoff frequency of 30 Hz. The envelope was digitally multiplied by the steady noise described above. To create speech-in-noise materials, the long-term root-mean-

square speech levels were held constant at a 70 dB SPL input level, and the long-term root-mean-square noise levels were adjusted for the desired SNR. The speech and noise were then digitally mixed together. Four signal-to-noise ratios, - 2, +2, +6, and +10 dB, were used to create conditions with a range of speech audibility.

Amplification

To create the linear amplification conditions, an individual frequency-gain target was generated for each subject using the NAL-R prescription and expressed as 2 cm3 coupler targets (Byrne and Dillon, 1986). An equalizer (Rane GE-30) and amplifier (Crown D-75) were used to adjust the frequency-gain response, and the final response was measured in a 2 cm3 coupler. In line with Dillon's (2001) suggestion that a deviation from target of 10 dB or greater would be of concern, the subject was excluded from participation if a match to target within 10 dB could not be obtained within the limits of our equipment at .25, .5, 1, 2, 3, or 4 kHz. In practice, this excluded potential subjects with precipitous, reverse slope, or cookie bite losses, resulting in a more homogenous subject group. Therefore, it supported our desire to select subjects with similar audiograms across a range of ages. Figure 2 shows individual target and measured gain at each frequency. Data points on the solid diagonal indicate an exact match to target.
The dashed diagonal lines indicate the 10 dB outer limit of acceptability. A good match (generally, within 5 dB) was achieved for most listeners above .5 kHz. Because this was intended as a control condition, the participants with normal hearing heard the same, high-frequency emphasis stimuli as the participants with hearing loss but with less overall gain, adjusted to a comfortable (based on pilot testing) presentation level of 74 dB SPL.

Table 2. Mean (and standard deviation) for the Mini-Mental State Examination, Forward and Backward Digit Span, and General Health Rating for Each Group

Group	MMSE	Digit Span Forward	Digit Span Backward	General Health
1	28.9 (1.8)	7.5 (1.4)	6.1 (1.4)	5.4 (.7)
2	28.4 (1.8)	6.8 (1.1)	5.2 (.9)	5.9 (1.3)
3	28.2 (1.6)	6.7 (.9)	5.2 (1.3)	5.9 (.9)
NH	29.7 (.7)	7.0 (.9)	5.4 (.8)	6.2 (1.1)

The sentence and noise combinations were digitally processed with a locally developed compression program implemented in C code. The program used a sliding exponential window to calculate the RMS value of the segment preceding each digital point. If the point value exceeded a compression threshold of 45 dB SPL, amplitude compression was applied. The NAL-NL1 prescription (Dillon, 1999) was used to generate an individual compression ratio for each subject. Because the differences in the individually prescribed NAL-NL1 compression ratios were small (range 1.6:1 to 2.4:1, mean 2.2:1), a 2.0:1 compression ratio was used for all subjects. For all conditions, the attack time was 5 m sec and the release time was 50 m sec (re: ANSI, 1996). This single-channel WDRC condition was not intended to assess the entire range of WDRC types (often multichannel) in current clinical use but, rather, to provide a simple assessment of the effect of amplitude compression on erformance relative to audibility. An individual frequency-gain target was generated for each subject using the NAL-NL1 software and expressed as 2 cm3 coupler targets (Dillon, 1999), and an equalizer (Rane GE-30) and amplifier (Crown D-75) were used to adjust the frequency-gain response, with the final response measured in a 2 cm3 coupler. As expected given the similarity of NAL-R and NAL-NL1 conversational-level targets, the match to target was similar to that shown in Figure 2.

Calculating Audibility for Linearly Amplified Speech

The long-term average spectra of the speech and noise were measured in 16 one third octave bands from .2 kHz to 8 kHz. All levels were expressed as dB SPL in a 2 cm3 coupler and represented sound levels received by an individual listener, incorporating input levels of the speech or noise, individual frequency-gain response, and earphone effects. Speech measurements were based on a concatenated set of sentences approximately two minutes in length. Separate measurements were obtained for three concatenated sentence sets, exclusive of pauses between words, which were randomly selected from three different passages of the Connected Speech Test. The three samples were similar (±2 dB between .25 and 4 kHz); accordingly, a single two minute segment was selected as representative of the overall speech spectrum. Noise measurements were based on a two-minute segment of noise. Measured spectra for the steady and amplitude modulated noises were virtually identical (±1 dB between .2 and 8 kHz), as expected because the amplitude-modulated noise was created from the steady noise. Accordingly, the values for the steady noises were used to represent both noise spectra. Audibility was calculated using the Aided Audibility Index, or AAI (Stelmachowicz et al, 1994), implemented via locally developed C language code. This was similar to the traditional Articulation Index (French and Steinberg, 1947; Fletcher and Galt, 1950) but also accounted for amplification characteristics such as output limiting distortion and reduction of the speech dynamic range from wide-dynamic range compression. A single AAI value was calculated for each subject/amplification type/signal-to-noise ratio combination.

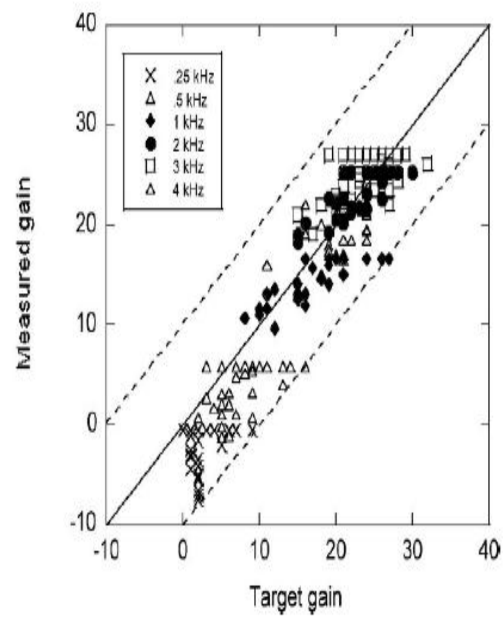

Figure 2. Comparison of target and measured gain. The diagonal line indicated an exact match to target. Dashed lines indicate the ±10 dB range considered acceptable for this study.

Inputs to the program were the subject's audiometric thresholds, converted from dB HL to dB SPL (ANSI, 1996) and the speech and noise levels for each condition. Importance weights were the CST weights provided by Sherbecoe and Studebaker (2002). Because the long-term average spectrum was the same for the steady as for the amplitude-modulated noise, data points for the two noise backgrounds for the same subject, amplification type, and signal-to noise ratio had the same AAI. However, we expected different recognition scores depending on how each noise affected that particular listener.

Calculating Audibility for WDRC Amplified Speech

Audibility for the WDRC-amplified conditions was calculated as described above, with a few modifications. Because speech and noise were mixed together prior to digital compression, it was not possible to access the speech and noise levels at the output of the compressor directly. To obtain these levels, speech and noise were separated after compression processing using a digital inversion technique (Souza et al 2006). In addition to the measured speech and noise levels and audiometric thresholds, compression ratios were also entered. These were measured in 1/3-octave bands, where the compression ratio was calculated as the ratio of the 5th–95th percentile ranges of the linear and compressed speech. Use of measured instead of nominal compression ratios was based on previous work (Souza and Turner, 1999) that demonstrated improved accuracy of AAI predictions with that method.

Procedure

The listener was seated in a double walled sound-treated booth. Stimuli were presented monaurally via an Etymotic Research ER-2 insert earphone. Two passages were presented in each condition. Passages were paired according to the instructions for the CST, in which predetermined passage pairs of are equal difficulty. As dictated by the test instructions, the listener was told the passage topic prior to each passage. After the listener was informed of the passage topic, one sentence was played at a time.
The experimenter was seated outside the sound booth and recorded the responses as the listener repeated the sentences through an intercom system. For each condition, a percent-correct score was calculated for each passage pair based on 50 words. Sixteen test conditions were presented in random order, each consisting of a different background noise (steady state, amplitude modulated), SNR (-2, +2, +6, and +10 dB), and amplification type (linear, WDRC).

RESULTS

Mean scores for each group and test condition, averaged across the four signal-to-noise ratios, are shown in Table 3. Scores were lower for the groups with hearing loss than for the group with normal hearing; among the groups with hearing loss, scores decreased with increasing age; and scores were slightly lower for WDRC-amplified speech in noise than for linearly amplified speech in noise. Variability was higher for the groups with hearing loss than for the group with normal hearing and increased slightly with increasing age. Figure 3 shows individual speech recognition scores as a function of audibility for the listeners with normal hearing. As expected, these listeners performed well even

Table 3. Mean Speech Recognition Score (and standard deviation), Averaged across the Four Signal-to-Noise Ratios, for Each Group and Test Condition

Amplification	Linear	Linear	WDRC	WDRC
Noise type	Steady	Amplitude modulated	Steady	Amplitude modulated
1	76.1 (21.3)	74.6 (23.4)	72.9 (24.5)	72.9 (24.7)
2	71.5 (23.4)	70.3 (23.3)	71.4 (21.8)	69.3 (24.8)
3	65.5 (27.4)	62.3 (27.0)	62.2 (25.5)	60.5 (27.1)
NH	94.6 (7.3)	94.0 (8.1)	93.7 (7.4)	92.9 (8.5)

at reduced signal audibility, reaching an asymptotic score of 100%. Sherbecoe and Studebaker's (2003) performance predictions for the Connected Speech Test are also shown, along with the 95% critical difference range for these materials (Cox et al, 1988). Scores for the linearly amplified speech were consistent with the predictions. Scores for the WDRC-amplified speech were also well predicted at moderate to high audibility, although our listeners with normal hearing performed better than predicted at low audibility. Performance for the three older groups with hearing loss is shown in Figure 4 (linear) and Figure 5 (WDRC). In each panel, predicted score according to Sherbecoe and Studebaker (2003) was plotted for comparison, along with the 95% critical difference values (Cox et al, 1988). For the linear condition, audibility ranged from about .30 to .75 AAI. The range of audibility was the same in each of the three groups, as expected because the mean audiogram was the same in each group. In comparison to the listeners with normal hearing, the listeners with hearing loss showed greater performance variability, and performance for each group was poorer than predicted on the basis of audibility.

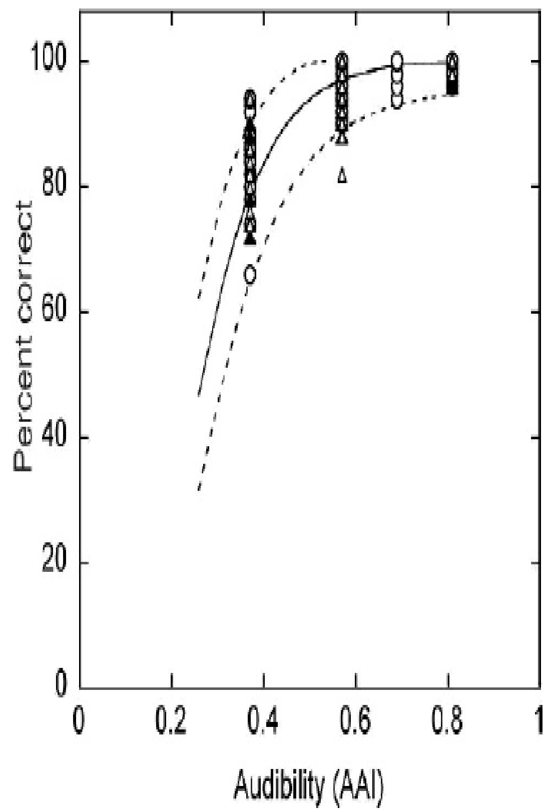

Figure 3. Percent correct scores for the listeners with normal hearing as a function of audibility. Results are shown for the linearly amplified speech in steady noise (filled circles) and amplitude modulated noise (open circles) and for the WDRC amplified speech in steady noise (filled triangles) and amplitude-modulated noise (open triangles). Solid line shows predicted performance, according to Sherbecoe and Studebaker (2003). Dashed lines show the critical difference range.

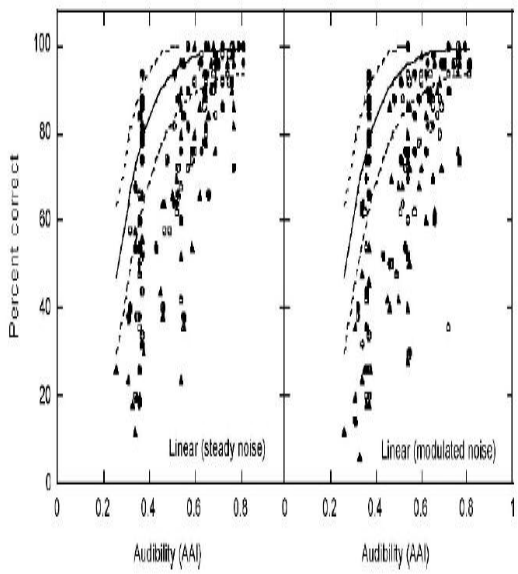

Figure 4. Percent correct scores for linearly amplified speech as a function of audibility. The left panel shows results for speech in steady noise, and the right panel shows results for speech in amplitude-modulated noise. Data shown are for Group 1 (filled circles), Group 2 (open circles), and Group 3 (filled triangles). Solid line shows predicted performance, according to Sherbecoe and Studebaker (2003). Dashed lines show the critical difference range.

Predicted and actual scores were converted to rationalized arcsine units (RAU; Studebaker, 1985), and the difference between the actual score and predicted score was calculated for each data point. To examine the effect of listener age, these data were submitted to a three-way, repeated-measures analysis of variance. Comparisons were made across the two noise types, two amplification types, and four participant groups. The three-way interaction was non significant ($p = .739$). The type of amplification did not interact with background noise ($p = .439$) or with age group ($p = .783$). In contrast to our hypothesis, noise type did not interact with age group ($p = .851$). The difference between actual and predicted score was greater for amplitude modulated than for steady noise ($p < .0005$), although the difference was small. On average, performance for steady noise was about 1.5% below performance for amplitude modulated noise. Across all conditions and age groups, the actual-predicted difference was larger for linear than for WDRC amplification ($p = .021$). This was not because of higher WDRC scores; on average, linear scores were higher by 1–2%. Instead, this difference reflected higher AAIs (and therefore higher predicted scores) for the linear conditions. There was a significant difference across the four groups ($p < .0005$). Post hoc analysis (Fisher's LSD) detailed these differences as follows. Each of the groups was significantly different from one another ($p < .0005$ for each comparison, except $p = .037$ for Group 2 vs. Groups 3 or 1). That is, the group with normal hearing was closest to the predicted scores, with the hearing-impaired groups falling below predicted scores by greater amounts as age increased (Table 4).

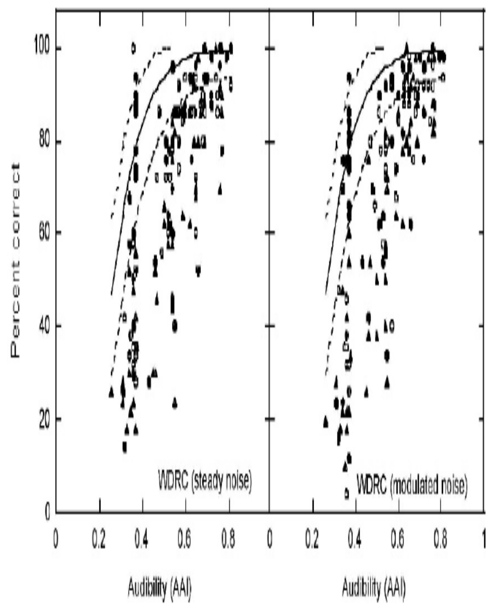

figure 5. Data as for Figure 4, except for the WDRC-amplified speech. The left panel shows results for speech in steady noise, and the right panel shows results for speech in amplitude-modulated noise. Data shown are for Group 1 (filled circles), Group 2 (open circles), and Group 3 (filled triangles).
Solid line shows predicted performance, according to Sherbecoe and Studebaker (2003). Dashed lines show the critical difference range.

Table 4. Mean Deviation from Predicted Score (in RAU) for Each Group

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Amplification	Linear	Linear	WDRC	WDRC
Noise type	Steady	Amplitude modulated	Steady	Amplitude modulated
1	-17.9	-20.4	-16.1	-16.5
2	-25.2	-26.5	-19.9	-22.3
3	-28.6	-32.6	-26.5	-27.8
NH	1.8	0.8	5.4	5.1

Note: Negative values indicate that the actual score was poorer than predicted on the basis of audibility.

DISCUSSION

Effects of Age

In the present study, performance worsened significantly with increasing age, even among listeners younger than 75 years. While these data were based on a small number of participants per group, they were consistent with several previous studies that suggested performance decline for difficult listening tasks begins as early as the sixth decade (e.g., Schum et al, 1991; Dubno et al, 2002; Sherbecoe and Studebaker, 2003). Because the three groups were well matched for amount of hearing loss, this finding was unlikely to be due to increasing threshold elevation. Indeed, the youngest of the three hearing-impaired groups had the poorest average thresholds within the 1–4 kHz range. Because we were not able to recruit participants of very advanced age (our oldest participant was 82), these data do not answer the question of whether there is an additional, rapid decrease in performance as listeners move into their late 80s and 90s, as some (e.g., Magnusson, 1996) have suggested. Such questions are of great interest to researchers as this portion of the population increases, but we have found that practical issues of health, transportation, and fatigue limit the willingness of those adults to volunteer for research studies. We treated age as a categorical variable
to allow comparison of performance across audiometrically matched groups. An alternative approach would have been to treat age as a continuous variable, recruit listeners of various ages regardless of audiogram, and apply statistical controls for degree of hearing loss. However, that technique is valid

only when the variables of interest (in this case, age and audiogram) do not covary (Newsom et al, 2003). We expected that as age increased, high frequency thresholds would also tend to increase (Gates et al, 1990), reducing the power of that approach.

Effects of Noise Type

With regard to steady versus amplitude modulated noise, our data confirmed the pattern suggested by multiple studies (e.g., Dubno et al, 1984, 2002; Schum et al, 1991; Hargus and Gordon-Salant, 1995; Magnusson, 1996; Magnusson et al, 2001; Humes, 2002), namely, that audibility was a better predictor of performance in steady noise than in amplitude-modulated (babble) noise. However, the difference in scores was smaller than that seen in other studies that compared steady noise to babble (e.g., Keidser, 1991; Souza and Turner, 1994). Also, in contrast to the idea that the oldest listeners might be less able to distinguish between the varying temporal patterns of the speech and the masker, we found no interaction between age and type of noise. Taken together, the small reduction in scores for the multi talker babble compared to steady noise and the lack of any age interaction suggested that the substantial deficit seen with advanced age in multitalker babble for previous studies was due to some effect not elicited here, such as cognitive confusion (i.e., informational masking). A similar conclusion was reached by Gordon-Salant and Wightman (1983), who found that synthetic consonant vowel syllables were affected more by synthetic consonant-vowel maskers than by spectrally similar masking noise or naturally spoken multi talker babble.

In other words, the more similar in percept the masker was to the target speech, the greater the masking effect.

Calculating Audibility

We used the AAI (Stelmachowicz et al, 1994) as an index of audibility. At present, this is the only index that incorporates nonlinear amplification characteristics. For linearly amplified speech, the AAI was nearly identical to the conventional Articulation Index or Speech Intelligibility Index, albeit with small differences in the assumed short-term speech range. Therefore, Speech Intelligibility Index derived performance predictions such as those developed by Sherbecoe and Studebaker (2003) seemed appropriate for comparison. This was further verified by the close agreement between predicted performance (using the Speech Intelligibility Index-derived transfer function) and our normal-hearing data (Figure 3). Previous work showed that the performance increase for a given increase in AAI was the same for linearly amplified as for WDRC amplified speech (Souza and Turner, 1999), suggesting that the same prediction function could be used for the WDRC condition. Because the long-term average spectrum of the amplitude-modulated noise and the steady noise was the same, the same noise levels were input to the AAI calculation for both noise backgrounds. This did not account for moment-to-moment fluctuations in noise amplitude. Several time-windowed versions of the audibility index have been proposed (e.g., Houtgast et al, 1992; Rhebergen and Versfeld, 2005), but all are intended to be applied when noise is 100%

amplitude modulated. For the continuous noise used here, even though it is not a constant amplitude noise, the standard audibility index calculation was more appropriate. In its conventional form, the AAI accounts for speech audibility. To the extent that speech recognition is reduced by degraded spectral resolution or other distortions inherent to hearing loss (e.g., Oxenham and Bacon, 2003), listeners with hearing loss would be expected to fall below predicted performance. Some researchers have proposed including a correction for hearing loss “desensitization” that would reduce predicted performance to be more typical of listeners with hearing loss. We purposely did not include such a correction in this case, for several reasons. First, although several such desensitization adjustments have been proposed (e.g., Pavlovic et al, 1986; Ching et al, 1997), none is universally accepted. Second, we were interested in performance decrements not accounted for by audibility. To that end, we expected that performance by the listeners with hearing loss would fall below predicted performance. Indeed, when considered as a single group of listeners with hearing loss, our results were similar to those reported by Sherbecoe and Studebaker (2003) for a variety of studies with the same materials. For example, for the linearly amplified speech presented in steady noise, the 35 listeners with hearing loss underperformed the predicted score by 24.4 RAU, on average, compared to the 25.1 RAU reported by Sherbecoe and Studebaker. We were more interested in whether the difference between predicted and actual performance varied across age groups, or with different background noises. Thus, the data presented here do not answer the question of whether lower-than-predicted performance for Group 1 is due to hearing loss, to age, or to a combination of those factors.

Wide-Dynamic Range Compression Amplification

For each presented signal-to-noise ratio, audibility was higher for the linear speech. This reflected the acoustic characteristics of our single-channel compressed signal. In recent work (Souza et al, 2006), we noted a poorer signal-to-noise ratio at the output of a single channel, fast-acting WDRC system, due to an increase in noise level during the pauses between words. Although this increased the long-term average noise level and therefore lowered the AAI, it may not significantly alter performance. At least for listeners with normal hearing, we expected that increased noise during speech pauses should have little effect on speech recognition, because at those points in the signal there was no speech to recognize. For listeners with normal hearing, the critical issue was any noise present simultaneously with target words. This may be why the listeners with normal hearing performed better than predicted at low AAIs (Figure 4). For listeners with hearing loss and less masking release (e.g., Bacon et al, 1998), the increase in noise during speech pauses may adversely affect performance for the following word. This study provided a limited view of performance relative to that predicted by audibility when speech is WDRC amplified. In this case, performance was slightly lower for WDRC-amplified speech. This was consistent with our previous work (e.g., Boike, 2004) but should not be assumed to be the case with all WDRC amplifiers. First, this study used a single, conversational-level input. Based on previous work, we would expect to see little advantage of WDRC amplification at this input level, and greater improvements over multiple input levels or for low-intensity inputs (Souza and Turner, 1998; Jenstad et al, 1999). Second, multichannel WDRC amplification may also offer greater benefit, especially when the noise is lower (or higher) in frequency than speech and when reduced gain in some channels might improve the signal-to-noise ratio. Investigation of those factors underlies the complexity of audibility predictions with advanced signalprocessing amplification.

Abbreviations: AAI = Aided Audibility Index; CST = Connected Speech Test; MMSE = Mini-Mental State Exam; RMS = root-mean square; WAIS = Wechsler Adult Intelligence Scale; WDRC = wide-dynamic range compression

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