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Clinical Experience with the Words-in-Noise Test on 3430 Veterans: Comparisons with Pure-Tone Thresholds and Word Recognition in Quiet

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Abstract

Background: Since the 1940s, measures of pure-tone sensitivity and speech recognition in quiet have been vital components of the audiologic evaluation. Although early investigators urged that speech recognition in noise also should be a component of the audiologic evaluation, only recently has this suggestion started to become a reality. This report focuses on the Words-in-Noise (WIN) Test, which evaluates word recognition in multitalker babble at seven signal-to-noise ratios and uses the 50% correct point (in dB SNR) calculated with the Spearman-Kärber equation as the primary metric. The WIN was developed and validated in a series of 12 laboratory studies. The current study examined the effectiveness of the WIN materials for measuring the word-recognition performance of patients in a typical clinical setting.

Purpose: To examine the relations among three audiometric measures including pure-tone thresholds, word-recognition performances in quiet, and word-recognition performances in multitalker babble for veterans seeking remediation for their hearing loss.

Research Design: Retrospective, descriptive.

Study Sample: The participants were 3430 veterans who for the most part were evaluated consecutively in the Audiology Clinic at the VA Medical Center, Mountain Home, Tennessee. The mean age was 62.3 yr (SD = 12.8 yr).

Data Collection and Analysis: The data were collected in the course of a 60 min routine audiologic evaluation. A history, otoscopy, and aural-acoustic immittance measures also were included in the clinic protocol but were not evaluated in this report.

Results: Overall, the 1000–8000 Hz thresholds were significantly lower (better) in the right ear (RE) than in the left ear (LE). There was a direct relation between age and the pure-tone thresholds, with greater change across age in the high frequencies than in the low frequencies. Notched audiograms at 4000 Hz were observed in at least one ear in 41% of the participants with more unilateral than bilateral notches. Normal pure-tone thresholds (≤20 dB HL) were obtained from 6% of the participants. Maximum performance on the Northwestern University Auditory Test No. 6 (NU-6) in quiet was ≥90% correct by 50% of the participants, with an additional 20% performing at ≥80% correct; the RE performed 1–3% better than the LE. Of the 3291 who completed the WIN on both ears, only 7% exhibited normal performance (50% correct point of ≤6 dB SNR). Overall, WIN performance was significantly better in the RE (mean = 13.3 dB SNR) than in the LE (mean = 13.8 dB SNR). Recognition performance on both the NU-6 and the WIN decreased as a function of both pure-tone hearing loss and age. There was a stronger relation between the high-frequency pure-tone average (1000, 2000, and 4000 Hz) and the WIN than between the pure-tone average (500, 1000, and 2000 Hz) and the WIN.

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Conclusions: The results on the WIN from both the previous laboratory studies and the current clinical study indicate that the WIN is an appropriate clinic instrument to assess word-recognition performance in background noise. Recognition performance on a speech-in-quiet task does not predict performance on a speech-in-noise task, as the two tasks reflect different domains of auditory function. Experience with the WIN indicates that word-in-noise tasks should be considered the "stress test" for auditory function.

Key Words: audiogram, hearing loss, signal-to-noise ratio, speech perception, words/speech in noise, words/speech in quiet

Abbreviations: BKB-SIN = Bamford-Kowal-Bench Speech-in-Noise Test; HINT = Hearing in Noise Test; HFPTA = high-frequency pure-tone average (1000, 2000, and 4000 Hz); HL = old listeners with sensorineural hearing loss; PTA = pure-tone average (500, 1000, and 2000 Hz); QuickSIN = Quick Speech-in-Noise Test; SNR = signal-to-noise ratio; SPRINT = Speech Recognition in Noise Test; SSN = speech-spectrum noise; WIN = Words-in-Noise Test; YNH = young listeners with normal hearing for pure tones

For the past 60 yr evaluating the ability of a patient to understand speech in quiet, usually with words, has been an intricate component of the audiologic evaluation. Early on, Carhart (1951) recognized that the abilities to understand speech in quiet could be divided into essentially two categories. Individuals in the first category had an *acuity* hearing loss, which today we would term a *sensitivity* hearing loss (Ward, 1964). Speech-recognition performance in quiet for individuals with sensitivity hearing losses continually increased (within limits) as the presentation level of the speech signal increased. This behavior is observed with conductive hearing loss and with many types of sensorineural hearing loss. Carhart indicated that individuals in the second category had a *clarity* hearing loss, the main characteristic of which was their inability to improve to any degree their speech-recognition performance as the presentation level of the speech signal in quiet was increased. Usually individuals in this second category had poor speech-recognition performance regardless of the presentation level.[1] Twenty years later, Carhart and Tillman (1970), using speech-in-noise paradigms to study speech perception in listeners with sensorineural hearing loss, observed that "it appears that by the time background talk reaches a level where it is just mildly disruptive to intelligibility of normal hearers it can become a serious masker for the sensorineural" (p. 279). Based on the data from their study and data from Groen (1969), Carhart and Tillman urged that in addition to the traditional pure-tone audiogram and "discrimination" loss measured with words in quiet, audiologic evaluations should include a measure of the ability of the patient to understand speech in background noise. Interestingly at that time, Carhart and his colleagues had developed two speech-in-noise tests designated NU-20, both of which incorporated the words from the Northwestern University Auditory Test No. 6 (NU-6 [Tillman and Carhart, 1966]). NU-20S used the Bell Telephone Intelligibility Sentences as the competing message or masker, whereas NU-20N used speech-spectrum noise (SSN) as the masker (Olsen and Carhart, 1967). Unfortunately, probably because of the lack of a commercial vehicle, NU-20S and NU-20N were relegated primarily to the research laboratory and were never implemented clinically, thus leaving a void in speech audiometry for a words-in-noise instrument that would endure for a number of years.

The majority of speech-in-noise tests developed during the following 35 yr were sentence materials presented either in SSN or in multitalker babble. These included the Speech Perception in Noise Test (Kalikow et al, 1977; Bilger, 1984), the Connected Speech Test (Cox et al, 1987), the Speech-in-Noise Test (Killion and Villchur, 1993) that evolved into the Quick Speech-in-Noise Test (QuickSIN [Killion et al, 2004]), the Hearing in Noise Test (HINT [Nilsson et al, 1994]), and the Bamford-Kowal-Bench Speech-in-Noise Test (BKB-SIN [Etymōtic Research, 2005]) that uses the Americanized BKB sentences (Bench et al, 1979). Sentences are an attractive stimulus as they are more representative of everyday speech than are isolated words; however, as Silverman and Hirsh (1955) suggested, "The speech stimulus that is required for the most effective diagnostic differentiation is not necessarily the most representative of everyday speech" (p. 1241). For a variety of reasons the sentence tests have not gained widespread implementation in clinic practice. Exceptions are the HINT sentences (in quiet), which are used widely in cochlear implant programs, and the QuickSIN, which is probably the most commonly used speech-in-noise test (Strom, 2006).

To fill the aforementioned void and following preliminary work (Wilson and Strouse, 2002), the Words-in-Noise (WIN) Test was developed (Wilson, 2003). The WIN Test consists of monosyllabic words presented in multitalker babble at seven signal-to-noise ratios (SNRs) from 24 to 0 dB in 4 dB decrements, with the presentation level of the words varied and the level of the babble fixed. The data can be displayed graphically with recognition performance as a function of SNR, but the primary metric is the 50% correct point (expressed in dB SNR), which is calculated with the Spearman-Kärber equation (Finney, 1952; see Appendix A). The

70 monosyllabic words used in the WIN are from NU-6 recorded by a female speaker (Department of Veterans Affairs, 1998). The noise is a six-talker babble originally recorded by G. Donald Causey (pers. comm., 1979; Sperry et al, 1997). In comparison with the standard SSN, which has a flat spectrum to 1000 Hz with a 12 dB/octave slope above 1000 Hz (American National Standards Institute, 2004), the babble has a similar spectrum but different amplitude-modulation characteristics (Wilson et al, 2007a, Figure 1, p. 524). In the WIN, each word was fixed temporally in a unique, 4.3 sec segment of babble. To avoid clicks at the segment boundaries, the beginning and end of each babble segment were edited at the negative-going zero crossings. The original WIN, which used 70 words (5 min), subsequently was shortened for clinical implementation to two 35-word lists (2.5 min) in which five words are presented at each SNR (Wilson and Burks, 2005). A stopping rule is used to terminate the test when all words at one SNR are incorrect. Normal performance on the WIN is a 50% correct point that is ≤6 dB SNR (Wilson et al, 2003).

Since the original WIN article (Wilson, 2003), a multitude of experiments have been conducted with the WIN materials, usually with a control group of young listeners with normal hearing for pure tones and an experimental group of ≥60-yr-old listeners with sensorineural hearing loss. Most often the inclusion criteria for the groups with hearing loss included a pure-tone average (500, 1000, and 2000 Hz) of ≤40 dB HL; thresholds at 500 and 1000 Hz of ≤30 dB HL and ≤40 dB HL, respectively; and maximum word recognition in quiet ≥40%. The 12 studies, which are summarized in Table 1, were conducted within the framework of the research laboratory, with listeners serving in only one study. The studies involved the 70-word and 35-word versions of the WIN, various types of maskers, intra- and intersession reliability, and comparisons with other speech-in-noise paradigms. The effects of age and hearing loss for pure tones were always under investigation. Among the studies, the mean 50% points on the WIN for young adult listeners with normal hearing range from 2.7 to 5.0 dB SNR, whereas for listeners with hearing loss the range of 50% points is from 9.4 to 15.8 dB SNR, usually dependent on the listener inclusion criteria.

The data from these laboratory studies (1) confirm the efficacy of using the WIN to separate listeners with hearing loss from listeners with normal hearing and (2) provide a gradient measure for how listeners with hearing loss recognize speech in background noise. The current study examined the effectiveness of the WIN materials for measuring recognition performance in noise in a typical clinic setting with patients for whom the WIN was intended (Bilger, 1984), i.e., patients with the gamut of hearing losses matriculating through an audiology clinic. The study focused on WIN performance with respect to age and hearing loss for pure tones using the WIN 50% points calculated with the Spearman-Kärber equation and the WIN psychometric functions as metrics.

METHOD

Participants

The 3430 participants were consecutive, new patients to the Audiology Clinic. The ages ranged from 20 to 89 yr (mean = 62.3 yr; SD = 12.8 yr). Gender was not recorded in the database, however, only 1.5% of the veterans evaluated in the Audiology Clinic during the study period were female. Although the database included data from 3430 veterans, for a variety of reasons including (1) "dead ears" and no responses to test stimuli and (2) data validation issues, complete data on all patients were not available, which accounts for the different number of participants involved in the various analyses.

Procedures

All data were collected during the course of a 60 min audiologic evaluation. The evaluation consisted of a case history, otoscopic examination, aural-acoustic immittance measures, pure-tone audiometry, the WIN, and NU-6 in quiet (Department of Veterans Affairs, 2006). The modified Hughson-Westlake method (Carhart and Jerger, 1959) was used for pure-tone audiometry, with bone-conduction testing as indicated. Thresholds for interoctave frequencies were obtained only when the thresholds for the adjacent octaves differed by ≥20 dB.

In lieu of a speech-recognition threshold, the protocol for the current data used the three-frequency pure-tone average (PTA; 500, 1000, and 2000 Hz) as the determinant of the WIN babble presentation level. The PTA is highly correlated with the speech-recognition threshold, which is a recognized measure of the audibility of speech (Carhart, 1946b). Thus, to avoid audibility issues, the multitalker babble of the WIN was presented either at 80 dB SPL when the PTA was ≤40 dB HL (American National Standards Institute, 2004) or at 90 dB SPL when the PTA was between 42 and 58 dB HL. The WIN was not administered when the PTA was ≥60 dB HL. Historically, investigations have focused on the relation between the PTA and the speech-recognition threshold measured with spondaic words (e.g., Carhart, 1946a, 1946b; Fletcher, 1950). Regarding the relation between pure-tone thresholds and the ability to understand speech, Harris et al (1956) realized that "certainly different equations would best fit spondee and PB speech scores" (p. 164), meaning that the pure-tone thresholds that best predict

Table 1. Summary of the Words-in-Noise Test (WIN) Results from 12 Studies Involving Young Adults with Normal Pure-Tone Thresholds (YNH) and Listeners of Various Ages with Hearing Loss (HL)

Study	Group (Age)	Material/ Condition	Mean Age (Years)	*n*	High-Frequency Pure-Tone Average (dB HL)	Mean 50% Point (dB SNR)	SD (dB)	Minimum (dB SNR)	Maximum (dB SNR)
Wilson et al, 2003	YNH	WIN	21.1	24	1.7	4.1	1.4	1.2	6.8
	HL (28–80 yr)	WIN	58.5	24	35.8	9.4	3.4	4.4	18.8
Wilson and Weakley, 2004	YHN	WIN	20.6	24	–	3.2	1.8	–1.6	6.0
		Digit Triplets in Babble				–14.7	2.7	–19.2	–9.4
	HL (>60 yr)	WIN	63.5	48	43.8	12.2	3.8	4.8	20.8
		Digit Triplets in Babble				–6.0	2.4	–12.8	–1.7
Wilson et al, 2005	HL (38–82 yr)	WIN—random level	64.0	40	43.4	12.7	3.8	4.8	20.4
		WIN—descending level				13.1	4.0	6.0	22.0
Wilson and Burks, 2005	HL (45–83 yr)	WIN List 1, test	67.9	48	44.8	13.8	4.1	3.6	23.6
		WIN List 1, retest				13.2	4.0	3.6	24.4
		WIN List 2, test				13.5	3.9	6.0	22.8
		WIN List 2, retest				13.1	3.8	6.8	23.6
McArdle et al, 2005	YNH	WIN	23.3	36	3.3	4.7	2.2	–2.0	10.8
		QuickSIN				4.1	2.1	2.5	12.5
		Digit Triplets in Babble				–11.8	2.8	–22.0	–6.9
	HL (31–85 yr)	WIN	65.5	72	41.6	12.4	3.6	4.4	21.2
		QuickSIN				11.7	5.2	2.5	25.5
		Digit Triplets in Babble				–4.0	3.6	–12.2	6.0
Wilson and Weakley, 2005	YNH	WIN	20.5	25	3.4	3.5	1.2	1.6	5.6
	HL (40–49 yr)	WIN	44.8	25	35.3	9.4	3.2	4.8	15.6
	HL (50–59 yr)	WIN	54.8	25	43.8	11.1	4.0	4.8	20.4
	HL (60–69 yr)	WIN	64.8	25	45.9	12.1	3.3	4.8	18.0
	HL (70–79 yr)	WIN	73.9	25	46.8	13.1	4.0	5.6	24.0
	HL (80–89 yr)	WIN	82.0	25	48.6	14.6	3.7	6.4	20.8
Wilson et al, 2006	HL (44–85 yr)	WIN Binaural	63.8	96	45.7	12.3	3.9	3.6	23.6
		Digit Triplets in Babble—LE				–3.5	3.3	–9.1	6.0
		Digit Triplets in Babble—RE				–3.3	2.9	–10.0	4.7
Wilson et al, 2007a	YNH	WIN	23.4	24	7.3	4.5	1.3	1.6	6.8
		WIN (Broadband Noise)				0.4	1.3	–3.3	2.7
		WIN (Speech-Spectrum Noise)				6.6	1.0	4.8	8.8
	HL (65–83 yr)	WIN	74.0	48	47.8	15.2	4.1	6.4	22.4
		WIN (Broadband Noise)				13.2	3.4	7.2	20.8
		WIN (Speech-Spectrum Noise)				15.8	3.5	8.4	22.0

(*Continued*)

Table 1. Continued

Study	Group (Age)	Material/ Condition	Mean Age (Years)	*n*	High-Frequency Pure-Tone Average (dB HL)	Mean 50% Point (dB SNR)	SD (dB)	Minimum (dB SNR)	Maximum (dB SNR)
Wilson et al, 2007b	YNH	WIN	24.9	24	3.3	3.9	1.0	1.6	5.6
		QuickSIN				4.3	1.6	2.0	7.5
		BKB-SIN				0.8	1.3	–2.5	3.0
		HINT				3.3	2.1	–0.3	9.3
	HL (53–87 yr)	WIN	70.8	72	47.8	14.0	4.3	2.0	23.2
		QuickSIN				12.3	5.0	2.5	24.0
		BKB-SIN				5.0	2.6	1.0	12.5
		HINT				9.0	4.3	2.3	20.0
Wilson and McArdle, 2007	HL (45–87 yr)	WIN List 1, test[1]	69.7	315	50.6	12.6	3.6	2.8	23.3
		WIN List 1, retest				12.5	3.7	3.6	26.1
		WIN List 2, test[1]				12.3	3.6	3.6	24.1
		WIN List 2, retest				12.9	3.6	4.5	26.0
	HL (54–86 yr)	WIN Session 1, test	66.9	48	44.3	13.4	4.0	5.2	21.2
		WIN Session 1, retest				13.0	3.5	6.0	20.4
		WIN Session 2, test[2]			43.5	13.2	3.3	6.0	21.2
		WIN Session 2, retest				13.1	3.6	7.6	20.4
	HL (52–87 yr)	WIN Session 1, test	71.9	48	58.8	15.8	3.2	8.4	22.0
		WIN Session 1, retest				15.4	3.0	9.2	21.2
		WIN Session 2, test[2]			57.1	15.5	3.1	10.0	22.0
		WIN Session 2, retest				15.3	2.9	8.4	20.4
Wilson and Cates, 2008	YNH	WIN	23.3	24	3.2	2.7	1.5	–0.4	7.6
		Speech Recognition in Noise Test (SPRINT), 200 words, @9 dB SNR				92.5%	2.4%	88.0%	97.5%
	HL (60–82 yr)	WIN	70.0	48	46.1	12.1	3.4	3.6	20.4
		SPRINT, 200 words, @9 dB SNR				65.3%	11.2%	40.0%	94.0%
Wilson et al, 2010	YNH (6–7 yr)	WIN	6.6	42	–	10.1	2.5	6.0	16.4
	YNH (7–8 yr)	WIN	7.5	42	–	7.4	2.3	2.0	12.4
	YNH (8–9 yr)	WIN	8.4	42	–	6.9	2.6	1.2	11.6
	YNH (9–10 yr)	WIN	9.6	42	–	5.4	2.5	–2.0	10.0
	YNH (10–11 yr)	WIN	10.5	42	–	6.4	2.5	0.4	11.6
	YNH (11–12 yr)	WIN	11.5	42	–	6.1	1.9	2.0	10.0
	YNH (12–13 yr)	WIN	12.5	42	–	6.1	1.9	2.0	10.0
	YNH (19–28 yr)	WIN	22.9	24	–	4.0	2.5	0.0	9.2

[1]12 mo between trials.
[2]>30 days between sessions.

spondaic word thresholds would not necessarily be the best predictors of recognition performance with other types of speech-recognition materials. The available data indicate that the higher frequencies (e.g., 1000 through 4000 Hz) are better correlated than the traditional PTA with speech recognition measured with more nominal speech materials like monosyllabic words and words in sentences (Goldstein, 1984; Suter, 1985; Humes et al, 1996). For this reason a high-frequency pure-tone average (HFPTA; 1000, 2000, and 4000 Hz) was incorporated into the evaluations used throughout the data analyses.

In the clinic WIN protocol, two half lists (25 words) of the NU-6 words spoken by the same female speaker used in the WIN were presented in quiet at levels corresponding to the word-presentation levels in the WIN at 0 and 24 dB SNR, which was either 80 and 104 dB SPL or 90 and 114 dB SPL. These two levels were selected to ensure that any degradation in recognition performance on the WIN, especially at the lowest SNRs, was not owing to audibility issues but, rather, to the masking effects of the multitalker babble. The speech materials were reproduced by CD players (Sony, Model CDP-361) and fed through audiometers (Grason-Stadler, Model 61) to ER-3A insert earphones. The audiometers were calibrated biannually with intra- and interaudiometer calibration maintained ±1 dB over the period of data collection. Testing was conducted in double-walled sound booths.

RESULTS AND DISCUSSION

Pure-Tone Thresholds

The mean left ear (LE) and right ear (RE) pure-tone thresholds (and standard deviations) from the 3430 participants are listed in Table 2 along with the *t*-test statistic of the mean LE/RE threshold differences. Threshold data from both ears were required for inclusion in the table, hence the different values for each frequency that are reflected in the degrees of freedom. The audiograms can be characterized as mild low-frequency hearing loss to 1000 Hz with a moderate to severe high-frequency component. Statistically, the mean LE and RE thresholds are the same in the lower frequencies (250 through 1000 Hz), with the LE thresholds in the higher frequencies at significantly (0.9 to 3.1 dB) higher hearing levels than the RE thresholds (2000 through 8000 Hz). Although these mean differences in the higher frequencies are significant statistically, the differences are less than the 5 dB step used in the measurement protocol and are not considered of clinical importance. This slight asymmetry in the high-frequency pure-tone thresholds with the RE having lower thresholds is a common finding in large-scale studies including population-based studies (Ward, 1957; Kannan and Lipscomb, 1974; Sutherland and Gasaway, 1978; Axelsson et al, 1981; Chung et al, 1983; Pirilä et al, 1991; Pirilä et al, 1992; Cox and Ford, 1995; Cruickshanks et al, 1998). From the 3430 participants, audiograms with normal hearing (≤20 dB HL at 250–8000 Hz) were obtained from 184 LEs (5.4%) and from 208 REs (6.1%).

The mean LE audiograms for the seven 20–80 yr decade intervals are shown in Figure 1. The numbers in parentheses designate the decade interval and the number of participants in each group. The mean pure-tone thresholds for the RE and standard deviations are listed in Table 1A in Appendix A. As age-related studies have shown, the greatest change in thresholds across years occurs in the higher frequencies. For example, from Figure 1, at 500 Hz the threshold difference between the 20 and 80 yr groups is 22.4 dB, whereas at 4000 Hz the difference is 53.4 dB, which

Table 2. Mean (and Standard Deviation) Pure-Tone Thresholds (dB HL) for the Left and Right Ears of the 3430 Participants

	Frequency (Hz)						
Variable	250	500	1000	2000	3000	4000	8000
Mean							
LE	23.7	26.1	28.6	42.7	58.3	60.4	54.6
RE	23.9	26.2	28.4	40.3	55.2	58.6	53.7
LE – RE	–0.2	–0.1	–0.2	2.4	3.1	1.8	0.9
SD							
LE	13.6	13.9	15.8	21.6	20.8	22.6	23.5
RE	13.8	14.0	15.9	21.2	21.6	23.3	24.0
t-test							
t	–1.07	–0.67	1.31	9.28	9.26	7.53	3.38
df	3370	3371	3371	3363	2138	3324	3055
p	.284	.504	.189	<.001	<.001	<.001	<.001

Note: The mean threshold differences (LE – RE) and *t*-test results also are included. For inclusion in the table, LE and RE thresholds for each participant at the individual frequencies (but not all frequencies) had to be measurable.

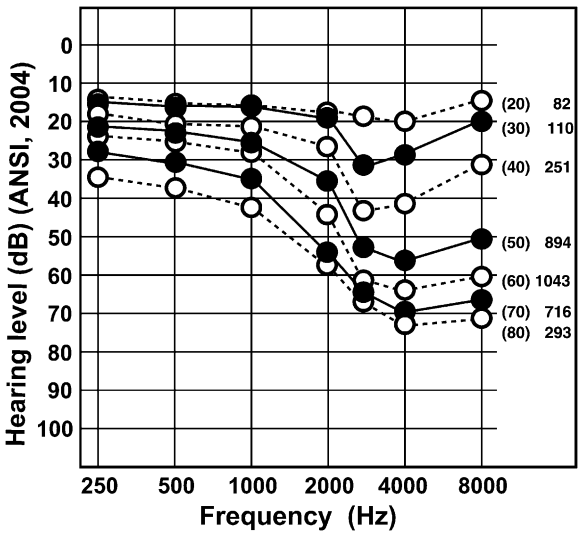

Figure 1. Mean left ear pure-tone audiograms for the participants in the seven decade interval groups. The decade and the number of participants in each decade are indicated in parentheses.

is a common finding in several studies (Bunch, 1929; Hinchcliffe, 1959b; Glorig and Davis, 1961; Rosen et al, 1962; Robinson and Sutton, 1979; Chung et al, 1983; Brant and Fozard, 1990). In general the pure-tone thresholds in each age group are the same as or slightly poorer than corresponding pure-tone thresholds from various epidemiology studies (e.g., Gates et al, 1990; Cruickshanks et al, 1998). The slightly poorer thresholds in the current cohort of veterans are not unexpected, as for the most part the participants had acknowledged a decrease in their hearing function and were in the process of seeking remediation. The epidemiology studies include many participants who have little or no hearing loss and who are not necessarily seeking remediation for hearing-related disorders.

Both the graphic LE audiograms in Figure 1 and the numeric RE audiograms in Table 1A indicate that the mean thresholds at 2000 and 8000 Hz are at lower hearing levels (better sensitivity) than the mean thresholds at 4000 Hz, with the RE 4000 Hz threshold in the 80 yr group being the exception. As an earlier analysis of the threshold data from these 3430 participants indicated, 40.6% had a 4000 Hz notch in at least one ear, with almost twice as many unilateral notches as bilateral notches (Wilson, 2011). Thus, the audiograms in Figure 1 and Table 1A reflect the minority influence that 4000 Hz notched audiograms had when averaged with audiograms that were not notched at 4000 Hz. Finally, the PTA was calculated on 3415 LEs and 3414 REs and categorized into four threshold ranges. Of the participants, 26.2% had PTAs ≤20 dB HL, 46.4% had PTAs between 22 and 40 dB HL, 23.8% had PTAs between 42 and 58 dB HL, and 3.6% had PTAs ≥60 dB HL. The PTA distributions for both ears were essentially identical (±1%). For the 3415 LEs, overall there was an 11.5 dB difference between the PTA (32.2 dB HL) and the HFPTA (43.6 dB HL). For the RE, the difference was 10.7 dB (PTA = 31.3 dB HL; HFPTA = 42.0 dB HL).

NU-6 QUIET

Presentation Level

Of the 3430 participants, 2859 (83.4%) completed NU-6 in both ears at the low and high presentation levels that corresponded to the presentation levels of the WIN words at 0 and 24 dB SNR. Overall, the mean performances at the respective presentation levels in the ears were different, with performance at the lower presentation level (mean = 73.8%; SD = 25.1%) 6–8% below performance at the higher level (mean = 81.7%; SD = 19.4%), which with 25 words is a one- to two-word difference. At the lower presentation level, the mean performance was 1.4% better in the RE than in the LE (74.5% vs. 73.1%), and at the higher presentation level the mean performance was 2.2% better in the RE (82.8% vs. 80.6%). Both of these mean differences, which reflect the asymmetry that was observed with the pure-tone thresholds, were small and amounted to less than the 4% value of each token on the 25-word list and are not considered important clinically. The mean recognition performances in percent correct on the NU-6 at the low and high presentation levels, which were separated by 24 dB, are listed for the LE and RE in the top rows of Tables 3 and 4. For tabular clarity, the corresponding standard deviations are listed in the bottom rows. The values in the two tables demonstrate different aspects of the relations among the data. In Table 3 the data were sorted by age, whereas in Table 4 the data were sorted by the HFPTA for each ear independently.

Age

Several features are demonstrated by the data in Table 3. First, the mean HFPTAs increase systematically as a function of age from 15 to 17 dB HL in the 20 yr group to 55 to 57 dB HL in the 80 yr group. Second, maximum recognition performance systematically declined as a function of age, ranging from 95% in the 20 yr group to 47–66% in the 80 yr group. This relation is common in the literature, as exemplified by Jerger (1973). Third, the difference between the recognition performances at the low and high presentation levels increased with age, ranging from little or no difference with the 20 yr group, which reflects ceiling effects, to a 13–16% difference with the 80 yr group. Fourth, from the standard deviations, there is slightly more variability in the measures made at the lower

Table 3. Mean and Standard Deviation for Recognition Performance (% Correct) by Ear on the Northwestern University Auditory Test No. 6 (NU-6) in Quiet at Low and High Presentation Levels (*n* = 2859)

			Left Ear			Right Ear		
				NU-6 (%)			NU-6 (%)	
Age Group	Mean Age	*n*	High-Frequency Pure-Tone Average (dB HL)	Low	High	High-Frequency Pure-Tone Average (dB HL)	Low	High
Mean								
20s	24.9	77	17.4	95.6	95.9	15.5	95.8	95.3
30s	35.0	93	20.2	91.4	93.7	19.3	92.2	94.2
40s	45.3	212	29.4	89.8	92.7	27.4	91.3	93.7
50s	55.9	768	38.5	82.2	87.0	36.4	83.2	88.5
60s	63.7	900	44.7	72.9	80.5	43.4	74.4	82.8
70s	74.1	580	52.1	59.7	71.7	50.5	61.2	74.1
80s	82.5	229	57.1	47.2	60.7	55.2	49.2	66.2
20–80s	61.9	2859	42.9	73.1	80.6	41.2	74.5	82.8
SD								
20s	2.4		10.5	6.9	5.5	9.4	5.4	9.3
30s	2.9		12.7	12.5	10.3	13.3	11.9	9.6
40s	2.7		14.9	15.9	11.7	13.9	14.2	10.6
50s	2.6		15.3	19.1	14.8	14.4	18.5	13.9
60s	2.9		14.4	23.8	19.5	14.5	23.1	17.7
70s	2.7		12.6	25.9	21.0	12.8	25.4	20.5
80s	2.4		10.8	25.5	23.2	10.2	24.5	23.0
20–80s	12.8		16.8	25.4	20.1	16.6	24.7	18.9

presentation level than in the measures made at the higher presentation level, probably owing to more of the scores from the higher presentation level being compressed at or close to ceiling.

High-Frequency Pure-Tone Average

The NU-6 data in Table 4 are sorted by the HFPTA, the ranges of which are listed in the first column of the

Table 4. Mean and Standard Deviation for Recognition Performance (% Correct) on the Northwestern University Auditory Test No. 6 (NU-6) Presented in Quiet at Low and High Presentation Levels by Ear and by High-Frequency Pure-Tone Average (HFPTA) over Eight 8.3 dB Ranges

	Left Ear					Right Ear				
				NU-6 (%)					NU-6 (%)	
HFPTA Range (dB HL)	Mean Age	*n*	HFPTA (dB HL)	Low	High	Mean Age	*n*	HFPTA (dB HL)	Low	High
Mean										
0–8.3	36.0	45	6.0	96.6	97.8	37.2	65	6.2	96.9	97.2
10–18.3	46.4	231	14.7	96.1	95.9	47.6	249	14.8	96.5	95.9
20–28.3	54.6	376	24.5	94.9	95.0	55.0	412	24.4	94.0	94.7
30–38.3	59.5	494	34.4	89.2	91.3	60.6	546	34.4	88.5	91.5
40–48.3	64.1	611	44.2	76.9	84.3	64.3	608	44.4	77.3	86.0
50–58.3	67.2	584	53.9	60.0	73.1	68.5	547	54.1	58.9	73.4
60–68.3	70.0	395	63.6	42.5	58.6	70.6	326	63.3	40.9	60.9
70–78.3	71.0	95	72.6	33.2	48.7	69.9	89	72.7	30.4	49.9
Overall	61.8	2831	42.5	73.6	81.0	61.8	2842	41.0	74.8	83.0
SD										
0–8.3	11.4		2.4	5.5	3.4	11.9		2.0	6.5	4.3
10–18.3	13.4		2.8	5.4	5.6	13.0		2.8	5.1	7.9
20–28.3	11.5		2.7	5.6	6.1	11.3		2.8	6.0	6.7
30–38.3	9.6		2.8	10.0	8.9	9.3		2.9	10.3	8.5
40–48.3	9.2		2.8	15.3	13.8	9.2		2.9	15.3	12.1
50–58.3	10.4		2.9	20.9	16.9	10.1		2.8	19.3	17.1
60–68.3	9.6		2.7	21.9	21.3	9.3		2.6	20.8	20.5
70–78.3	9.2		2.4	19.2	21.3	9.9		2.8	16.7	21.9
Overall	12.8		16.3	25.0	19.7	12.8		16.4	24.4	18.4

table, with the mean HFPTAs listed in the fourth column (LE) and ninth column (RE). First from the table, the mean ages and the number of participants in each HFPTA category are similar for the LE and RE. Not surprisingly, there is a direct relation between HFPTA category and age. As anticipated, there is an inverse relation between the HFPTA and recognition performance on NU-6 for both the low and high presentation levels; increases in the HFPTA produced decreases in recognition performance. Between the lowest and highest HFPTA categories, recognition performance decreased ~65% at the low presentation levels and ~48% at the high presentation levels. When the HFPTA is <40 dB HL, the differences between performances at the two presentation levels are minimal, reaching only 2.1% (LE) and 3.0% (RE). For the four higher HFPTAs, the differences between performances at the two presentation levels systematically increase from 7–8% in the 40 to 48.3 dB HL category to 15–20% in the 70 to 78.3 dB HL category.

The relation between the better of the two word-recognition performances on NU-6 presented in quiet to the LE (ordinate) and the LE HFPTA (abscissa) for 3282 of the participants is illustrated in Figure 2. To avoid superimposed datum points, the data were jittered.[2] The datum points are clustered in the upper portion of the graph, indicating good to excellent performance on the NU-6 materials in quiet. The majority of the participants had word-recognition scores ≥80% correct, with 48.9% of the participants scoring >90% correct and 19.9% scoring 80–88%. Thus, only 31.2% of the participants scored <80% correct on the NU-6 in quiet. The slope of the second-degree polynomial used to describe the data in Figure 2 (r = 0.75) is gradual until the 40 dB HFPTA, after which the function becomes steeper. At the 50% correct point, the slope is –1.7%/dB, which means that a 10 dB increase in the HFPTA results in a 17% decrease in word-recognition performance.

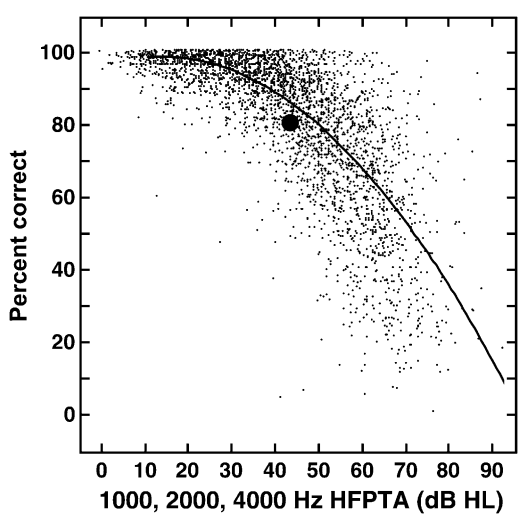

Figure 2. Bivariate plot of the higher recognition performances on the Northwestern University Auditory Test No. 6 materials presented to the left ear of 3282 participants and the high-frequency pure-tone average. The data were jittered. The largest symbol is the mean datum point. The second-degree polynomial (R^2 = 0.57) is used to describe the data.

WORDS-IN-NOISE TEST

The WIN data were evaluated using the 50% correct point (dB SNR) on each individual participant function and the morphology of each psychometric function. Overall, 3291 completed the WIN on both ears (LE, mean = 13.8 dB SNR, SD = 5.1 dB; RE, mean = 13.3 dB SNR, SD = 5.1 dB). Although small, the 0.5 dB difference between means was significant (t = 1.96; df = 3290; p < .000), which, as with the pure-tone thresholds and the words in quiet, demonstrates slightly better performance on materials presented to the RE than on materials presented to the LE. The mean 50% points on the WIN of 13.3 to 13.8 dB SNR are in excellent agreement with data from the previous WIN laboratory studies, which, as mentioned in the introduction, range from 9.4 to 15.8 dB SNR. For the LE, 224 (6.8%) had normal performance on the WIN defined as a 50% correct point of ≤6 dB SNR (Wilson et al, 2003; mean = 5.1 dB SNR; SD = 1.1 dB). The average age of the LE participants was 46.3 yr (SD = 14.0 yr), and the mean HFPTA was 19.7 dB HL (SD = 9.6 dB). For the RE, 265 (8.1%) had normal performance on the WIN (mean = 4.8 dB SNR; SD = 1.3 dB). The 265 participants had a mean age of 48.5 yr (SD = 13.9 yr), with a mean HFPTA of 19.6 dB HL (SD = 9.9 dB). In contrast to those with normal performances on the WIN, 3067 (93.2%) LEs and 3026 (91.9%) REs had performances on the WIN >6 dB SNR that were considered abnormal (LE, mean = 14.4 dB SNR, SD = 4.6 dB; RE, mean = 14.1 dB SNR, SD = 4.6 dB). The 0.3 dB difference between the LE and RE means is equivalent to less than one word. Not surprisingly, the latter groups were 15 yr older and had 24 dB more hearing loss (HFPTA) than the participants who had normal WIN performances. The mean ages of the 3067 LE and 3026 RE participants were 63.0 and 63.1 yr, respectively, both with 11.9 yr standard deviations.

Psychometric Functions

The mean recognition performances on the WIN at the various SNRs are shown as psychometric functions in Figures 3, 4, and 5. The figures illustrate different aspects of the relations among the data. In Figure 3, the overall WIN functions for the LE (datum points and solid line) and RE (dashed line) of 3132 participants are depicted in the lower right panel; these participants also completed the NU-6 in quiet protocol. The remaining panels of Figure 3 present the data for the participants in the seven decade age intervals. The functions in Figure 4

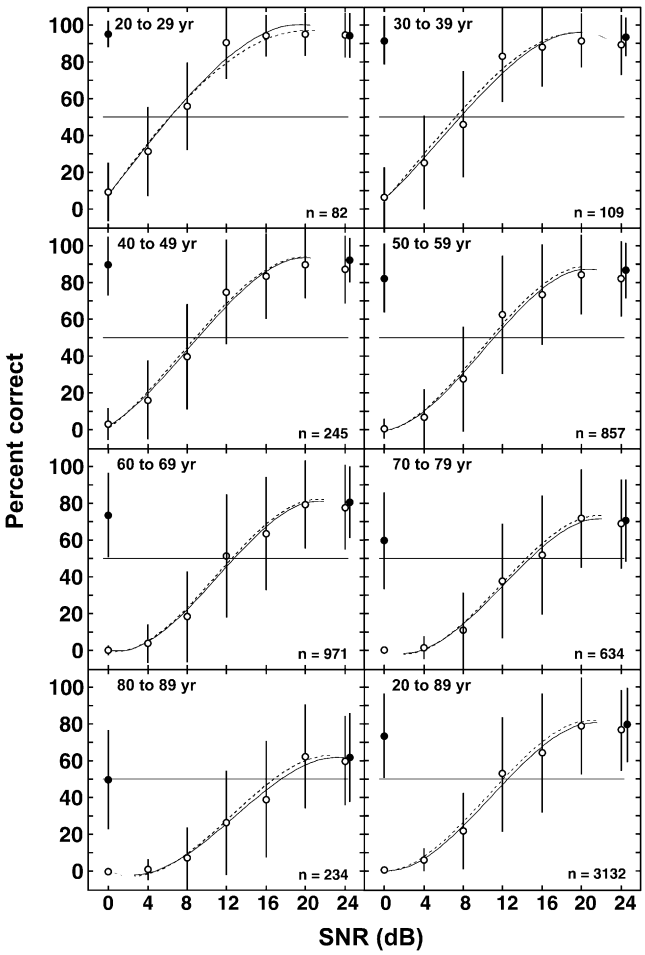

Figure 3. Recognition performance on the Words-in-Noise Test (WIN) shown as a function of signal-to-noise ratio (SNR) for the seven age groups from 20 to 89 yr. The mean left ear datum points are shown along with the standard deviations, which are depicted with the vertical lines. The lines connecting the datum points are the best-fit, third-degree polynomials. The dashed line represents the data from the right ear. In each graph the solid symbols depict the recognition performances obtained on the Northwestern University Auditory Test No. 6 materials presented in quiet at the presentation levels that corresponded to the presentation levels of the WIN words at the two extreme SNRs.

are similar except each panel represents an 8.3 dB HFPTA interval. The filled datum points in Figures 3 and 4 are the recognition performances obtained when the NU-6 words were presented at the presentation levels corresponding to the presentation levels of the WIN words at 0 and 24 dB SNR. In both figures the lines connecting the datum points are the best-fit, third-degree polynomials that are used to describe the data. To facilitate comparisons, the mean LE functions for the age groupings from Figure 3 are illustrated in the top panel of Figure 5, with the mean LE functions for the HFPTA groupings from Figure 4 shown in the bottom panel of Figure 5. (Note: Table 2A in Appendix A lists the mean LE and RE 50% points [and standard deviations] obtained with the Spearman-Kärber equation for the seven 10 yr intervals and the 50% points computed from the polynomials in Figure 3 along with the corresponding slopes at the 50% points. Table 3A in Appendix A provides the same listings as in Table 2A except in terms of the eight 8.3 dB HFPTA intervals.[3])

Consider first the data in terms of the seven decade age intervals in Figure 3 (and Table 2A). First, the overall mean age was 61.6 yr, and the between-ear differences (LE – RE) were 0.3 to 2.3 dB for the HFPTA and <1 dB for the WIN 50% points. There is a direct relation between age and the HFPTA, which increased about 40 dB from the youngest to the oldest age group, and between age and the WIN 50% point, which increased 10–11 dB from the youngest to the oldest group. Age and the slopes of the functions (Fig. 3) had an inverse relation with the slopes, becoming about 3%/dB more gradual between the youngest and oldest age groups, which is probably reflecting the larger intersubject variability in the older groups.

At 20 and 24 dB SNR in each of the panels in Figure 3, recognition performances were essentially equal for the words in babble (open symbols) and the NU-6 words in quiet (filled symbols), which means that at those particular SNRs the babble had no disruptive or masking effect on the intelligibility of the words presented at those levels. At the other SNR extreme (0 dB SNR), recognition performance on the NU-6 words in quiet was substantially better than recognition performance on the words in babble, indicating that the babble accounted for most of the decrease in performance that was observed at the 0 dB SNR and that audibility was not an issue. Finally, from the data in Table 2A, the 1–2 dB differences between the WIN 50% points determined by the Spearman-Kärber equation and by calculations from the polynomial used to describe the mean data are consistent with data from previous studies (Wilson, 2003; Wilson et al, 2007a). The differences are simply owing to the different assumptions underlying the two calculation methods.

WIN and HFPTA

The data in Figure 4 (and Table 3A) are sorted by degree of hearing loss using the HFPTA of each ear. First, the LE/RE distributions of participants in the hearing loss categories are slightly different, with more REs in the lower HFPTA ranges and more LEs in the higher HFPTA ranges. These differences reflect the previously described slightly better hearing sensitivity in the RE than in the LE. Second, as previously noted, as the hearing levels of the pure-tone thresholds (HFPTA) increase, there is a corresponding increase in both age and the 50% point on the WIN. Third, the standard deviations for all measures are fairly consistent across the hearing loss range, which is expected as the data were in effect filtered arithmetically into the various 8.3 dB threshold ranges. Finally from Table 3A, the slopes of the functions are

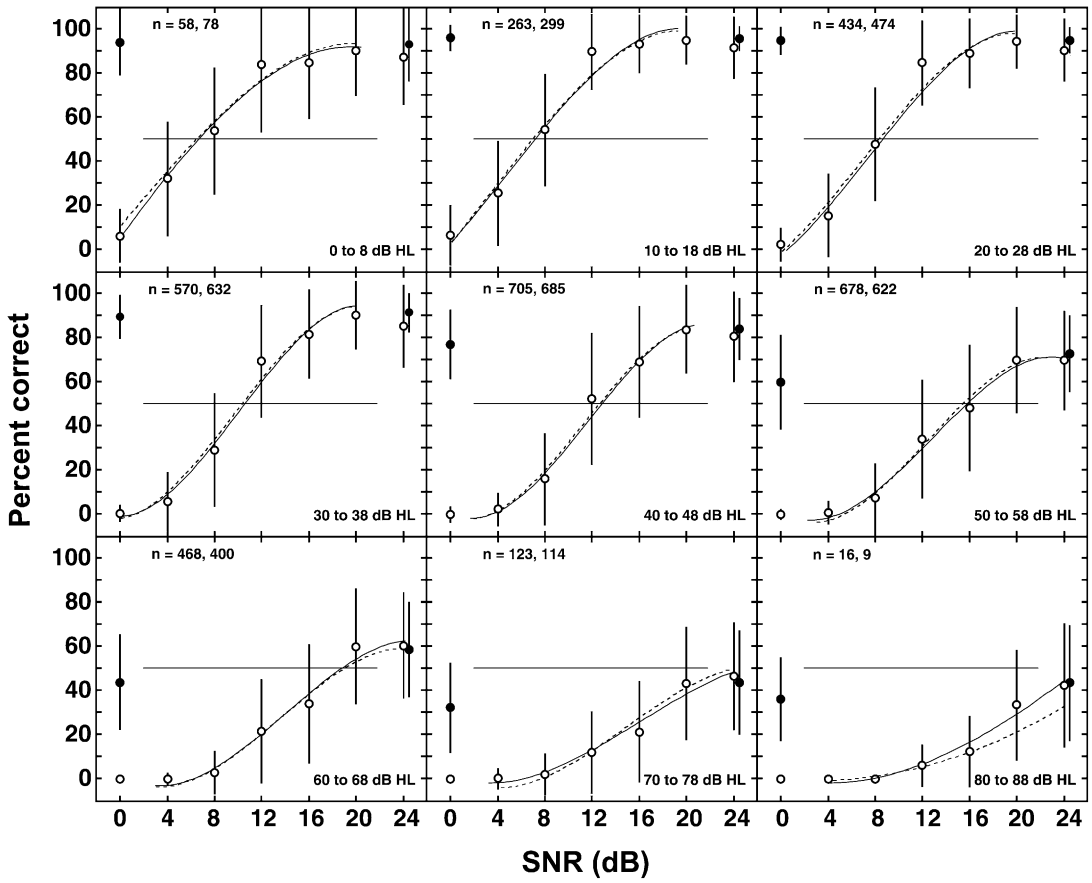

Figure 4. Recognition performance on the Words-in-Noise Test (WIN) shown as a function of signal-to-noise ratio (SNR) for the nine hearing loss groups based on high-frequency pure-tone averages. The mean left ear datum points (N = 3315) are shown along with the standard deviations, which are depicted with the vertical lines. The lines connecting the datum points are the best-fit, third-degree polynomials. The dashed line represents the data from the right ear (N = 3313). In each graph the solid symbols depict the recognition performances obtained on the Northwestern University Auditory Test No. 6 materials presented in quiet at the presentation levels that corresponded to the presentation levels of the WIN words at the two extreme SNRs. The numbers in the upper left of each panel are the number of participant LEs and REs, respectively.

fairly consistent at 5.7–7.0%/dB in the lower HFPTA ranges, with noticeably more gradual slopes at the two highest HFPTA ranges. The consistency in the lower HFPTA ranges is attributable to the "bandpass filtering" effect that the 8.3 dB ranges created. At the highest HFPTAs, however, the gradualness in the slopes is attributable to the lack of much improvement in performance as the SNR was increased to the most favorable levels. Even at 24 dB SNR, performance was below 50% correct, as was performance on the words in quiet. Increasing the presentation level of the words in both the noise and quiet paradigms at the higher levels did not produce appreciable improvements in word-recognition performance.

Relations among Hearing Loss, Age, and the WIN

The relations among the mean LE functions from Figures 3 and 4 are shown in Figure 5, with the data sorted by age group (top panel) and by hearing loss (bottom panel). The item of interest in Figure 5 is the spread of the functions at the 50% points. By age, the spread was 10.7 dB between the 20–29 yr group (6.3 dB SNR) and the 80–89 yr group (17.0 dB SNR). In contrast, the spread for the hearing loss sort was 17.8 dB between the 0–8.3 dB HL group (6.3 dB SNR) and the 70–78.3 dB HL group (24.1 dB SNR). This difference in the spreads of the functions can be interpreted as an indication of the degree of hearing loss being more influential than age on word-recognition performance in noise.

Another perspective on the relation between pure-tone sensitivity and recognition performance on the WIN is provided in Figure 6, in which LE 50% points on the WIN (abscissa) are depicted as a function of the LE PTA (top panel) and the LE HFPTA (bottom panel) for 3143 participants. The data in both panels demonstrate a direct relation between pure-tone thresholds and performance on the WIN. The linear regression is better fit to the HFPTA data (R^2 = 0.56) than to the PTA data (R^2 = 0.42), and the slope of the regression is steeper for the HFPTA (2.5 dB/dB) than for the PTA (1.8 dB/dB).

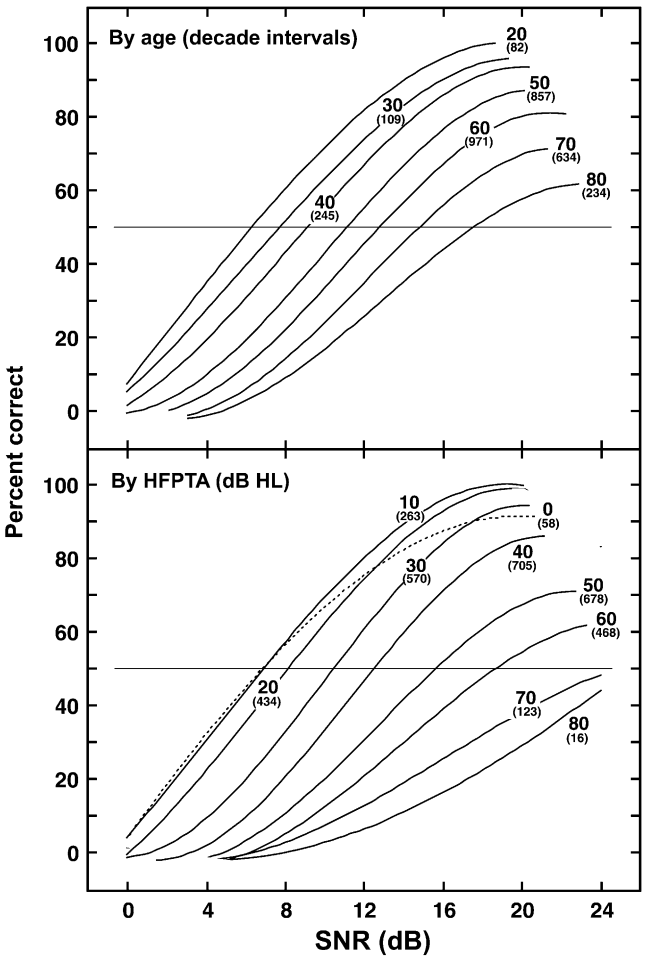

Figure 5. Polynomial functions used to describe the mean recognition performances when the Words-in-Noise Test was presented to the left ear of the individuals in the seven age groups (Figure 3) and of the individuals in the nine high-frequency pure-tone average (HFPTA) decade intervals (Figure 4). The large numbers indicate the age decade (top panel) and the HFPTA interval (bottom panel). The number of participants involved with each function is indicated in parentheses.

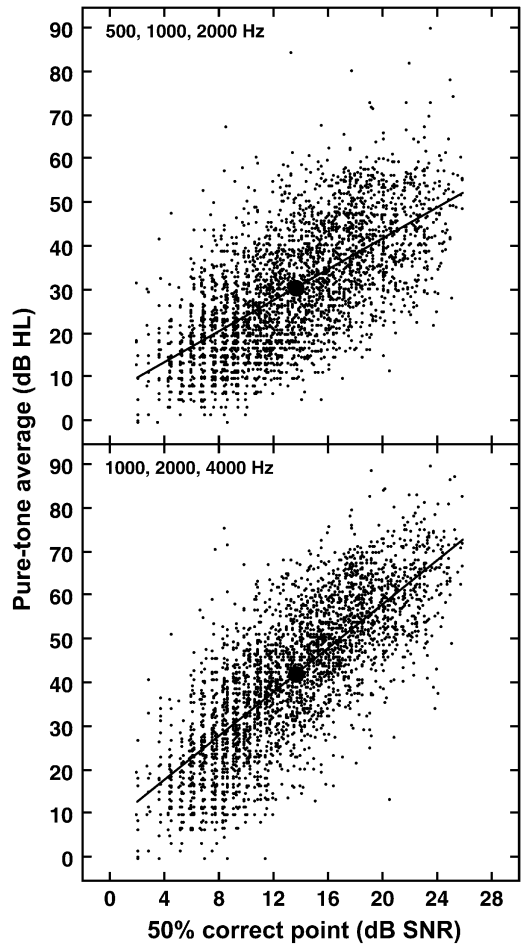

Figure 6. Bivariate plots of the average pure-tone thresholds (ordinate) and the 50% correct point on the Words-in-Noise Test (abscissa) from the left ears of 3143 participants. The traditional pure-tone average data are in the top panel, and the high-frequency pure-tone average data are in the bottom panel.

(Although not plotted here, almost identical results were obtained with the corresponding data from the RE, with $R^2 = 0.41$ and 0.57 and slopes = 1.7 and 2.4 dB/dB for the PTA and HFPTA data, respectively.) The steeper slope and the better fit of the regression to the HFPTA data indicate a stronger relation between the HFPTA thresholds and performance on the WIN than between the more traditional PTA thresholds and performance on the WIN. These findings substantiate the earlier discussion that the HFPTA is better correlated than the PTA with performance on monosyllabic words (Goldstein, 1984; Suter, 1985; Humes et al, 1996).

The relations described for the data in Figures 5 and 6 support the notion that the degree of pure-tone hearing loss is a more influential determinant of word-recognition performance in noise than is age. This notion is enhanced by the data in Figure 7, in which the WIN 50% points (dB SNR) for the individual participants are plotted as a function of age under two conditions. The data in the top panel of Figure 7 are the WIN 50% points from the LEs of 3266 participants, whereas the data in the lower panel are the WIN 50% points from the LEs of 586 participants that were parsed using arithmetic filters to produce homogeneous pure-tone thresholds among the various age groups. In this manner the effects of age could be examined on groups of listeners with different ages but with the same or very similar pure-tone thresholds.

To accomplish this goal, the overall mean LE pure-tone thresholds were calculated for 3266 participants. The mean threshold at each frequency was rounded to the nearest multiple of 5 dB (e.g., a 23.8 dB HL mean threshold became 25 dB HL). Then a 20 dB arithmetic filter was applied to the individual threshold data at 250–4000 Hz. For example, if the mean threshold were 25 dB HL, then the acceptable, idealized threshold range included thresholds at 15, 20, 25, 30, and 35 dB HL. If the

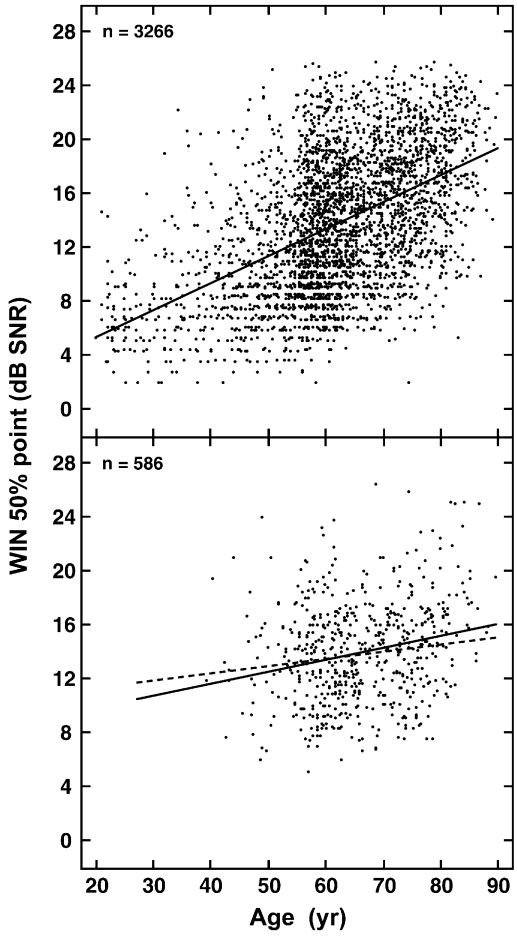

Figure 7. Bivariate plots of performance on the Words-in-Noise Test (ordinate) versus age (abscissa). The data were jittered. The top panel includes data from left ears only, whereas the bottom panel includes data that were filtered (see text) to a predetermined range of threshold values from an equal number of left and right ears. The solid lines are linear regressions used to describe the individual data. The dashed line in the bottom panel is the linear regression used to describe the data that were filtered further at 8000 Hz.

thresholds at each of the five octave frequencies were within the respective idealized threshold ranges, then the threshold data for that particular ear were included in the compiled data set.

After the first iteration, the data for the 20 and 30 yr groups were eliminated from further analyses mainly because the majority of thresholds were too low (good), which left 380 LE and 350 RE data sets. Only the data from one ear of each participant were used in the analyses, which resulted in 586 ears equally distributed between LEs and REs. The features of importance in Figure 7 are the slopes of the regression lines in each panel. The steeper the slope of the regression, the more influence the variable has on the outcome measure. If the slope of the regression were zero, then age would be a random factor. For the data from all of the participants depicted in the top panel, the slope was 0.2 dB/yr, contrasted with the slope of the solid line in the bottom panel of 0.09 dB/yr. The steeper function in the top panel reflects the effects that both hearing loss and aging have on word-recognition performance in noise. In the bottom panel, hearing loss for pure tones was held fairly constant across age, thereby producing a flattened linear regression that reflects mainly the effects that age has on the ability to understand speech in background noise. The dashed linear regression represents a further flattening of the regression (slope = 0.05 dB/yr) when the 8000 Hz thresholds were filtered and the data set was reduced to 394 ears. Although the effects of pure-tone hearing loss were held fairly constant in the data (Fig. 7, bottom panel), there continued to be some decrease in WIN performance with increasing age. Given that with increasing age there is a decrease in functioning throughout the auditory system (Schuknecht, 1955; Hinchcliffe, 1959a; Gates et al, 2008), the above findings are reasonable, as the only adjustments or compensations that were made with the data were with the pure-tone thresholds, which make up only one domain of auditory function.

The 20 yr group consisted of many participants who had normal pure-tone thresholds (≤20 dB HL) from 250 through 8000 Hz. Because the upper cutoff for performance on the WIN was defined as the 90th percentile (6 dB SNR) obtained by young adults (college students) with normal hearing (Wilson et al, 2003), it was of particular interest to examine the WIN performances of this youngest group of participants. The results from the LE and RE essentially were the same, therefore, only the results for the RE are reported. Of 82 20-yr-olds, 48 (58.5%) had normal pure-tone thresholds using the above definition, with a mean HFPTA of 10.2 dB HL. The mean WIN 50% point for these 48 participants was 6.4 dB SNR (SD = 2.7 dB), which is 0.4 dB above the 6.0 dB SNR cutoff used to define normal performance. Of the 48 participants, 25 had WIN 50% points ≤6.0 dB SNR (mean = 4.3 dB SNR; SD = 1.3 dB) and a mean HFPTA of 8.7 dB HL (SD = 3.2 dB). The remaining 23 participants, again with so-called normal hearing, had a mean WIN 50% point of 8.6 dB SNR (SD = 1.8 dB), with a mean HFPTA of 11.9 dB HL (SD = 5.0 dB). The remaining 34 of the 82 20-yr-old participants (41.5%), who were characterized as having a pure-tone hearing loss, had a HFPTA of 23.3 dB HL and a mean WIN 50% point of 8.1 dB SNR (SD = 3.1 dB). These relations suggest that even in the youngest group of participants, slight differences in pure-tone thresholds can be reflected in different performances on the WIN.

Relations between Recognition Performances on NU-6 in Quiet and the WIN

Finally, Figure 8 is a bivariate plot of the higher of the two NU-6 scores (ordinate) and the WIN 50% point

(abscissa) from 3222 LEs that completed both tasks. Again, the data were jittered. The function in the graph is the best-fit, second-degree polynomial used to describe the data. The shaded region of the graph represents normal performance on the WIN (≤6 dB SNR [Wilson et al, 2003]). Recognition performances on the NU-6 in quiet are considered in three categories. First, 1601 (49.7%) of the veterans had recognition performance scores on the NU-6 that were ≥92%, which were considered excellent performances. Second, 649 veterans (20.1%) had performances on the NU-6 between 80 and 88% correct, which were considered good performances. Third, 972 participants (30.2%) had performances on the NU-6 that were considered poor, i.e., ≤76% correct.

In contrast to NU-6 in quiet, on which 70% of the participants had recognition performances that were good or excellent, the WIN results indicate that only 222 veterans (6.9%) had normal performances, with 3000 (93.1%) having abnormal performances. Of the 222 participants, 218 (98.2%) also had excellent word recognition in quiet (i.e., ≥92% correct). In contrast and most important, 1383 (46.1%) of the 3000 participants with abnormal performances on the WIN had excellent performances on the NU-6 in quiet (≥92%), and 646 participants (21.5%) with abnormal performances on the WIN had good performances on the NU-6 in quiet (80–88%). Thus, almost 70% of the participants with an abnormal performance on the WIN had good to excellent word-recognition performances on the NU-6 in quiet. One could argue that if the NU-6 words in quiet were presented at a lower presentation level, then performance would be decreased accordingly below the good and excellent categories and be more aligned with performance on a words-in-noise task. Such a strategy in quiet, however, involves manipulations in the audibility (sensitivity) domain, whereas with the words-in-noise paradigm the manipulations are in the suprathreshold domain of auditory function. The contention here is that listening in quiet and listening in noise are two different domains of auditory function.

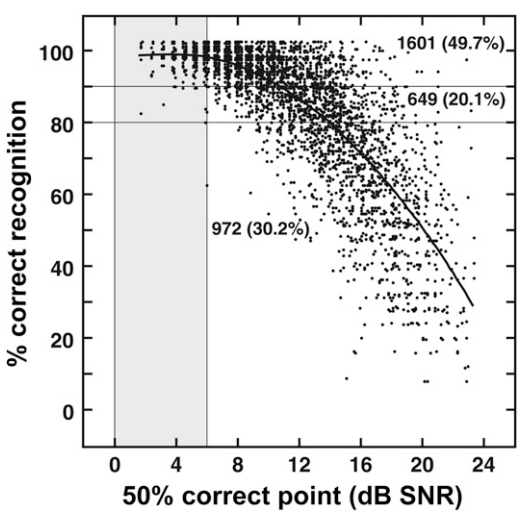

Figure 8. Bivariate plot of the 3222 left ear higher word-recognition performances on the Northwestern University Auditory Test No. 6 (NU-6) in quiet at the two presentation levels versus the LE Words-in-Noise Test (WIN) 50% points calculated from the individual data with the Spearman-Kärber equation. The function is the best-fit, second-degree polynomial used to describe the data ($y = 96.62 + 1.2053x - 0.1404x^2$; $R^2 = 0.61$). The shaded region defines normal recognition performance on the WIN (Wilson et al, 2003). The numbers in the graph (and percents) indicate the number of veterans in each of three categories of performance on the NU-6.

Comment

The data in Figure 8 prompt two conclusions. First, recognition performance on a words-in-noise task cannot be predicted from performance on a words-in-quiet task. Most individuals with hearing loss and normal performances on the words-in-quiet task had abnormal performances on the WIN. The reverse relation, however, did not occur. Second, the words-in-quiet and the words-in-noise tasks assess different domains of auditory function. More often than not, recognition performance on a words-in-quiet task gives little, if any, indication of the difficulty a patient with hearing loss has understanding speech, whereas a words-in-noise task will almost always indicate some degree of difficulty understanding speech. Words in quiet represent an optimum listening condition, whereas a words-in-noise task represents a difficult, but common, listening condition. From this point of view, a words-in-noise task puts substantial pressure on the auditory system and should be considered as the "stress test" of auditory function.

Finally, regarding the speech-in-noise paradigm, it is instructive to consider how speech signals and noise signals combine and interact in terms of physical acoustics to produce resultant speech-in-noise signals. It is well established that the frequency and amplitude cues contained in a speech signal (i.e., the temporal fine structure [Rosen, 1992; Lorenzi et al, 2006; Moore, 2008]) provide much of the information necessary for the intelligibility of the speech signal. Additional cues are provided by the amplitude modulations of the temporal fine structure envelope. Collectively the temporal fine structure and the amplitude modulations of the envelope of the temporal fine structure constitute the waveform of the signal. Although in audition the use of temporal fine structure has been reserved for meaningful sounds like speech, nonmeaningful noise signals likewise can be considered as having a temporal fine structure and an amplitude-modulated envelope. With a random noise the temporal fine structure by definition is random, as is the envelope of the noise waveform. With a multitalker babble noise the temporal fine structure

is more speechlike than random noise but "unorganized." As alluded to by Drullman (1995), the contention here is that noise when combined with speech, in effect, distorts the temporal fine structure of a speech signal just as do overt algorithms that are applied to the speech signal to produce distortions (e.g., filtering, temporal jittering, and spectral smearing [Baer and Moore, 1993; Pichora-Fuller et al, 2007]). When the speech and noise signals are combined at a favorable SNR (e.g., 20 or 24 dB with the WIN), the relatively large amplitude of the speech signal dominates the relatively small amplitude of the noise signal, resulting in a waveform that is almost identical to the speech waveform except that the noise is superimposed on the speech waveform, appearing on the waveform as a "ripple." The ripple is actually the noise "riding" on the dominant temporal fine structure of the speech signal. In this example, the noise has little or no effect on the waveform of the speech signal, and that is why most listeners, even those with sensorineural hearing loss, achieve WIN recognition performance in babble at 20 and 24 dB SNR that is the same as their recognition performance on the same materials presented in quiet (see Figures 3 and 4).

In contrast to the favorable SNR conditions just described, when the speech and noise signals are combined at an unfavorable SNR (e.g., 0 or 4 dB with the WIN), the relatively large amplitude of the noise signal dominates the relatively small amplitude of the speech signal. The resultant speech-in-noise waveform is almost identical to the noise waveform except for embedded "hints" of the organized speech waveform. At the poor SNRs the temporal fine structure of the speech signal is substantially disrupted (distorted) by the corresponding temporal fine structure of the dominant (larger amplitude) noise signal. Listeners with sensorineural hearing loss have, to some degree, internally or intrinsically introduced distortions caused by end-organ and central physiologic factors (Houtgast and Festen, 2008). When the external signal–laden distortions are coupled with the internally generated distortions, the combined distortions adversely affect recognition performance more than either distortion alone. In contrast to listeners with hearing loss, young listeners with normal hearing for pure tones basically are void of internal distortions, enabling them to perform better than individuals with hearing loss on the speech-in-noise paradigm. These are the same principles advanced by Bocca and Calearo (1963) 48 yr ago in their studies of central auditory disorders that involved a variety of distortions applied to the speech signal.

Data from the WIN or any comparable speech-in-noise task provide several benefits to the patient with a sensorineural hearing loss. First, a speech-in-noise task provides a tangible performance (or score) that can be used to address the common complaint expressed by many, if not most, patients of difficulty understand speech, especially in the presence of background noise. Second, in counseling the patient, the speech-in-noise information can be used to develop the appropriate amplification strategy, to help determine patient expectations with hearing aids and/or assistive listening devices, and to define subjective outcome measures.

SUMMARY

The mean pure-tone threshold data from the 3430 participants revealed a mild to severe hearing loss for pure tones, with the thresholds for the frequencies above 1000 Hz being slightly better in the RE than in the LE. The threshold differences were <5 dB but were statistically significant. There was a direct relation between age and the pure-tone thresholds, and the change in pure-tone thresholds across age groups was greater in the high frequencies than in the low frequencies. About 41% of the participants had a 4000 Hz notch in at least one ear, with an average notch depth of 23 dB. With NU-6 in quiet, there was 1–3% better recognition performance on the words presented to the RE than on the words presented to the LE. Performance on NU-6 was ≥90% correct by 50% of the participants and ≥80% by 70% of the participants. In contrast, only 7% of the participants had normal performances on the WIN. Recognition performance on both the NU-6 and the WIN decreased as a function of both pure-tone hearing loss and age. Overall, RE performance on the WIN was slightly but significantly better than LE performance. Performance on the WIN was more closely associated with pure-tone thresholds than with age. There was a stronger relation between the HFPTA and the WIN than between the PTA and the WIN. The results from the current WIN clinical study coupled with the results from the 12 laboratory studies on the WIN amply demonstrate that the WIN (1) provides a valid and reliable measure of word recognition in background noise (babble), (2) enables word recognition both in quiet and in noise to be evaluated with the same words spoken by the same speaker, (3) can be used on a diverse clinic population from children through adults, and (4) is ready for routine clinic implementation.

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NOTES

1. Subsequently, the acuity and clarity hearing losses described by Carhart (1951) were transformed into attenuation and distortion hearing losses by Stephens (1976) and were incorporated into a formalized two-component model of hearing loss by Plomp (1978).

2. To avoid superimposed datum points, in several figures the data were jittered using one of three algorithms, including two randomized, multiplicative algorithms between 1.025 and 0.975 in 0.005 steps and between 1.0075 to 0.9925 in 0.0025 steps and a randomized additive algorithm between 0.4 and –0.4 in 0.1 steps. This process accounts for the instances in which scores appear to exceed 100%.
3. Again, the different number of participants in the various analyses reflect that only participants with complete pure-tone and WIN data in both ears were included in Figures 3 and 5 (top panel) and Table 2A, whereas data from only one ear of the participants were required for inclusion in Figures 4 and 5 (bottom panel) and Table 3A.

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Table 1A. Mean (and Standard Deviation) Pure-Tone Thresholds (dB HL) for the Right Ears of the Seven Age Groups of Participants

		Frequency (Hz)						
Age	*n*	250	500	1000	2000	3000[1]	4000	8000
Mean								
20s	82	14.1	15.4	14.7	15.9	14.9	16.3	11.5
30s	110	16.1	17.3	16.1	18.4	28.3	25.6	22.3
40s	251	18.5	20.4	20.2	24.5	37.9	39.2	31.5
50s	892	21.5	23.4	24.1	33.4	49.5	53.6	48.1
60s	1040	23.5	25.8	28.0	42.2	58.6	63.3	59.5
70s	713	28.0	30.9	35.3	51.9	64.8	69.6	68.2
80s	292	33.2	37.1	41.1	56.2	65.9	71.9	73.5
SD								
20s		7.9	8.5	10.0	10.3	8.5	14.3	16.7
30s		11.1	10.9	11.5	14.0	22.3	20.7	21.1
40s		12.5	12.6	13.9	15.7	21.7	21.8	22.1
50s		12.7	12.3	13.6	18.6	21.4	22.2	22.6
60s		13.0	13.3	14.6	20.3	19.7	19.8	18.7
70s		14.2	14.5	16.1	18.2	16.8	16.7	15.3
20–80s		14.2	20.9	14.9	15.3	15.0	14.6	13.4

Note: For inclusion in this table, all thresholds had to be measurable, hence the *N* of 3380.

[1]3000 Hz was tested in 70.9% of the participants.

Table 2A. Mean (and Standard Deviation) for 50% Points (dB SNR) on the Words-in-Noise Test by Ear, Calculated with the Spearman-Kärber Equation (SK 50%)

			Left Ear				Right Ear			
Age	Mean Age	*n*	HFPTA (dB HL)	SK 50% (dB SNR)	Poly 50% (dB SNR)	Slope (%/dB)	HFPTA (dB HL)	SK 50% (dB SNR)	Poly 50% (dB SNR)	Slope (%/dB)
Mean										
20s	24.9	82	17.2	7.1	6.8	8.4	15.6	7.1	6.3	7.0
30s	35.1	109	20.4	8.8	7.8	8.0	20.1	8.2	7.2	7.6
40s	45.3	245	29.6	10.1	9.1	7.0	27.3	9.7	8.7	6.9
50s	55.9	857	38.3	12.4	10.7	6.3	36.3	11.9	11.2	6.2
60s	63.6	971	44.6	14.1	12.9	5.8	43.2	13.7	12.4	5.9
70s	74.1	634	52.1	16.2	14.9	5.1	50.4	15.7	14.3	5.3
80s	82.5	234	56.3	18.2	17.8	5.2	55.0	17.5	17.0	4.6
20–80s	61.6	3132	40.9	13.2	12.4	5.6	40.9	13.2	11.9	5.7
SD										
20s	2.4		10.3	2.8			9.4	3.0		
30s	2.8		12.8	4.2			13.8	4.1		
40s	2.7		14.7	4.3			13.4	4.3		
50s	2.6		14.6	4.5			14.3	4.4		
60s	2.9		14.2	4.5			14.2	4.7		
70s	2.6		12.5	4.3			12.5	4.5		
80s	2.3		11.1	4.1			1.3	4.2		
20–80s	12.7		16.5	5.2			16.4	5.1		

Note: The 50% points computed from the polynomials in Figure 3 (Poly 50%) and the slopes of the functions at the 50% point are also listed. HFPTA = high-frequency pure-tone average.

Table 3A. Mean (and Standard Deviation) for the 50% Point (dB SNR) on the Words-in-Noise Test (WIN) by High-Frequency Pure-Tone Average (HFPTA), Range Calculated with the Spearman-Kärber Equation (SK 50%), for Left Ears (*n* = 3299) and Right Ears (*n* = 3304)

	Left Ear						Right Ear					
HFPTA Range (dB HL)	Mean Age	*n*	HFPTA (dB HL)	SK 50% (dB SNR)	Poly 50% (dB SNR)	Slope (%/dB)	Mean Age	*n*	HFPTA (dB HL)	SK 50% (dB SNR)	Poly 50% (dB SNR)	Slope (%/dB)
Mean												
0–8.3	39.6	58	6.2	6.3	6.7	5.8	36.9	78	6.1	6.2	6.3	5.7
10–18.3	46.3	263	14.6	7.9	6.9	6.6	48.0	299	14.8	7.7	6.8	6.5
20–28.3	54.6	434	24.4	9.0	8.2	6.7	55.2	474	24.5	9.2	8.2	6.7
30–38.3	59.8	570	34.4	11.2	10.5	7.0	60.5	632	34.4	11.2	10.2	6.9
40–48.3	63.7	705	44.3	13.8	12.5	6.6	64.3	685	44.3	13.8	12.5	6.6
50–58.3	67.4	678	53.9	16.8	15.6	5.0	68.5	622	54.1	16.7	15.2	5.3
60–68.3	70.0	468	63.6	18.9	18.7	3.7	70.6	400	63.3	19.0	18.8	3.3
70–78.3	70.9	123	72.7	21.1	24.7	1.9	70.2	114	72.7	20.9	24.1	1.0
SD												
0–8.3	11.2		2.4	2.0			11.7		2.0	2.8		
10–18.3	13.7		2.8	3.1			12.9		2.8	3.1		
20–28.3	11.3		2.8	2.9			11.5		2.8	3.1		
30–38.3	9.8		2.8	3.3			9.5		2.9	3.3		
40–48.3	9.4		2.8	3.5			9.5		2.9	3.7		
50–58.3	10.1		2.9	3.5			10.0		2.8	3.5		
60–68.3	9.6		2.7	3.5			9.2		2.6	3.5		
70–78.3	8.8		2.3	3.3			10.2		2.7	2.7		

Note: The 50% points computed from the polynomials in Figure 4 (Poly 50%) and the slopes of the functions at the 50% point are also listed.