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# An Evaluation of the World Health Organization and American Medical Association Ratings of Hearing Impairment and Simulated Single-Sided Deafness

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**Abstract**

**Background:** According to the World Health Organization (WHO), a pure-tone threshold average (PTA) ≤25 dB HL for the better ear represents “no impairment.” This implies that patients with single-sided deafness (SSD) would have “no or very slight hearing problems.” According to the American Medical Association (AMA), a patient with SSD would receive a binaural hearing impairment rating of 16.7%. The premise of the WHO and AMA methods is that PTA is related to the ability to perceive speech in everyday environments.

**Purpose:** The overall goal of the study was to evaluate the WHO and AMA criteria for the rating of hearing impairment. The purpose of this study was to quantify the impact of simulated SSD on the ability to recognize speech in the presence of background noise in terms of binaural and spatial advantage measures.

**Research Design:** Study participants were tested using the standard protocol for the Hearing in Noise Test (HINT) in both binaural and monaural conditions using a simulated soundfield environment under headphones. The target sentences were presented at 0°. Binaural thresholds were obtained for the Noise Front (0°), Noise Left (270°), and Noise Right (90°) listening conditions. Monaural thresholds were collected for each ear for the Noise Front condition and for the unshadowed ear for the Noise Left and Noise Right conditions. Binaural advantage was determined by subtracting the binaural from the monaural thresholds. Spatial advantage was determined by subtracting the Noise Side from the Noise Front thresholds.

**Study Sample:** Twenty-five young native speakers of English with normal pure-tone thresholds (≤25 dB HL, 250–8000 Hz) participated in the study.

**Data Collection and Analysis:** Pure-tone threshold data were collected using the modified Hughson–Westlake procedure. Speech recognition in noise data were collected using a Windows-based HINT software system. The binaural and spatial advantage measures were calculated from the HINT thresholds. Statistical analyses included descriptive statistics, correlation coefficients, and matched-pairs *t*-tests.

**Results:** The average binaural advantage for the Noise Front conditions was 1.21 dB ($p < 0.01$) or a maximum estimated intelligibility improvement of 12.01% when the speech and noise were presented at 0°. The average binaural advantage across the Noise Side conditions was 11.25 dB ($p < 0.01$) or a maximum estimated intelligibility improvement of 84.09% when the noise was spatially separated from the speech. The average spatial advantage for the binaural conditions was 6.72 dB ($p < 0.01$) or a maximum estimated intelligibility improvement of 60.03%. The average spatial advantage for the monaural conditions was −3.32 dB or a maximum estimated decrease in intelligibility of 32.27%.

**Conclusions:** The results do not support the WHO or AMA hearing impairment ratings for SSD. The WHO and AMA criteria for the determination of hearing impairment should be updated to include speech recognition in noise testing with and without the spatial separation of the speech and noise stimuli. In this way actual, as opposed to inferred perceptions of speech in noisy environments, may be determined. This will provide a much-needed improvement in the ratings of hearing impairment.

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**Key Words:** audiology, binaural advantage, directional advantage, gold standard, pure-tone thresholds, single-sided deafness, spatial advantage, speech recognition in noise ability

**Abbreviations:** AAO-ACO = American Academy of Otolaryngology and the American Council of Otolaryngology; AI = articulation index; AMA = American Medical Association; CPMR = Council on Physical Medicine and Rehabilitation; HINT = Hearing in Noise Test; ICF = International Classification of Functioning, Disability and Health; KEMAR = Knowles Electronics Mannequin for Auditory Research; PTA = pure-tone average; SD = standard deviation; SNR = signal-to-noise ratio; SSD = single-sided deafness; SSQ = Speech, Spatial, and Qualities of Hearing scale; WHO = World Health Organization

## INTRODUCTION

In the field of audiology, pure-tone threshold testing has been called the “gold standard” for auditory assessment (Sindhusake et al, 2001; Shargorodsky et al, 2010). The degree of hearing loss has been described in terms of pure-tone average (PTA) or pure-tone thresholds. According to Goodman (1965), normal hearing corresponds to a range of PTAs for thresholds at 500, 1000, and 2000 Hz. On the other hand, Jerger and Jerger (1980) described normal hearing based on individual pure-tone thresholds that fall in the range of 0–20 dB HL for 250–8000 Hz (re: ANSI-69). Steinberg et al (1940) reported that individuals with pure-tone thresholds of 25 dB HL (at frequencies up to 1760 Hz) will be aware of a hearing impairment for the perception of speech under conditions of public address, such as in a church, theater, or around the conference or dinner table.

### The World Health Organization (WHO) and American Medical Association (AMA) Ratings of Hearing Impairment and Single-Sided Deafness (SSD)

The WHO states that a $\text{PTA}_{0.5,\ 1.0,\ 2.0,\ 4.0\ \text{kHz}} \leq 25$ dB HL for the better ear represents no impairment (Mathers et al, 2000). According to this classification scheme, a patient with normal pure-tone thresholds for the better ear and a profound hearing loss for the poorer ear ($\text{PTA}_{0.5,\ 1.0,\ 2.0,\ 4.0\ \text{kHz}} \geq 81$ dB HL) would have “no or very slight hearing problems.” Olusanya et al (2014) wrote that this definition excludes individuals with mild or unilateral hearing impairment. The WHO’s classification of hearing disregards any functional impairment of speech perception in background noise for unilateral hearing loss or SSD.

The WHO published the International Classification of Functioning, Disability and Health (ICF). This document recognizes contextual factors such as environmental noise on hearing impairment. The ICF lists each function of an individual and defines disability as a decrement of each functioning domain. According to WHO (2010), the ICF is impractical for the determination of disability in daily practice; therefore, they developed the WHO Disability Assessment Schedule to address this need and provide a standardized method to measure health and disability across cultures. In the section on cognition, there is one question regarding speech recognition in noise ability. Danermark et al (2013) commented that the ICF and the ICF Core Sets were developed as a way to counteract the fragmented approach of specialization found in modern healthcare. Currently, however, there is no formal audiological test battery associated with the ICF Core Sets.

The AMA’s *Guides to the Evaluation of Permanent Impairment* (AMA, 2008) states that if the $\text{PTA}_{0.5,\ 1.0,\ 2.0,\ 3.0\ \text{kHz}}$ is $\leq$25 dB HL, there is no impairment present for the ability to hear “everyday sounds under everyday listening conditions.” If the $\text{PTA}_{0.5,\ 1.0,\ 2.0,\ 3.0\ \text{kHz}}$ is $>$91.7 dB HL, the binaural hearing impairment is rated at 100% because this represents the loss of the ability to hear everyday speech. Moreover, a patient with SSD and a $\text{PTA}_{0.5,\ 1.0,\ 2.0,\ 3.0\ \text{kHz}} \leq 25$ dB HL for the better ear would receive a binaural hearing impairment rating of 16.7%. According to the AMA, for every dB greater than a PTA of 25 dB HL, a monaural hearing impairment of 1.5% is assigned. When only one ear exhibits a hearing impairment, 0% impairment is assigned for the unimpaired ear and the following formula is used: binaural hearing impairment = [5(percent hearing impairment for the better ear) + (percent hearing impairment in the poorer ear)]/6. In the case of SSD, the monaural hearing impairment is 0% for the better ear and 100% for the poorer ear. The binaural hearing impairment according to the formula is [5(0%) + (100%)]/6 = 16.7%. However, the ratings of binaural hearing impairment for the perception of speech in everyday listening conditions are not supported by the literature for simulated or actual single-sided hearing deficits.

### Early Discussions on Monaural Versus Binaural Hearing

Vern O. Knudsen was the president of the Acoustical Society of America from 1933 to 1935. In his lecture at the 10th anniversary meeting, he reported an investigation of binaural advantage (Knudsen, 1939). Eight participants with “normal hearing” were tested, first with both ears open and then with one ear wearing a "special type of stopper" which provided an attenuation of about 35 dB. The average speech recognition score was 72% for the binaural condition and 69% for the monaural condition. It was noted that several participants were aware of an increase in listening difficulty during the monaural condition. The author also noted, "On other occasions I have engaged in group conversation with one of my ears closed, and have found it difficult to shift auditory attention from one speaker to another; it is especially trying when two or more persons speak at the same time."

Koenig (1950) used a "binaural telephone system" with a separate microphone, amplifier, and receiver for each ear of the study participants. For an alternate condition, the signals from only one microphone were delivered to both ears. No systematic data collection was reported for this study. The author noted that the binaural system provided the ability to squelch reverberation and background noise as compared to the system with a common microphone routed to each ear. Haskins and Hardy (1960) reported critical observations of patient preferences for two versus one hearing aid for bilateral hearing losses. The authors wrote that, "much work must be devoted to the development of better indicators of success in terms of stereophonic hearing: and especially of ability to handle informational material in the presence of competing messages."

### Self-Report of Hearing Difficulties for Patients with Unilateral Hearing Losses and SSD

Even though the WHO considers patients with unilateral hearing impairment or SSD to have "no impairment," there is evidence that these types of hearing losses result in noticeable hearing difficulties. Dwyer et al (2014) used the Speech, Spatial, and Qualities of Hearing scale (SSQ) subscales (Gatehouse and Noble, 2004; Gatehouse and Akeroyd, 2006) to determine the self-perception of hearing difficulties for participants with normal hearing and unilateral hearing loss. The 21 participants in the normal-hearing group had unaided thresholds <30 dB HL for both ears. The 30 members of the unilateral hearing loss group had a mean PTA (0.25–6.0 kHz) of 13.0 dB HL for the better ear and a severe-to-profound hearing loss for the poorer ear. The authors did not report the pure-tone thresholds or PTA for the poorer ears in this study. According to the SSQ responses, the unilateral hearing loss group reported significantly poorer speech recognition in background noise ability than the normal-hearing group ($p < 0.001$).

Douglas et al (2007) used the SSQ to document the self-report of hearing abilities for control and SSD groups. There were 127 participants in the control group with an age range from 50 to 80 years (mean = 52 years, SD = 13.2 years). The mean hearing threshold for the better ear was 16.4 dB HL (SD = 12.6 dB). No "significant hearing asymmetry" was found for the control-group participants. Forty-four patients with profound unilateral hearing loss after an acoustic neuroma surgery were in the SSD group. The age range was from 20 to 74 years (mean = 51.3 years, SD = 13). The average hearing threshold for the better ear was 16.4 dB HL (SD = 13.2) for the patient group. The authors did not report the pure-tone thresholds or PTA for the poorer ears in this study. The SSQ ratings of speech recognition in noise ability for the SSD group were significantly poorer than those in the control group ($p < 0.05$).

### Quantification of Speech Recognition in Noise Deficits for Simulated and Actual Asymmetrical Conductive Hearing Losses

Carhart (1965) evaluated the binaural advantage for 16 "normal hearers." The ages of the participants were not given. Target monosyllabic words (phonetically balanced items, Normative Update Test 2) were presented at 0° and 32 dB HL from one soundfield loudspeaker. A second soundfield loudspeaker positioned at 90° was used for the presentation of competing sentences. The level of the competing sentences was varied to achieve signal-to-noise ratios (SNRs) of −24, −18, −12, and −6 dB. The SNR represents the difference in levels between the signal (speech) and the noise (competing sentences). For example, a −24 dB SNR indicates that the signal was 24 dB below the level of the noise. The more negative the SNR, the more difficult the listening task. A more positive SNR represents a more favorable listening condition. Testing was also conducted for a quiet condition. Each loudspeaker was six feet from the participant. The monaural listening condition was achieved by occluding the ear closest to the competing sentences with an earplug (shadowed ear condition). Mean discrimination scores (percent correct) were obtained for each condition. While the binaural advantage was only 1.2% for the quiet condition, it ranged from 3.3% to 8.7% across the noise conditions. From these data, the authors determined that the binaural advantage provided an overall improvement in SNR of 2.5 dB.

Persson et al (2001) measured speech recognition in noise ability for binaural and monaural listening conditions. Sixteen individuals with pure-tone thresholds ≤20 dB HL from 250 to 8000 Hz participated in the study. The mean age was 28 years. Testing was conducted in an anechoic chamber. Speech stimuli were delivered via a loudspeaker at 0° for all conditions. Noncoherent speech-weighted noise was presented bilaterally from loudspeakers positioned at ±45° or ±90°. All soundfield loudspeakers were 1.25 m from the center of each participant's head. The noise was low-pass filtered with a cutoff frequency of 1 kHz. A "hearing protector" was used for one ear to simulate a monaural listening condition (simulated conductive hearing loss). Earplug types varied across participants. The criterion for sufficient attenuation was ≥25 dB when both ears were plugged. When this criterion was met, an earplug was removed from one of the ears for the monaural condition.

Two types of speech in noise tests were administered. One test used a recording of a male speaker reciting 50 phonetically balanced Swedish words presented at 65 dBC while the noise was presented at 60 dBC (5 dB SNR). Each word was preceded by the carrier phrase, "Now you hear..." A percent correct score was determined for the noise ±45° and ±90° conditions. The second test was a just-follow-conversation test. The target speech was a recording of a female speaker reading text from a novel. The level of the noise was fixed at 60 dBC. Each participant was instructed to adjust the volume control so that they could just follow the context if they really concentrate on listening. The mean SNR was calculated for each participant. For all test conditions, performances for the binaural listening condition were significantly better than for the monaural listening condition ($p < 0.05$). With minimum attenuation of 25 dB provided by the earplugs, speech presented at 65 dBC would have reached the plugged ears at ~40 dBC. Thus, there may have been some contribution from the plugged ears during the monaural test conditions. The range of earplug attenuation across participants was not reported. Nonetheless, this study demonstrates the binaural advantage for a simulated unilateral hearing loss, even though the ear with the earplug may have contributed to the "monaural" speech recognition performances.

Byun et al (2015) determined the effect of surgical correction of unilateral congenital atresia on 26 children from 10 to 16 years of age. The participants were tested presurgery and 12 mo postsurgery. The self-perception of hearing ability was evaluated using the Korean version of the SSQ. The ability to recognize speech in speech-spectrum noise was measured using the Korean version of the Hearing in Noise Test (HINT; Moon et al, 2008) in a soundfield. The mean $\text{PTA}_{(0.5,\ 1.0,\ 2.0,\ 3.0\ \text{kHz})}$ improved from 63.9 to 39.4 dB 1 year postsurgery ($p < 0.001$). A comparison of mean speech recognition in noise performances revealed improvements for all HINT conditions 12 mo postsurgery. Speech was always presented at 0°. For the test condition where the noise was presented toward the atretic ear, the HINT threshold improved 1.5 dB postsurgery ($p = 0.014$). For the Noise Front condition, a nonsignificant improvement of 0.8 dB was found postsurgery. For the condition where the noise was directed toward the nonatretic ear, the HINT threshold improved 1.7 dB postsurgery ($p = 0.0005$). The HINT Noise Composite Score improved by 1.0 dB postsurgery ($p = 0.045$). SSQ scores improved postsurgery for 82.6% of the participants. A significant improvement for mean SSQ scores was found 12 mo postsurgery ($p < 0.05$).

### Binaural Advantage for Speech Recognition in Noise Ability in a Simulated Soundfield

Arsenault and Punch (1999) determined the binaural advantage for speech recognition in noise ability for 10 participants with pure-tone thresholds ≤20 dB HL for 250–6000 Hz. The speech stimuli were nonsense syllables (consonant–vowel or vowel–consonant) from the City University of New York Nonsense Syllable Test (Resnick et al, 1975). Speech was presented at 0° and fixed at 65 dBC. Cafeteria noise was presented at 270° (noise left condition). The level of the cafeteria noise was adjusted for five SNR conditions; −8, −4, 0, 4, and 8 dB SNR. Recordings of the stimuli were made using a Knowles Electronics Mannequin for Auditory Research (KEMAR) for each of the SNR conditions. The speech and noise recordings were presented to 10 participants with normal pure-tone thresholds. The ages of the participants were not presented in this study. A mean binaural advantage of 4.9 dB was found for the binaural noise left versus monaural (shadowed ear) performances. A mean binaural advantage of 12.3 dB was found for the binaural noise left versus monaural (unshadowed ear) performances.

### The Effects of the Spatial Separation of Speech and Noise Signals on Binaural and Monaural (Simulated Conductive Hearing Loss) Speech Recognition in Noise Ability

Dubno et al (2008) evaluated the benefit of the spatial separation of speech and noise stimuli and the binaural advantage. The authors examined the differences between spatial separation of the target speech and speech-shaped noise both with and without the head shadow effect. The HINT (Nilsson et al, 1994; Vermiglio, 2008) was used with a nonstandard protocol to measure speech recognition in noise ability. The speech-shaped noise was presented at 62 dB SPL. The level of the speech was adaptively varied based on the participant's response. A 3-dB step-size was used for first four reversals and a 2-dB step-size was used for the remaining eight reversals. Fifteen to 17 sentences were presented to obtain each HINT threshold. The threshold was defined as the average level of the last six reversals. Each data point was the average of two thresholds. HINT sentences were presented at 0° and speech-shaped noise at 0°, 90°, or ±90° in the soundfield. The results showed that spatial separation of the speech and noise provided a greater benefit with the head shadow effect (4.8 dB SNR) than without the head shadow effect (1.6 dB SNR) ($p < 0.0001$).

In the binaural and monaural listening conditions for the second experiment, HINT sentences (speech) were presented at 0° and the speech-shaped masker was presented at 90° in the soundfield. For the monaural listening condition, the ear closest to the noise was plugged. This could also be called the "shadowed" monaural condition where the head blocks the noise as it reaches the unplugged ear. The authors found that even with an unfavorable SNR, thresholds for binaural listening were significantly better compared with the monaural listening condition (1.6 dB; $p < 0.0001$). According to the authors, "with the speech emanating from the front and the noise to one side, thresholds measured with the near ear plugged improved significantly with the addition of a second [unshadowed] ear with an unfavorable SNR. Thus, the advantage of interaural difference cues provided by a second ear outweighed that ear's poorer SNR." This study shows the importance of conducting speech recognition in noise ability where the head shadow effects may influence performance. This is in contrast to pure-tone threshold testing where there are no head-shadow effects.

Dubno and colleagues used an E-A-R foam earplug (Aearo Company, Indianapolis, IN). According to the authors, the earplug was inserted deeply into the participant's ear canal and maximum attenuation was confirmed by the participant. The authors further stated that the articulation index (AI) values predicted minimal contribution of the plugged ear to speech recognition in noise ability, "as estimated from participants' thresholds, the levels of the speech and masker, and the manufacturer's specification for attenuation across frequency provided by the earplug." The noise-reduction rating for the E-A-R foam earplug was 29 dB. The highest average level of the speech at threshold in this study was ~61 dB SPL. This means that at threshold the sentences would reach the plugged ear at ~32 dB SPL. Because all of the participants had normal hearing, the sentences would have reached the plugged ear above threshold. Again, the "deaf" ear in this study would have heard the speech stimuli delivered "monaurally." This may have influenced the binaural advantage found in this study. Furthermore, whereas the authors used the AI to predict the contribution of the plugged ear, Vermiglio et al (2012) demonstrated that the AI is not a strong predictor of speech recognition in noise ability.

## Summary of Literature Review

Pure-tone thresholds have been used as the "gold standard" for the assessment of the ability to hear (Shargorodsky et al, 2010). The WHO has stated that as long as the better hearing ear has a $\text{PTA}_{(0.5,\ 1.0,\ 2.0,\ 4.0\ \text{kHz})} \leq 25$ dB HL, the individual will have no or very slight hearing problems (Mathers et al, 2000). However, this conclusion has not been borne out in self-report studies of patients with unilateral hearing loss (Dwyer et al, 2014; Byun et al, 2015) or SSD (Douglas et al, 2007). According to the SSQ results, the patient groups in these studies reported significantly poorer speech recognition in noise ability than the control groups. Furthermore, measurable speech recognition in noise deficits have been found for participants with a simulated unilateral conductive hearing loss (Persson et al, 2001; Dubno et al, 2008) and unilateral congenital atresia (Byun et al, 2015). Deficits have also been found for simulated SSD in a virtual soundfield environment (Arsenault and Punch, 1999).

Binaural advantage for speech recognition in noise ability has been demonstrated within atretic patients pre- and postsurgery (Gray et al, 2009; Byun et al, 2015), and between control participants and patients with unilateral hearing losses (Ruscetta et al, 2005). Dubno et al (2008) investigated binaural advantage within participants between binaural and monaural (plugged) conditions. However, since the monaural condition included an earplug for the nontest ear, the extent of the binaural advantage may have been limited because of the potential audibility of the speech stimuli for the plugged ear. Arsenault and Punch (1999) measured the binaural advantage for the ability to recognize nonsense syllables in cafeteria noise. Testing was conducted binaurally and monaurally under headphones in a simulated soundfield environment via KEMAR recordings. This approach decreases the risk of audibility of the speech stimulus by the nontest ear when compared with studies that used an earplug for the monaural listening conditions. Their methods included testing with the spatial separation of the speech and noise signals.

## Purpose

The overall goal of the present study was to evaluate the WHO and AMA ratings of hearing impairment for SSD. The purpose of the study was to demonstrate binaural advantage and conversely the impact of simulated SSD for speech recognition in noise ability. Similar to the study by Arsenault and Punch (1999), participants with normal pure-tone thresholds were evaluated binaurally and monaurally. However, instead of listening to nonsense syllables in cafeteria noise, the participants listened to HINT sentences in steady-state speech-shaped noise in a simulated soundfield environment. All stimuli were presented under headphones. This method provides less interference from crossover to the nontest ear than previous studies that used earplugs. The listening conditions included the spatial separation of the speech and noise stimuli. Both binaural and spatial advantage measures were determined for the participants. The spatial advantage (or the improvement in speech recognition in noise ability with the spatial separation of the speech and noise stimuli) was determined for the binaural and monaural conditions. The following research questions were addressed:

- What is the binaural advantage for speech recognition in noise ability within participants?
- What is the relationship between monaural and binaural HINT thresholds?
- What is the spatial advantage for the binaural condition?
- What is the spatial advantage for the monaural condition?

## METHODS

Permission to conduct this research study was obtained from the East Carolina University Institutional Review Board. Participation criteria included normal pure-tone thresholds (≤25 dB HL for 500–8000 Hz) and clear ear canals bilaterally. All participants were native speakers of American English. Twenty-eight participants were initially tested for this study. Data from three participants were omitted because of pure-tone thresholds poorer than 25 dB HL. The average age was 20.8 years (SD = 1.27). The age range was from 19 to 25 years. Data from 24 females and one male were included in this study.

The American English HINT (Nilsson et al, 1994; Vermiglio, 2008) was used to measure the ability to recognize speech in steady-state noise. Sentences were presented in "speech-shaped" noise at a fixed level of 65 dBA. Each HINT condition was conducted using a single list of 20 sentences. Testing was conducted in a simulated or "virtual" soundfield environment using KEMAR head-related transfer-functions. All stimuli were prerecorded. The sentences were presented at 0° for each test condition. The noise was presented at 0°, 90°, and 270° for the Noise Front, Noise Right, and Noise Left conditions, respectively. All test conditions were randomized. Telephonic TDH-50P headphones were used to deliver the stimuli. Headphone testing allows for the evaluation of monaural (or simulated SSD) and binaural hearing ability under conditions where the speech and noise are spatially separated.

The simulated binaural and monaural noise conditions delivered under headphones are illustrated in Figures 1–3. The Noise Front condition was measured binaurally and monaurally. The monaural Noise Front thresholds were measured for the left and right ears. The Noise Left and Noise Right thresholds were measured for the ear closest to the noise source ("unshadowed ear"). The monaural Noise Left thresholds were measured for the left ear and the monaural Noise Right thresholds were measured for the right ear.

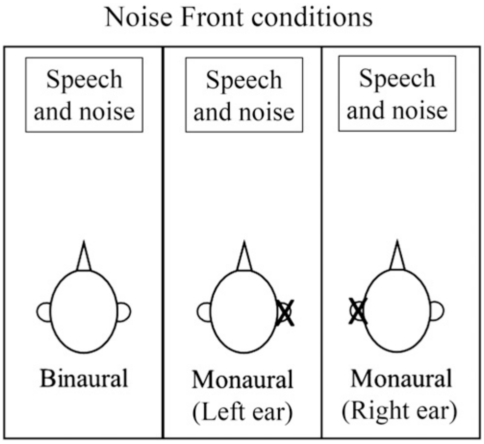

**Figure 1.** Illustration of the binaural and monaural Noise Front conditions simulated under headphones.

The HINT uses an adaptive protocol where the level of the sentence presentation varies based on the response of the participant. The participant's task is to listen to and repeat the sentence heard in the presence of the speech-shaped noise. If the participant correctly repeats the sentence, the level of the speech for the following sentence is decreased. If the participant incorrectly repeats the sentence, the level of the speech for the following sentence is increased. A 4-dB step-size is used for the first four sentence presentations. A 2-dB step-size is used for the remaining sentences. The HINT threshold is the SNR where a participant recognizes 50% of the sentences. The "variability" was also determined. This is the standard deviation (SD) of the SNRs used for each test run. It is a measure of the stability or consistency of the participant's responses. The binaural advantage for each HINT condition was determined by subtracting the binaural from the monaural threshold for each noise condition. The spatial advantage was determined by subtracting the Noise Side threshold from the Noise Front threshold for the binaural and

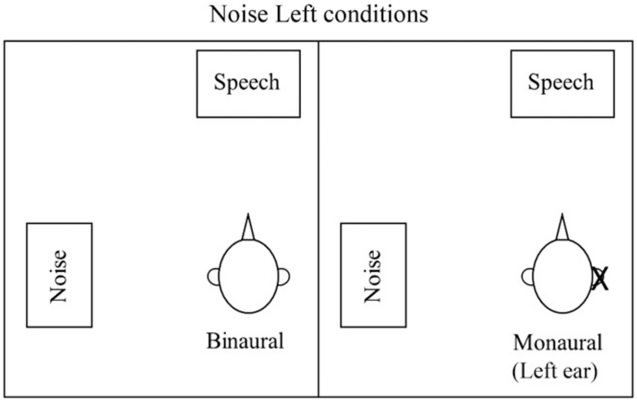

**Figure 2.** Illustration of the binaural and monaural Noise Left conditions simulated under headphones. The "unshadowed" ear is used for the monaural condition.

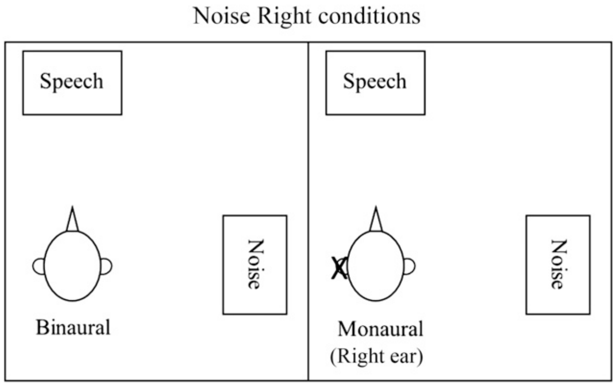

**Figure 3.** Illustration of the binaural and monaural Noise Right conditions simulated under headphones. The "unshadowed" ear is used for the monaural condition.

monaural conditions. The HINT test was administered using custom software provided by the House Ear Institute in Los Angeles, CA.

Statistical analyses were conducted using the JMP Pro (V.12) software. The matched pairs *t*-test was conducted to determine if there were statistically significant differences between the binaural and monaural conditions. The Pearson correlation coefficient was calculated between binaural and monaural test results.

## RESULTS

The descriptive statistics for the HINT thresholds are presented in Table 1. The more negative the threshold in dB SNR, the better the speech recognition in noise performance. The average binaural Noise Front threshold was –1.76 dB SNR. This indicates that when the speech signal is 1.76 dB below the level of the noise, the participants on average recognize 50% of the sentences. The average binaural thresholds for the Noise Left and Noise Right conditions were –8.58 and –8.38 dB SNR, respectively. The average monaural thresholds for the Noise Front (left ear) and Noise Front (right ear) conditions were –0.41 and –0.70 dB SNR, respectively. The average monaural thresholds for the Noise Left and Noise Right conditions were 3.00 and 2.53 dB SNR, respectively. The descriptive statistics for the variability of each threshold run are presented in Table 2. The average mean variability across all HINT conditions was 1.96 dB. This indicates that the participant responses were consistent across the test conditions.

The binaural advantage represents the improvement in speech recognition ability for two ears versus one. Figure 4 illustrates the binaural advantage for the Noise Front conditions. Most of the 25 participants demonstrated a binaural advantage. However, a monaural advantage was found for two (8%) of the participants. Figure 5 shows a binaural advantage for all 25 participants (100%) for the Noise Side conditions. The descriptive statistics for the binaural advantage are presented in Table 3. This was determined by subtracting the binaural from the monaural thresholds for each HINT condition. A positive value indicates a binaural advantage. Negative values indicate a monaural advantage. Table 4 shows that significant binaural advantages were found for the Noise Front and Noise Side conditions with Bonferroni correction ($p < 0.01$). On average, binaural speech recognition in noise performances were significantly better than the monaural performances. The average binaural advantage for the Noise Front condition was 1.2 and 11.25 dB for the Noise Side conditions.

According to Nilsson et al (1994), a 1-dB change in SNR is equivalent to a 10% change in speech recognition ability. Freed (personal communication) created a feature in a previous version of the HINT system (HEI, 2007) that was used to estimate the maximum change in intelligibility of a given HINT threshold in reference to the mean normal performance. Freed's method was used to estimate the maximum change in intelligibility (Table 4) for the monaural as compared to the binaural thresholds (or predicted maximum binaural improvement in percent correct). For the Noise Front listening condition, the maximum improvement in speech recognition ability for two ears versus one is 13.44% in reference to the monaural left-ear condition and 10.57% in reference to the monaural right-ear condition. The average binaural advantage for the Noise

**Table 1. Descriptive Statistics for All HINT Thresholds (dB SNR)**

| | HINT Noise Front Binaural | HINT Noise Front Monaural (Left ear) | HINT Noise Front Monaural (Right ear) | HINT Noise Left Binaural | HINT Noise Left Monaural (Left ear) | HINT Noise Right Binaural | HINT Noise Right Monaural (Right ear) |
|---|---|---|---|---|---|---|---|
| Mean | −1.76 | −0.41 | −0.70 | −8.58 | 3.00 | −8.38 | 2.53 |
| SD | 0.92 | 1.21 | 1.21 | 1.97 | 1.51 | 1.95 | 1.30 |
| n | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| Maximum | 1 | 1.7 | 1.9 | −0.7 | 6.5 | −0.6 | 5.2 |
| Minimum | −3.7 | −3.2 | −3.1 | −11 | 0.7 | −10.7 | 0.1 |
| Range | 4.7 | 4.9 | 5.0 | 10.3 | 5.8 | 10.1 | 5.1 |

**Table 2. Descriptive Statistics of the Variability for All HINT Thresholds**

| | HINT Noise Front Binaural | HINT Noise Front Monaural (Left ear) | HINT Noise Front Monaural (Right ear) | HINT Noise Left Binaural | HINT Noise Left Monaural (Left ear) | HINT Noise Right Binaural | HINT Noise Right Monaural (Right ear) |
|---|---|---|---|---|---|---|---|
| Mean | 1.82 | 1.74 | 1.94 | 2.06 | 2.04 | 2.10 | 2.00 |
| SD | 0.27 | 0.31 | 0.44 | 0.45 | 0.51 | 0.50 | 0.38 |
| n | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| Maximum | 2.6 | 2.4 | 3 | 3.2 | 3.6 | 3 | 2.9 |
| Minimum | 1.4 | 1.2 | 1.3 | 1.6 | 1.2 | 1.5 | 0.4 |
| Range | 1.2 | 1.2 | 1.7 | 1.6 | 2.4 | 1.5 | 1.5 |

*Notes:* Variability = standard deviation for each HINT threshold search.

Front conditions was 12.01%. By contrast, the maximum improvement in speech-recognition ability for the Noise Side conditions was much greater: 85.33% for the Noise Left condition and 82.85% for the Noise Right condition. The average maximum improvement across the Noise Side conditions was 84.09%.

Recall that the spatial advantage represents the improvement in thresholds when the noise is spatially separated from the speech. The spatial advantage is illustrated in Figure 6 for the binaural conditions and Figure 7 for the monaural conditions. For the binaural conditions, all participants with the exception of one demonstrated a spatial advantage. All of the participants demonstrated a spatial advantage for the monaural conditions. The spatial advantages are presented in Table 5. This was determined by subtracting the Noise Side from the Noise Front thresholds for the binaural and monaural conditions. The average spatial advantage was 6.72 and −3.32 dB for the binaural and monaural conditions, respectively. This indicates that while a significant improvement in HINT performance was found when the speech and noise were spatially separated for the binaural condition, a significant spatial deficit was found for the monaural (unshadowed) condition ($p < 0.01$). In other words, when referencing the unshadowed ear (monaural condition), it is easier to recognize speech in noise when the stimuli are delivered from 0° than when the noise is spatially separated from the speech. The estimated maximum intelligibility improvement for the binaural conditions was 60.73% in reference to the Noise Left condition and 59.33% in reference to the Noise Right condition. There was an estimated maximum intelligibility change of 60.03% across the binaural conditions. For the monaural conditions, there was a significant spatial advantage: −33.09% in reference to the Noise Left condition and −31.44% in reference to the Noise Right condition. Across these two conditions, there was an average estimated maximum intelligibility change of −32.27%. This indicates that for the monaural conditions it was much easier to listen to speech in noise when both stimuli are presented from 0° than when the speech and noise are spatially separated. This may be considered intuitive because the noise is directed toward the test (unshadowed) ear for the monaural conditions.

The correlation coefficients for the binaural versus monaural conditions and $p$-values are presented in

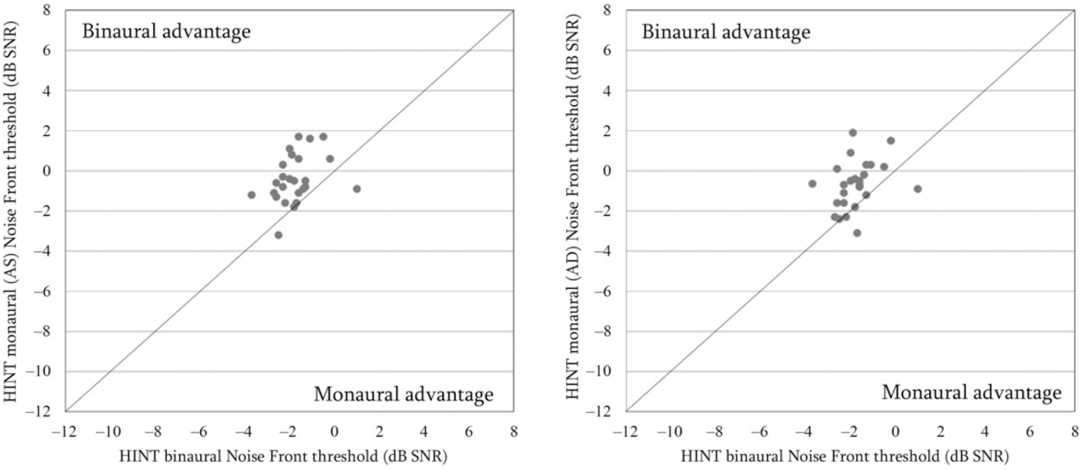

**Figure 4.** Binaural advantage for the Noise Front condition (AS = left ear, AD = right ear).

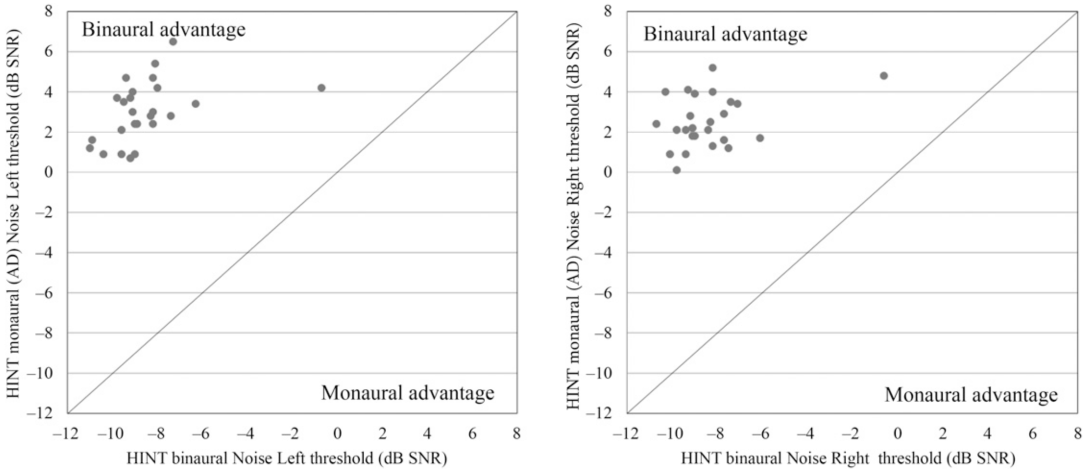

**Figure 5.** Binaural advantage for the Noise Side conditions (AS = left ear, AD = right ear).

Table 6. No significant correlations were found between the binaural Noise Front and Noise Side thresholds. A relatively strong positive correlation was found between the binaural Noise Left and Noise Right performances ($r = 0.6372$, $p < 0.05$). A moderate correlation was found between binaural Noise Left and monaural Noise Left thresholds ($r = 0.4264$, $p < 0.05$) and between the binaural Noise Left and monaural Noise Right thresholds ($r = 0.4560$, $p < 0.05$). No significant correlations were found between the binaural Noise Right and monaural Noise Front or Noise Side thresholds. A significant positive correlation was found for monaural Noise Front (left versus right ear) thresholds ($r = 0.5719$, $p < 0.05$). However, no significant correlation was found between the monaural Noise Side conditions. Significant positive correlations were also found between the monaural Noise Front (left ear) versus the monaural Noise Left conditions ($r = 0.5451$, $p < 0.05$) and between the monaural Noise Front (left ear) versus the monaural Noise Right conditions ($r = 0.4546$, $p < 0.05$). While no significant correlation was found between the monaural Noise Front (right ear) and the monaural noise Left thresholds, a significant correlation was found between the Noise Front (right ear) and the monaural Noise Right thresholds ($r = 0.4334$, $p < 0.05$).

## DISCUSSION

A significant binaural advantage was found for all of the HINT conditions ($p < 0.01$). The average binaural advantage for the Noise Front condition was 1.21 dB. This corresponds to an estimated maximum change in intelligibility of 12.01%. The average binaural advantage for the Noise Side conditions was 11.25 dB. This corresponds to an estimated maximum change in intelligibility of 84.09%. In other words, in reference to the unshadowed ear for the Noise Side condition, an individual on average will detect up to 84.09% more of the conversation with two ears than when listening with only one ear. This is in stark contrast to the degree of hearing impairment for SSD as determined by the WHO and AMA methods based on PTA. Recall that Arsenault and Punch (1999) found a binaural advantage for the recognition of nonsense syllables in cafeteria noise of 12.3 dB for the "Noise Left" condition. This is similar to the 11.58 dB binaural advantage for the present study for the recognition of sentences in steady-state speech-shaped noise for the Noise Left condition.

A significant spatial advantage was found for the binaural and monaural conditions ($p < 0.01$). The average binaural spatial advantage was 6.72 dB. This corresponds to an estimated maximum change in

**Table 3. Descriptive Statistics for the Binaural Advantage (dB)**

| | Binaural Advantage Noise Front (Re: Left ear) | Binaural Advantage Noise Front (Re: Right ear) | Binaural Advantage Noise Left | Binaural Advantage Noise Right |
|---|---|---|---|---|
| Mean | 1.35 | 1.06 | 11.58 | 10.92 |
| SD | 1.25 | 1.27 | 1.90 | 1.92 |
| n | 25 | 25 | 25 | 25 |
| Maximum | 3.3 | 3.8 | 14.1 | 14.3 |
| Minimum | −1.9 | −1.9 | 4.9 | 5.4 |
| Range | 5.2 | 5.7 | 9.2 | 8.9 |

**Table 4. Binaural Advantage = Average Monaural Minus Binaural Thresholds for each HINT Condition (Matched Pairs Analysis in JMP)**

| | Noise Front (AS) | Noise Front (AD) | Average Noise Front | Noise Left | Noise Right | Average Noise Side |
|---|---|---|---|---|---|---|
| Binaural advantage | 1.35 dB | 1.06 dB | 1.21 dB | 11.58 dB | 10.92 dB | 11.25 dB |
| *p*-value with Bonferroni correction | <0.0006 | 0.0024 | <0.0006 | <0.0006 | <0.0006 | <0.0006 |
| Estimated maximum intelligibility change | 13.44% | 10.57% | 12.01% | 85.33% | 82.85% | 84.09% |

*Notes:* AS = left ear; AD = right ear.

intelligibility of 60.03%. However, the average spatial advantage for the monaural HINT condition was −3.32 dB, which corresponds to an estimated maximum change in intelligibility of −32.27%. In other words, for the monaural condition the participants performed poorer when the speech and noise were spatially separated than when the stimuli were presented from the same location. Spatial advantage is not reflected in the results from the PTA methods used by the WHO and AMA.

### The Monaural Test Condition and Simulated SSD

The results demonstrated the binaural advantage and conversely the effect of simulated SSD in a virtual soundfield environment presented under headphones. It should be noted that although no signal was presented to the simulated deaf ear during the monaural conditions, it was possible for stimuli delivered to the monaural test ear to reach the simulated deaf ear. Recall that TDH-50P headphones were used for the delivery of all stimuli for the present study. According to Blackwell et al (1991), the TDH-50P has a mean interaural attenuation of 51.25 dB for 250 Hz, 57.08 dB for 500 Hz, 60.00 dB for 1000 Hz, 60.00 dB for 2000 Hz, and 64.17 dB for 4000 Hz. Across the frequency range of 250–4000 Hz, there is an average attenuation of 58.5 dB for the TDH-50P headphones. The highest average HINT threshold was 3 dB SNR for the monaural Noise Left condition. This means that across test conditions the highest level of the sentences at threshold was 68 dBA. This speech level minus the average interaural attenuation for the TDH 50P headphones of 58.5 dB, results in an average speech level of 9.5 dBA delivered to the "deaf" ear. According to the unpublished norms at East Carolina University, the HINT threshold in quiet is 25.42 dBA. Therefore, the speech stimulus presented to the hearing ear in the monaural condition would reach the simulated deaf ear via bone conduction at an inaudible level. Overall, the monaural conditions in this study appear to be a reasonable simulation of SSD. This is in contrast to studies that have used an earplug for the monaural listening condition where the nontest ear may have heard the target speech delivered to the test ear (Persson et al, 2001; Dubno et al, 2008).

### SSD and the Rating of Hearing Impairment

Recall that according to the WHO (Mathers et al, 2000), a better ear $\mathrm{PTA}_{(0.5,\ 1.0,\ 2.0,\ 4.0\ \mathrm{kHz})} \leq 25$ dB HL represents "no impairment." This implies that patients with SSD would have "no or very slight hearing problems." The results of the present study and previous studies, however, do not support this classification

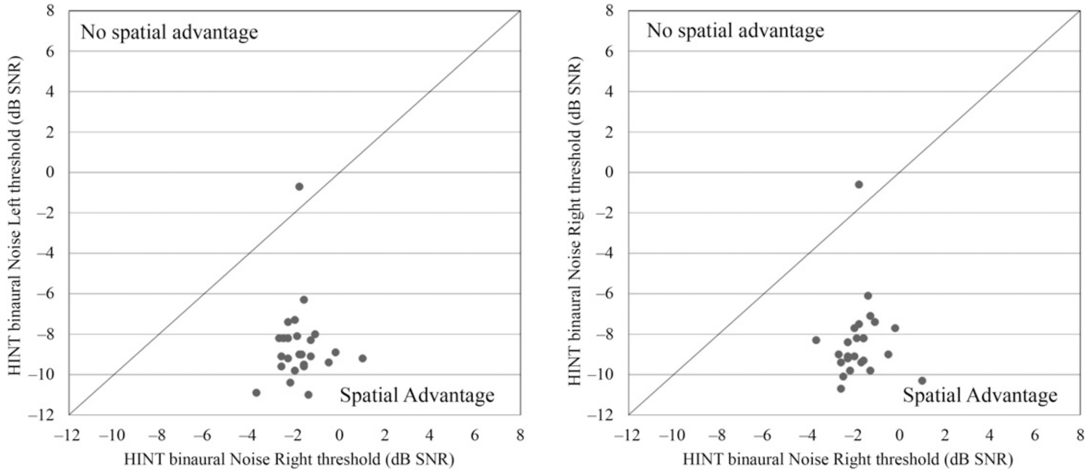

**Figure 6.** Spatial advantage for the binaural conditions.

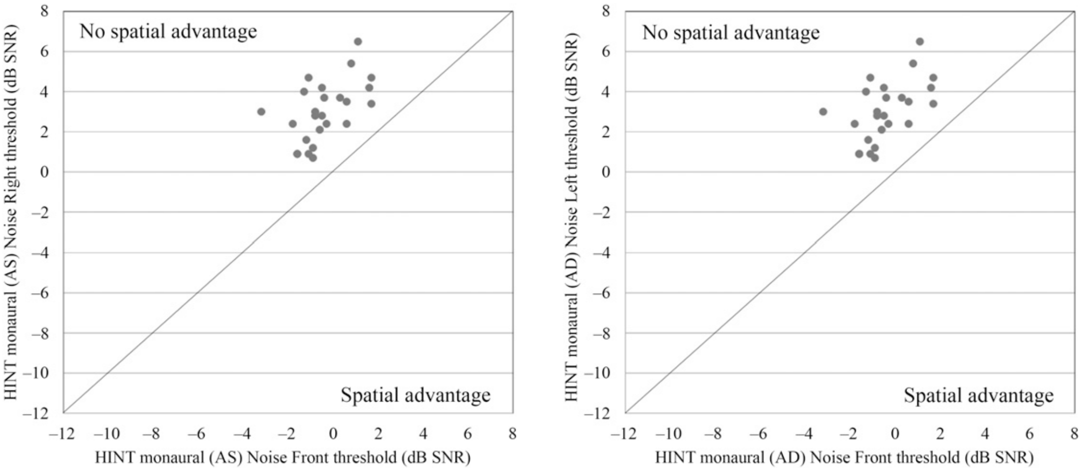

**Figure 7.** Spatial advantage for the monaural conditions.

when the ability to recognize speech in background noise is a factor and especially in conditions where the speech and noise are spatially separated. Even though the WHO has published the ICF, which recognizes contextual factors such as environmental noise on hearing impairment, speech recognition in noise ability is not a factor for the WHO's classification of hearing impairment. The AMA *Guides* (AMA, 2008) have adopted the terminology and conceptual framework of disablement as put forth by the WHO's ICF. The ICF framework is intended to describe and measure health and disability.

According to the AMA *Guides*, hearing loss is evaluated using pure-tone thresholds. This is considered an "objective" measure of hearing. However, a pure-tone threshold test relies on the subjective impression of audibility from the patient. The AMA *Guides* states that binaural hearing impairment is determined through the evaluation of pure-tone thresholds for both ears. However, the term "binaural" means the perception of sound with both ears. The combination of monaural pure-tone thresholds is not equivalent to hearing with both ears together. The rationale behind the rating of hearing impairment is related to the ability to hear "everyday speech."

According to the *Hearing Handicap Guide* published by the American Academy of Otolaryngology and the American Council of Otolaryngology (AAO-ACO, 1979), a handicap or impairment is "a medical condition that affects one's personal efficiency in the activities of daily living." The AAO-ACO wrote that the basis for the calculation of hearing handicap should be modified to reflect the understanding of speech, not only in a quiet environment but also in the presence of some noise. At that time, they noted that there was no standardized test for this assessment; therefore, they recommended a determination of hearing impairment based on the decibel sum of pure-tone threshold levels for 500, 1000, 2000, and 3000 Hz. According to their rating scheme, pure-tone thresholds of 25 dB HL from 500 to 3000 Hz would represent 0% hearing impairment. For a deaf ear, the patient would have a hearing impairment of 100%. The binaural impairment is equal to five times the percent impairment for the better ear plus one times the percent impairment for the poorer ear. This amount is then divided by six to determine the percent of handicap. For the patient with SSD in this example, the percent handicap is equal to 16.7%. This is the same method for the determination of hearing impairment described in the AMA *Guides*.

AAO-ACO (1979) referenced recommendations for the improvement of the evaluation of hearing impairment from the Council on Physical Medicine and Rehabilitation (CPMR, 1955). The CPMR noted, "…the most valid way to measure the ability to hear speech correctly is to use words or sentences." They further commented

**Table 5. Spatial Advantage = Noise Front Minus Noise Side Thresholds for Each for the Binaural and Monaural Conditions (Matched Pairs Analysis in JMP)**

| | Binaural NF - NL | Binaural NF - NR | Average Binaural | Monaural (AS) NF - NL | Monaural (AD) NF - NR | Average Monaural |
|---|---|---|---|---|---|---|
| Spatial advantage | 6.82 dB | 6.62 dB | 6.72 dB | −3.41 dB | −3.23 dB | −3.32 dB |
| *p*-value with Bonferroni correction | <0.0006 | <0.0006 | <0.0006 | <0.0006 | <0.0006 | <0.0006 |
| Estimated maximum intelligibility change | 60.73% | 59.33% | 60.03% | −33.09% | −31.44% | −32.27% |

*Notes:* NF = Noise Front threshold; NR = Noise Right threshold; NL = Noise Left threshold.

**Table 6. Correlation Coefficients for the Binaural vs. Monaural Conditions (*p*-values in Parentheses)**

| | Binaural Noise Left | Binaural Noise Right | Monaural Noise Front (AS) | Monaural Noise Front (AD) | Monaural Noise Left (AS) | Monaural Noise Right (AD) |
|---|---|---|---|---|---|---|
| Binaural noise front | 0.0288 (0.8914) | 0.0425 (0.8400) | 0.3395 (0.0969) | 0.3103 (0.1311) | −0.1421 (0.4979) | 0.3067 (0.1359) |
| Binaural noise left | | **0.6372 (0.0006)** | 0.1880 (0.3681) | 0.0696 (0.7409) | **0.4264 (0.0335)** | **0.4560 (0.0220)** |
| Binaural noise right | | | 0.1551 (0.4590) | 0.1823 (0.3831) | 0.1964 (0.3467) | 0.3598 (0.0773) |
| Monaural noise front (AS) | | | | **0.5719 (0.0028)** | **0.5451 (0.0048)** | **0.4546 (0.0224)** |
| Monaural noise front (AD) | | | | | 0.3697 (0.0689) | **0.4334 (0.0304)** |
| Monaural noise left (AS) | | | | | | 0.2526 (0.2232) |

*Notes:* AS = left ear; AD = right ear. Significant correlations at the $p < 0.5$ level are presented in bold font.

that, "hearing and recognizing the spoken word is more than receiving a set of independent signals; it is a dynamic process in which time is a factor and in which there are complicated interactions. It seems logical to use speech as the material in a test of the ability to hear speech." The authors recommended that once the test materials are developed, the methods for calculating hearing disability should be verified in terms of sentence intelligibility.

The AAO-ACO (1979) PTA method for the determination of hearing handicap was based in part on a study conducted by Kryter et al (1962). The authors evaluated the relationship between speech recognition in noise ability and pure-tone thresholds for 114 adult male soldiers with various audiometric configurations. Speech recognition ability was conducted in quiet and in noise with a spectrum shape similar to the long-term idealized spectrum of speech. Testing was conducted using words and sentences. The speech stimulus was delivered at 65 dB [sic]. Speech-recognition ability was determined for a range of SNRs. The results demonstrated a strong relationship ($R = 0.806$) between a PTA$_{(1.0,\ 2.0,\ 3.0\ \text{kHz})}$ and speech recognition in noise ability. The authors concluded that this PTA would be a reasonably valid method for the determination to understand everyday speech. There are two problems with this conclusion. First, the authors omitted data from participants with normal pure-tone thresholds, and second, the strong positive relationship between PTA$_{(1.0,\ 2.0,\ 3.0\ \text{kHz})}$ and speech recognition in noise results was most likely driven by the audibility of the test materials.

Not all investigations of the relationship between PTA and speech recognition in noise performances have revealed strong correlations. Vermiglio et al (2012) reported no significant relationships between PTA (0.5–2.0, 3.0–6.0, or 0.5–6.0 kHz) and thresholds for the HINT Noise Front condition. Wilson et al (2007) reported weak but significant correlations between PTA (0.5–2.0 kHz) and Bamford-Kowal-Bench Speech-In-Noise test results ($r = 0.292$, $p < 0.05$). On the other hand, Tschopp and Züst (1994) reported a relatively strong relationship between PTA (0.5–4 kHz) and the German Speech-in-Noise test ($r = 0.740$, $p < 0.05$). The strength of the relationships between PTA and speech recognition in noise ability may be affected by the audibility of the stimulus (Vermiglio, 2007). This in turn is dependent on the level of the stimuli and the configuration of hearing sensitivity. Furthermore, listeners with normal pure-tone thresholds may exhibit a range of speech recognition in noise performances that match those of hearing-impaired participants (Dickson et al, 1946; Vermiglio et al, 2012). The ability to recognize speech in noise should be measured directly and not inferred from the PTA.

## Measures of Speech Recognition in Noise Ability

The measurement of the ability to recognize speech in noise has been investigated over the past 80 years. Fletcher (1929) demonstrated how performance improved as the SNR improved. Fry (1942) suggested that pure-tone thresholds would not represent a complete assessment of the ability to hear. He recommended the development of a speech-recognition-in-noise test for Royal Air Force candidates. The development of this "efficiency test" was presented by Dickson et al (1946). The test protocol included listening to recorded words and sentences in the presence of aircraft noise. The authors noted "...it was difficult to predict from a subject's audiogram whether he was likely to do well or badly in an articulation test in a noise field." They also stated that speech recognition in noise scores from a "sample of subjects with 'normal' audiograms may scatter just as widely as those from a group of subjects with varying degrees of hearing loss." The authors recommended a two-part protocol for hearing evaluations. The first part was the efficiency test. If the candidate failed this test, no further evaluations were conducted and the candidate was rejected. If the candidate passed the efficiency test, then pure-tone threshold testing was conducted to rule out any clinical reason for rejecting the candidate in spite of passing the efficiency test. It is apparent from the protocol that the ability to recognize speech in background noise was considered more important than the ability to detect pure-tone stimuli. Even though speech recognition in noise testing has been conducted since the 1920s, it has not found widespread use in audiology clinics today. ASHA (2015) noted in a survey of 1811 audiologists that only 30% routinely conduct a validation of outcomes using speech recognition in noise testing.

Dr. Shelly Chadha, the medical officer for the WHO Program for Prevention of Deafness and Hearing Loss, reported that the WHO defines disabling hearing loss as "hearing loss that is >40 dB" in the better hearing ear for adults (Fabry and Clark, 2017). She also stated that hearing problems and the resources available to address these problems vary across the world. She noted that, "The public health perspective requires developing a model of service and care that may ensure best practice but also allow customization to meet regional or country-specific issues." Although speech recognition in noise testing may not be available for all areas of the world, when it is available it would be preferable to rate hearing impairment based on speech-in-noise test results than PTA.

## Summary and Conclusion

According to the WHO and AMA PTA methods, the degree of hearing impairment for an individual with SSD is none or "slight." This is contrary to self-report data from patients with SSD (Douglas et al, 2007). Studies that have investigated the binaural advantage where the nontest ear was plugged during the monaural condition (Carhart, 1965; Persson et al, 2001; Dubno et al, 2008) may have produced results that were confounded by the audibility of the stimuli for the nontest ear. This may have resulted in an underestimation of the binaural advantage. An alternative to measuring binaural benefit is to obtain monaural and binaural speech recognition in noise thresholds under headphones in a virtual soundfield environment (Arsenault and Punch, 1999). This minimizes the risk of the nontest ear hearing the speech stimuli for the monaural test conditions.

It was noted by the CPMR (1955) that speech would be a better test stimulus than pure-tone thresholds when determining the degree of hearing impairment. Furthermore, the AAO-ACO (1979) made this very important point, "The limit of normal for the hearing of speech may reasonably be assumed for the present to be comparable to that for the hearing of pure-tones in the speech-frequency range, but it should be defined more precisely in the future when more measurements and better validation become available." Today we have the instruments for a better validation of hearing impairment than PTA. The use of speech recognition in noise testing allows clinicians, researchers, and physicians to quantify hearing impairment not solely on pure-tone threshold results, but on the ability to perceive speech in background noise.

It is clear from the results of the present and previous studies that the PTA method used by the WHO and AMA for the determination of hearing impairment underestimates the effect of SSD on the perception of speech in the presence of background noise. The WHO and AMA criteria for the determination of hearing impairment should be updated to include speech recognition in noise testing with and without the spatial separation of the speech and noise stimuli. In this way, actual, as opposed to inferred perceptions of speech in noisy environments may be determined. This will provide a much-needed improvement in the ratings of hearing impairment.

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