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Original Article

Sentence perception in listening conditions having similar speech intelligibility indices

Samantha J. Gustafson & Andrea L. Pittman

Department of Speech and Hearing Science, Arizona State University, Tempe, AZ USA

Abstract

Objective: The objective of this study was to examine the relation between bandwidth and speech perception in normally hearing adults and children at a single value of the Speech Intelligibility Index (SII). *Design:* The SII of meaningful and nonsense sentences were held constant for each of three bandwidths to test the hypothesis that perception would be equivalent in each condition. The sentences were filtered to produce three bandwidth conditions (low-pass cut-off frequency: 0.8, 1.25, 2.5 kHz) and the sensation level within each bandwidth was adjusted to produce a similar SII (0.43–0.48). Sentences were presented in broadband noise to facilitate equivalent audibility across subjects in each bandwidth condition. *Study sample:* Participants were 20 adults between the ages of 19 and 47 years and 20 eight-year-old children. All participants had normal hearing. *Results and conclusion:* Contrary to the hypothesis, performance of both groups increased significantly as bandwidth increased. Significant main effects of group and sentence type were also found. These results indicate that performance was governed largely by the bandwidth of the stimuli and that those effects were not represented well in the SII.

Sumario

Objetivo: El objetivo de este estudio fue examinar la relación entre el ancho de banda y la percepción del lenguaje en adultos normoyentes y niños, con un valor único del Índice de Inteligibilidad del Habla (SII). *Diseño:* El SII de oraciones con y sin sentido se mantuvo constante para cada uno de los tres anchos de banda para probar la hipótesis de que la percepción puede ser equivalente en cada condición. Las oraciones fueron filtradas para producir tres condiciones de ancho de banda (filtro pasa-bajo a frecuencias: 0.8, 1.25, 2.5 kHz) y el nivel de sensación en cada ancho de banda fue ajustado para producir un SII similar (0.43–0.48). Se presentaron las oraciones en medio de ruido de banda ancha para facilitar la audibilidad equivalente entre sujetos en cada condición de ancho de banda. *Muestra:* Los participantes fueron 20 adultos de edades entre 19 y 47 años y veinte niños de ocho años de edad. Todos eran normoyentes. *Resultados y conclusiones:* Contrario a la hipótesis, el desempeño de los dos grupos aumentó significativamente conforme el ancho de banda aumentaba. También se encontraron efectos significativos mayores en cuanto a grupos y tipo de oración. Estos resultados indican que esos efectos no estaban bien representados en el SII.

Key Words: Children; Adults; Speech intelligibility index; Bandwidth; Speech perception

Listeners with hearing impairment often experience difficulty understanding speech due to a reduced audibility of the incoming signal. The purpose of a hearing aid is to improve audibility without exceeding the user's comfort levels. Because hearing loss can assume a wide range of audiometric configurations, the degree to which audibility is improved with amplification varies across individuals. Several subjective measurements are available to assess the benefit that a hearing aid user receives from amplification. However, for populations that cannot participate in subjective measures (e.g. infants & young children), objective methods must be used to fit and verify the audibility that has been provided. The basis for many of these objective fitting methods is the speech intelligibility index (SII). This index is used to quantify the audibility of speech relative to hearing thresholds and to estimate the speech intelligibility that the listener will experience with amplification. The SII has been standardized and incorporated into clinical hearing aid fitting algorithms as well as real-ear verification instruments. Clinicians who have a working knowledge of the SII and an awareness of its limitations are in a better position to optimize amplification for their clients.

The SII is a standardized procedure (ANSI,1997) defined as the sum of the suprathreshold levels in equivalent frequency bands multiplied by the degree to which each frequency band contributes to speech intelligibility. Using the following formula:

$$SII = \frac{1}{30}\sum_{i=1}^{18}[SNR_i + 15]W_i \qquad (1)$$

i is the center frequency of each third-octave band (TOB), SNR_i is the speech-to-noise ratio within the ith third-octave band plus

Correspondense: Arizona State University, Speech and Hearing Science, P.O. Box 870102, Tempe, AZ 85287, USA. E-mail: samantha.gustafson@asu.edu

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Abbreviations

ANSI	American National Standards Institute
FIF	Frequency importance function
SD	Standard deviation
SII	Speech intelligibility index
SNR	Signal-to-noise ratio
TOB	Third-octave band

15 dB which represents the peak level of speech across frequency. Speech-to-noise ratio is calculated as the rms level of the speech (+15 dB) relative to the rms level of the noise within each band. These values are multiplied by the importance of each band (W) and summed. Finally, the speech-to-noise ratio is restricted to a range of 0 to 30 dB by the 1/30 multiplier. The resulting value is a number between 0 and 1. An SII of 0 would be inaudible to the listener, whereas an SII of 1 is considered to be completely audible and should result in maximum intelligibility.

The weight, or importance, assigned to a frequency band indicates the degree to which that frequency contributes to intelligibility. The relative contribution of each frequency band can differ for speech materials that vary in context, resulting in unique frequency importance functions (FIF). The current standard of the American National Standards Institute (1997) recognizes six different FIFs for stimuli, ranging from nonsense syllables to continuous discourse. These importance functions are made available in the standard because the development of these functions for specific stimuli is not a trivial process. For example, Sherbecoe and Studebaker (2002) recently provided an additional FIF for the connected speech test by examining performance under conditions that simultaneously varied in bandwidth and signal-to-noise ratio (SNR). The process required measures of speech perception at six SNRs for each of 16 bandwidth conditions (a total of 96 test conditions).

The derivation of FIFs using this sort of procedure shows a direct relation between bandwidth and SNR for various speech materials (Sherbecoe & Studebaker, 2002; Duggirala et al, 1988; French & Steinberg, 1947; Studebaker & Sherbecoe, 1991; Studebaker et al, 1987, 1993). The resulting transfer function relating performance to SII is generally sigmoidal with maximum performance occurring at mid-range SII values depending on the difficulty of the stimuli (e.g. nonsense syllables vs. continuous discourse). This function is used to estimate performance based on the SII and is especially useful when speech perception cannot be measured directly (e.g. infants and young children).

However, a disparity between predicted and observed performance occurs when the SII is applied to listeners with hearing impairment (Dubno et al, 1989; Humes, 2002; Pavlovic & Studebaker, 1984). To improve the agreement between predicted and observed performance, several correction factors were added to the SII calculation (Ching et al, 1998; Magnusson, 1996; Pavlovic et al, 1986; Sherbecoe & Studebaker, 2003; Studebaker et al, 1997). For example, a level distortion factor was included in the most recent revision of the ANSI standard to accommodate signal distortion that can occur at high presentation levels (ANSI, 1997). Studebaker et al (1997) introduced the hearing loss desensitization factor to accommodate distortion arising from hearing loss, particularly for thresholds in the severe to profound range. Earlier, a proficiency factor was suggested to accommodate differences in clarity across talkers as well as the experience of the listener with regard to both the speech material and the talker (Pavlovic & Studebaker, 1984). Although the gap between predicted and observed performance improved substantially, variations in performance persist for a narrow range of SII values representing the changing portion of the performance-intensity function (Dubno et al, 1989; Stelmachowicz et al, 2000a, 2000b; Ching et al, 1998). In normally-hearing individuals, this range of SII values represents low-level speech that can be avoided or accommodated easily. But for listeners with moderate to severe hearing loss, these levels may represent their usable dynamic range for speech.

Recently, several additional limitations associated with FIFs were identified that may contribute to the variability in performance observed in hearing-impaired listeners. Specifically, assigning importance to individual frequency bands implies that the information in those bands is mutually exclusive. Such an approach does not take into account the potential redundancy of information across contiguous bands (Steeneken & Houtgast, 1999) or the synergistic manner in which information may combine across distant frequency bands (Musch & Buus, 2001a, 2001b). This limitation was noted in the ANSI (1997) standard stating that the SII should not be used in cases of sharply filtered bands of speech or noise.

The extent of this limitation may be greater than anticipated and may directly impact the application of the SII to objective hearing aid fitting procedures. For some individuals, the severity of the hearing loss or bandwidth limitations of the hearing aid can make amplification in the region of hearing loss difficult or impossible to achieve. In those cases, some researchers have suggested that these individuals will benefit more from an amplified signal that is limited to lower frequencies as long as the overall SII is sufficient to maintain intelligibility (Byrne et al, 2001; Ching et al, 2001). For example, amplification in a region of severe hearing loss is reduced or abandoned altogether and amplification in regions with less hearing loss is increased to achieve the desired SII. This sort of redistribution of sensation level occurs often during the hearing aid fitting process (Rankovic, 1991; Humes & Riker, 1992; Seewald et al, 2005) and assumes that intelligibility can be maintained by redistributing the sensation level within one frequency band to another frequency band. Although this has been shown to be acceptable for neighboring frequency bands (Steeneken et al, 1999), the extent to which information from a broad range of frequencies can be conveyed within a narrower frequency region is unknown.

The purpose of the present study was to examine the relation between bandwidth and speech perception at similar values of SII. Specifically, sentence perception for conditions having equivalent SII but varying bandwidths (and therefore varying sensation levels) were obtained. The sentences were low-pass filtered at four cut-off frequencies between 0.25 and 8 kHz and adjusted in sensation level to achieve similar SII values in each bandwidth condition. It was hypothesized that performance would be equivalent as a function of bandwidth. Also, performance was examined in children compared to adults, and for sentences varying in contextual difficulty (meaningful and nonsense sentences). Because children have been shown to require higher sensation levels and wider bandwidths to perform as well as adults (Kortekaas & Stelmachowicz, 2000; Stelmachowicz et al, 2001; Pittman, 2008b; Mlot et al, III, 2010), it was expected that the performance of the adults would be better overall and that the children's performance would reflect their developing speech perception skills. Also, differences in performance have been observed for both adults and children for materials that vary in contextual difficulty (Nittrouer & Boothroyd, 1990; Stelmachowicz et al, 2000). Therefore, the performance of both groups was expected to be poorer for the nonsense sentences than for the meaningful sentences. The results of this study were expected to reveal the degree to which performance is affected as a function of bandwidth when similar SII values are provided in each condition.

Method

Participants

Twenty adults (19 to 47 years of age, mean: 30.8 years) and twenty children (8.0 to 8.92 years, mean: 8.38 years) participated in this experiment. The distribution of males to females was 3:17 for the adults and 11:9 for the children. Criterion for normal hearing was thresholds ≤20 dB HL at octave frequencies from 0.25 to 8 kHz. The right ear was chosen if the hearing thresholds in both ears were normal. If the right ear thresholds exceeded 20 dB HL and the left ear thresholds were normal, the left ear was tested. Eight-year-old children were recruited because this age group is mature enough to participate reliably in lengthy test sessions and yet young enough to demonstrate developing speech perception skills.

All participants spoke English as their native language and none reported having a history of speech or language impairments. Participants volunteered their time and were paid ten dollars per hour. Testing required no more than a single, two-hour session. Informed consent/assent was obtained for all participants according to the procedures required by the Institutional Review Board at Arizona State University.

Stimuli

The sentences from Stelmachowicz et al (2000) were used as stimuli. Each sentence contained four words. Half of the sentences were both grammatically and semantically correct whereas the other half were grammatically correct, but semantically meaningless. The same words were used in the construction of both types of sentences. Although the sentences have been referred to as high- and low-predictability in previous studies (Nittrouer et al, 1990; Stelmachowicz et al, 2000), they will be referred to as meaningful and nonsense sentences hereafter. These sentences were chosen to represent utterances that children may encounter on a regular basis. Meaningful sentences represent more familiar communication (e.g. 'Warm sun feels good') whereas nonsense sentences represent information that is less familiar or new to a child (e.g. 'Jokes sleep on fields').

The sentences were produced by a female talker with a standard American dialect and recorded digitally at a sampling rate of 22.5 kHz using a microphone with a flat frequency response to 10 kHz (AKG, C535 EB). The sentences were recorded into Adobe Audition v1.5, edited, and saved to separate files after being adjusted to the same rms level. Of the 120 sentences provided in Stelmachowicz et al (2000), 112 were divided equally among eight subsets of 14 sentences each (seven meaningful and seven nonsense). Two subsets were assigned to each of four bandwidth conditions (described below). One subset (14 sentences) was presented for recognition in each bandwidth condition and then the process was repeated with the other subset. In addition, the order of the bandwidth conditions was counterbalanced across participants. The sentences within each subset and condition remained the same throughout testing.

Bandwidth conditions

The sentences were frequency shaped to produce four bandwidth conditions having low-pass cut-off frequencies of 0.8, 1.25, 2.5, and 8 kHz. Using customized laboratory software, each stimulus file was digitally processed upon presentation according to the selected bandwidth condition. To facilitate equivalent SII across bandwidths and subjects, the stimuli were presented in broadband noise. Figure 1 shows the level of the speech stimuli developed in a 6-cm^3 coupler as a function of frequency. The 1% peaks of speech in each one-third octave band are shown for each bandwidth condition (dashed lines). Also, the 1/3-octave band levels (solid line) and spectrum level (dotted line) of the noise are shown as a function of frequency. Due to a procedural error, the sensation level of the 8 kHz condition was lower than intended and resulted in an SII of only 0.32. This condition was removed from the analyses; however, the results are mentioned in the next section.

The amplitude of each 1/3-octave band was held constant from 0.2 kHz through the cut-off frequency where the signal was low-pass filtered at a rejection rate of 80 dB/octave. The sensation level of the frequency bands below the cut-off frequency were adjusted together to provide a target SII of 0.50. The experimental SII values were chosen based on the performance-SII functions provided in Stelmachowicz et al (2000) and were expected to result in high but not maximum performance for both groups (~70–80%).

The speech intelligibility index for each subject was calculated using Equation 1 and the FIF for short passages (ANSI, 1997). Stimuli were analysed in 18 TOBs with a 40-ms Hanning window (50% overlap) after being transduced by the earphone (Sennheiser 25-1) and recorded in a 6-cm^3 coupler. SII values for each bandwidth condition were calculated relative to each participant's unmasked hearing thresholds at octave frequencies and average adult real-ear-to-coupler- difference values. Average SII values are given in Figure 1 for each bandwidth condition. Recall that the target SII value was 0.50 for each bandwidth condition. This analysis showed that the measured SII was 0.43–0.48 across bandwidths with a maximum difference of 0.05 SII. Based on a similar study with the same stimuli and population (Stelmachowicz et al, 2000), performance at this SII should be just below maximum (~80%) and the range of SII values (0.05) was expected to yield differences in performance of less than

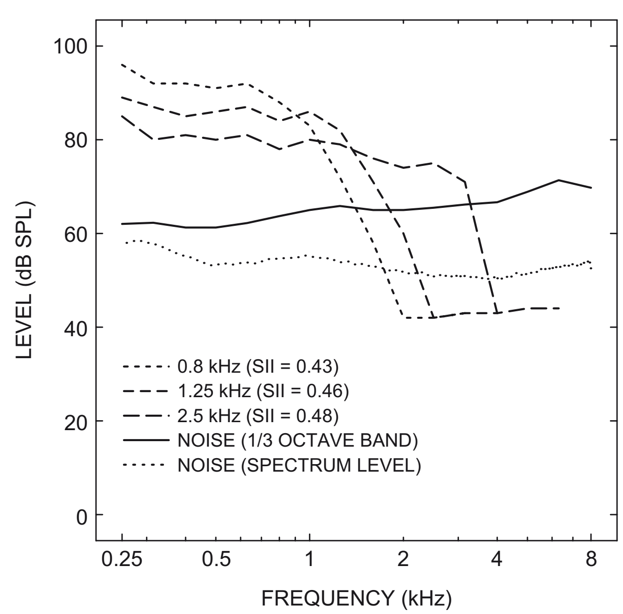

Figure 1. One-third octave band (solid line) and spectrum levels (dotted line) of the broadband noise plotted as a function of frequency. Also plotted are the 1% peaks of the long-term average spectra of the speech stimuli and the corresponding SII values for each.

20% across bandwidth conditions. Differences >20% would suggest a significant effect of bandwidth.

Procedures

Prior to testing, normal hearing was confirmed through a series of clinical procedures. The ear canal was inspected visually to rule out any ear-canal anomalies that may preclude participation. A screening tympanometer (GSI 37 Auto Tymp) was used to confirm normal middle-ear function (ASHA, 1997). Pure-tone thresholds were obtained using insert earphones (Etymotic ER 3A) and a clinical audiometer (GSI 61). All tests were conducted in a sound-treated booth that met ANSI standards for ambient noise (ANSI, 1999). Masked hearing thresholds were then obtained monaurally using supra-aural earphones (Sennheiser 25-1). An earphone was placed on the non-test ear; however, no masking or stimuli were presented.

During testing, listeners were informed that they would hear a series of four-word sentences as well as the same noise used to obtain the masked thresholds. They were instructed to ignore the noise, repeat the sentences aloud, and to guess if necessary. For each trial, the number of words repeated correctly in each sentence was recorded by an examiner seated inside the sound-treated room with the participant. The examiner selected a number between 0 and 4 displayed on a touch-screen computer monitor. A second examiner was seated outside the room and recorded the responses manually. A response was considered incorrect if the word was omitted or repeated with any modifications (e.g. 'cat' instead of 'cats'). The scores from each examiner were later compared and averaged. For both groups, the correlation coefficients between the two examiners were ≥0.98, so the average of the two scores was used. This level of correlation between examiners was the same as that reported in Stelmachowicz et al (2000) (≥0.98) for normal-hearing children and adults using the same stimuli and scoring procedure.

Results

Performance was calculated as the proportion of words repeated correctly. Table 1 shows the average performance of the children and adults for each sentence type and bandwidth condition. The numbers in parentheses are standard deviations. The italicized values are averages collapsed across sentence type and bandwidth. Differences between groups (about 20%) were consistent with previous research comparing the speech perception of adults and children (Neuman & Hochberg, 1983; Pittman & Stelmachowicz, 2000; Elliott et al, 1986; Fallon et al, 2002). Likewise, differences between the meaningful and nonsense sentences (<10%) were consistent with previous research (Stelmachowicz et al, 2000; Boothroyd & Nittrouer, 1988). Both groups performed more poorly on the nonsense sentences however, the difference was quite small (7% for the adults and 9% for the children). With respect to the hypothesis of equivalent performance across bandwidth conditions, the results showed that the performance of both groups increased as a function of bandwidth (≥39%) rather than the expected variation of ≤20%.

Figure 2 shows average performance (+1 SD) as a function of bandwidth for the adults (upper panel) and the children (lower panel). The parameter in each panel is sentence type. Performance improved with bandwidth for both groups and for both sentence types. The adult's performance increased 40% from the narrowest to the widest bandwidth condition. The children's performance increased 39–46% for the same conditions and materials, suggesting that they received slightly more benefit from increasing bandwidth with familiar speech material. The data were subjected to a repeated measures analysis of variance with group (adults, children) and sentence type (meaningful, nonsense) as the between-subjects factors and bandwidth (0.8, 1.25, 2.5 kHz) as the within-subjects factor. The data were arcsine transformed prior to statistical analysis (Studebaker, 1985). Significant main effects for group ($F_{(1,38)}$ = 70.19; $p \leq 0.001$), sentence type ($F_{(1,38)}$ = 104.69; $p \leq 0.001$), and bandwidth ($F_{(2,76)}$ = 479.89; $p \leq 0.001$) were revealed. Post-hoc analyses (pairwise comparisons with a Bonferroni adjustment for multiple comparisons) were conducted to identify differences across bandwidth conditions for each sentence type and group. The analyses revealed that performance improved significantly in each bandwidth condition for both sentence types and for both groups. No group × sentence type interaction ($F_{(1,38)}$ = 0.20; $p = 0.657$), or group × bandwidth interaction ($F_{(2,76)}$ = 3.69; $p = 0.029$) were revealed. These results indicate that both groups received the same benefit from increasing bandwidth. Finally, a significant interaction between bandwidth × sentence type was revealed ($F_{(2,76)}$ = 8.39; $p = 0.001$). Post hoc analyses revealed a slightly greater increase in performance with increasing bandwidth for the meaningful sentences than for the nonsense sentences (on the order of 4.5%).

Because an importance function has not been developed for these materials, it is possible that the FIF for short passages was not the optimal choice from those provided in the ANSI standard. That is, another FIF may better predict the relation between performance and bandwidth. Further analyses were conducted using the five remaining FIFs provided in the ANSI (1997) standard. Table 2 shows the SII values calculated for each FIF as well as the range in values across bandwidth conditions. The SII values were found to increase by ≤0.11 across bandwidth conditions with the FIF for short passages yielding the smallest increase. Although the other FIFs resulted in a greater increase in SII across bandwidth conditions, it is not sufficient to explain the results of the present study. An increase in

Table 1. Performance in percent correct (1 SD) for the meaningful and nonsense sentences for each group and bandwidth condition. Numbers in italics are averages. Due to a procedural error during testing, the SII for the 8 kHz was lower than that of the other bandwidth conditions. Therefore, the values for the 8 kHz condition are listed below but were not included in the averages.

	Adults			*Children*		
BW (kHz)	*Nonsense*	*Meaningful*	*Average*	*Nonsense*	*Meaningful*	*Average*
0.8	42 (10)	50 (12)	*46 (11)*	23 (9)	29 (11)	*26 (10)*
1.25	68 (9)	74 (8)	*71 (8)*	43 (14)	52 (12)	*48 (13)*
2.5	82 (6)	90 (6)	*86 (6)*	62 (15)	75 (9)	*69 (12)*
Average	*64 (8)*	*71 (9)*	*68 (9)*	*43 (13)*	*52 (11)*	*47 (12)*
8.0	68 (9)	86 (10)		45 (15)	65 (18)	

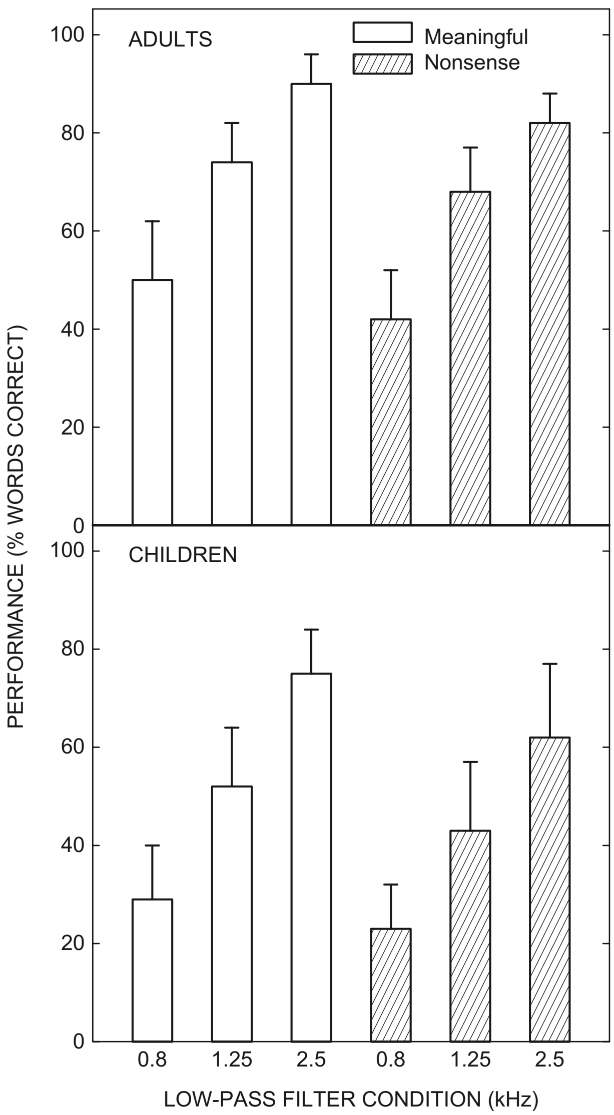

Figure 2. Average (+1 SD) performance for adults (upper panel) and children (lower panel) in each bandwidth condition for the meaningful (open bars) and nonsense (hatched bars) sentences.

SII of at least 0.20 would be necessary to produce similar results (Stelmachowicz et al, 2000).

However, the SII values generated with these FIFs may provide some insight regarding the characteristics of FIFs that better capture the effects of bandwidth on speech perception. Figure 3 shows the FIFs grouped according to their range of values across bandwidths conditions. The functions resulting in the greatest range, and therefore the closest relationship to performance, are shown in the upper panel (0.10–0.11) and the functions resulting in the smallest range are shown in the lower panel (0.05–0.09). The most apparent difference in the distributions of importance across frequency can be seen in the low frequencies. The FIFs that resulted in the largest range of values across bandwidth (upper panel) showed a systematic increase in importance between 0.8 and 2.5 kHz whereas the other FIFs did not. This suggests that FIFs for which importance increases with frequency may better capture the effect of bandwidth on speech perception, at least for bandwidths extending to 2.5 kHz.

Table 2. SII values as a function of bandwidth for the six frequency-importance functions provided in the ANSI (1997) standard.

Frequency importance function (FIF)	*Bandwidth (kHz)* 0.8	1.25	2.5	*Range*
Nonsense syllables	0.27	0.30	0.38	0.11
CID W-22 words	0.39	0.44	0.49	0.1
NU-6 words	0.37	0.40	0.46	0.09
Short passages	0.43	0.46	0.48	0.05
Speech in noise (SPIN)	0.34	0.38	0.44	0.1
Diagnostic rhyme test (DRT)	0.40	0.44	0.47	0.07

8-kHz bandwidth condition

Additional evidence demonstrating this limitation of the SII can be found in the results for the 8-kHz bandwidth condition. Recall that these data were removed from the analyses when the SII for that condition was found to be lower than intended (0.32 rather than 0.50). However, the results are worth mentioning. Figure 4 shows the long-term average speech spectra for the 1.25 and 8 kHz bandwidth conditions relative to the broadband noise. Although the SII was substantially lower in the broadest bandwidth condition, performance within each group was equivalent in both conditions (68% for the adults, 43–45% for the children). This performance-bandwidth relationship indicates that the SII within a narrow bandwidth must be increased substantially above that of a broad frequency range to achieve equivalent performance.

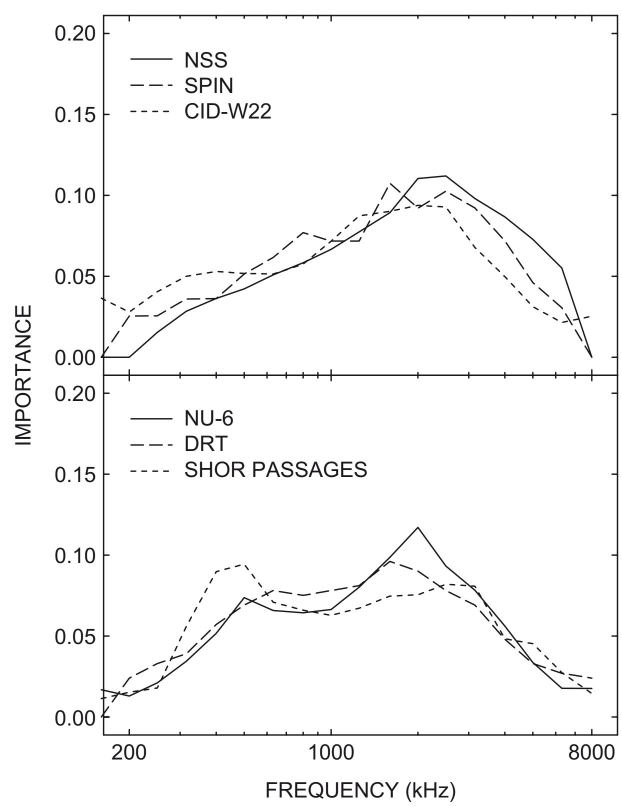

Figure 3. Importance as a function of frequency for the six FIFs provided in the ANSI (1997) standard. The three functions in the upper panel resulted in a wider range of SII values across bandwidth compared to the three functions in the lower panel.

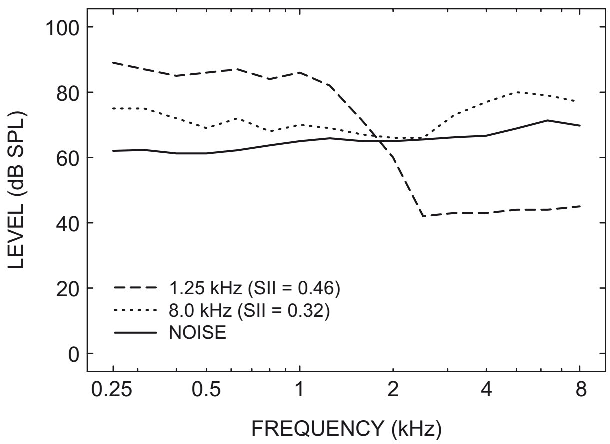

Figure 4. One-third octave band levels (solid line) of the broadband noise plotted as a function of frequency. Also plotted are the 1% peaks of the long-term average spectra of the speech stimuli for the 1.25 and 8 kHz bandwidth conditions (dashed lines).

These results suggest that hearing loss cannot be accommodated easily by redistributing sensation level (and therefore SII) to lower frequencies.

Discussion

In this study, speech intelligibility indices were held constant across three bandwidth conditions to test the hypothesis that similar speech perception would be observed in each condition. An SII value was chosen to produce high but not maximum performance (0.50). The hypothesis was tested for speech materials that varied in contextual difficulty (meaningful and nonsense sentences) and in terms of the listeners' experience with speech perception (children and adults). As expected, the results showed poorer overall performance for the children compared to the adults and for the nonsense sentences compared to the meaningful sentences. Contrary to the hypothesis of equivalent performance for equivalent SII, both groups demonstrated significant increases in performance with increasing bandwidth for both types of sentences. Optimal performance of 80 to 90% was achieved by the adults in the widest bandwidth condition (2.5 kHz) and decreased 40% in the narrower bandwidth conditions even though sensation level for those narrower bandwidths increased. These results indicate that speech perception improved with the addition of high-frequency information and that equivalent SII in limited bandwidths is not sufficient to maintain perception. Finally, both the children and adults experienced similar benefits of increasing bandwidth.

These results are consistent with studies showing that increasing the bandwidth of a signal increases a listener's ability to perceive and learn speech. Increased audibility of high-frequency information has been shown to increase speech perception and learning in children (Hornsby & Ricketts, 2003; Kortekaas et al, 2000; Stelmachowicz et al, 2001, 2002, 2004; Pittman, 2008a; Seewald et al, 2005; Kamm et al, 1985) as well as listening comfort and speech perception in adults (Hornsby & Ricketts, 2006; Pascoe, 1975; Skinner et al, 1982; Skinner & Miller, 1983; Simpson et al, 2005). However, performance has also been shown to deteriorate for some listeners with severe-to-profound high-frequency hearing loss (Hogan & Turner, 1998; Ching et al, 1998). For these individuals, some investigators suggest that they will benefit more from a signal that is limited to lower frequencies if SII can be maintained (Byrne et al, 2001; Ching et al, 2001). The results of the present study suggest that although equivalent audibility may be achieved within a narrower bandwidth, it may not be sufficient to maintain speech perception. It should be noted however, that performance for listeners with hearing impairment was not examined in this study. The results for the children and adults with normal hearing must therefore be carefully and conservatively extended to this population.

Of greater concern is that these data contradict nearly 100 years of research contributing to the development of FIFs and the SII. One possible explanation is that the SII model has not been tested directly by holding SII constant and varying sensation level and bandwidth. Whereas FIFs are derived by manipulating bandwidth and sensation level, those data cannot be used to prove the assumptions of the SII model. Another possibility is that the FIFs provided in the standard are not appropriate for these materials. Perhaps an importance function specific to these stimuli would better predict performance over a narrow range of SII values. Although possible, it is unlikely since the transfer function would have to be exceedingly steep to accommodate the 40% increase in performance over the narrow range of SII values observed in this study (0.05 to 0.10). It would also mean that the FIFs provided in the ANSI standard may be inappropriate for materials other than those for which they were generated. This creates a problem when the SII is used in clinical applications (Kamm et al, 1985). Verification that the amplified speech signal is sufficient for a given hearing loss would only be valid if the speech material (the actual recorded stimuli used to create the FIF) were used. Not only is this unlikely to happen, it defeats the purpose of providing generalizable FIFs in the ANSI standard. The most likely explanation for these results is that the effect of bandwidth on speech perception is not fully captured in the frequency importance functions of the speech intelligibility index. Further development and implementation of the speech recognition sensitivity model (Musch et al, 2001a, 2001b), or the speech transmission index (Steeneken et al, 1999) may provide more sensitive estimates of speech intelligibility for use with hearing-impaired listeners by accounting for the synergistic and redundant information across frequency bands.

Conclusions

In the present study the SII for nonsense and meaningful sentences was held constant across three bandwidth conditions to test the hypothesis that equivalent performance would be achieved in each condition. Contrary to predictions, the performance of both adults and children improved significantly with bandwidth for both types of sentences. It was concluded that the effect of bandwidth on speech perception is not fully captured in the calculation of the speech intelligibility index.

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