Associations and Dissociations Between Psychoacoustic Abilities and Speech Perception in Adolescents With Severe-to-Profound Hearing Loss

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Purpose: To clarify the relationship between psychoacoustic capabilities and speech perception in adolescents with severe-to-profound hearing loss (SPHL).
Method: Twenty-four adolescents with SPHL and young adults with normal hearing were assessed with psychoacoustic and speech perception tests. The psychoacoustic tests included gap detection (GD), difference limen for frequency, and psychoacoustic-tuning curves. To assess the perception of words that differ in spectral and temporal cues, the speech tests included the Hebrew Early Speech Perception test and the Hebrew Speech Pattern Contrast test (L. Kishon-Rabin et al., 2002). All tests were conducted for the listeners with normal hearing at low and high presentation levels and for the participants with SPHL at 20 dB SL.
Results: Only GD thresholds were comparable across the 2 groups at similar presentation levels. Psychoacoustic performance was poorer in the group with SPHL, but only selected tests were correlated with speech perception. Poor GD was associated with pattern perception, 1-syllable word identification, and final voicing subtests.
Conclusions: Speech perception performance in adolescents with SPHL could not be predicted solely on the basis of spectral and temporal capabilities of the auditory system. However, when the GD threshold was greater than 40 ms, speech perception skills were predictable by psychoacoustic abilities.

KEY WORDS: speech perception, psychoacoustics, frequency selectivity, temporal resolution, hearing impaired

The purpose of this study was to elucidate the meaning of and constraints on the relationship between psychoacoustic abilities and speech perception in adolescents with severe-to-profound hearing loss (SPHL). Although the general contribution of psychoacoustic abilities to speech perception is widely acknowledged (e.g., Boothroyd, 1991, 1993, 1997; Dreschler & Plomp, 1985; Gordon-Salant & Fitzgibbons, 1993; Lamore, Verweij, & Brocaar, 1990; Moore, 1991; Vestergaard, 2003), the correlations between these abilities and the quality of speech perception in individuals with hearing loss have yet to be specified.

Studies of adults who have hearing impairment have established a general but complex association between psychoacoustic abilities and speech perception performance (e.g., Dreschler & Plomp, 1985; Festen & Plomp, 1983; Lamore et al., 1990). Psychoacoustic capabilities permit the auditory system to resolve fine details in the spectrum as well as in

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the temporal waveform of the speech signal (Humes, 1982; Moore, 1989; Summerfield, 1987). Loss of this resolution results in poor sensory evidence available to the listener and consequently in reduced phoneme and word identification (Boothroyd, 1993; Boothroyd, Mulhearn, Gong, & Ostroff, 1996). However, the individual correlations between psychoacoustic capabilities and speech perception have not been specified sufficiently. Some research suggests that perception of words in isolation or within sentences is correlated with frequency resolution when the words are presented in quiet (Faulkner, Rosen, & Moore, 1990; Lamore et al., 1990) and especially in noise (Bonding, 1979; Dreschler & Plomp, 1985; Festen & Plomp, 1983; Irwin & McAuley, 1987; Tyler, Wood, & Fernandes, 1982). Additional studies indicate that speech perception in quiet was correlated with temporal resolution (Dreschler & Plomp, 1985; Festen & Plomp, 1983; Gordon-Salant & Fitzgibbons, 1993, 1999; Irwin & McAuley, 1987); however, other studies have reported only weak correlations between these two classes of phenomena (Lutman & Clark, 1986; Nelson, Nittrouer, & Norton, 1995; Strouse, Ashmead, Ohde, & Grantham, 1998).

A possible explanation for the equivocal results may be related to the fact that speech perception of words and sentences is highly influenced by the listener's linguistic knowledge (Boothroyd, 1997; Cole & Jakimik, 1980). Most studies that have investigated the relationship between psychoacoustic abilities and speech perception performance have used open-set speech tests (e.g., Arlinger & Dryselius, 1990; Festen & Plomp, 1983; Gordon-Salant & Fitzgibbons, 1993; Lamore, Verweij, & Brocaar, 1985). The results of such tests are assumed to be influenced by both sensory evidence provided by the auditory system and linguistic knowledge. It is possible that a listener with profound hearing loss may be able to supplement poor sensory evidence with linguistic information. In this case, speech perception scores may be high despite poor psychoacoustic abilities. In younger listeners with hearing impairment and with limited linguistic experience, one may observe poor perception of speech that is inconsistent with good psychoacoustic abilities. Thus, one should be cautious when inferring psychoacoustic capabilities on the basis of performance on speech perception tests (Cramer & Erber, 1974; Erber, 1979; Erber & Alencewicz, 1976; Geers, 1994; Kirk, Diefendorf, Pisoni, & Robbins, 1997; Moog & Geers, 1990).

Of the various psychoacoustic abilities, frequency and temporal resolution are likely the most fundamental for speech perception (Glasberg & Moore, 1989; Moore, 1989). However, the specific contribution of each of these measures to speech perception in the presence of profound hearing loss is not obvious. Previous studies have reported that poor frequency-resolving capabilities result in a reduction of the ability for fine analyses of the spectral components of speech and, consequently, in poor speech intelligibility (e.g., Faulkner et al., 1990; Tyler et al., 1982). This is in keeping with evidence suggesting that, for the perception of speech, individuals with SPHL rely on temporal information as well as on duration and amplitude changes carried by the speech waveform (e.g., Rosen, 1992; Rosen, Faulkner, & Smith, 1990). Assessing psychoacoustic measures such as frequency and temporal resolution is important in order to understand their unique contribution to the perception of speech. In many studies, however, this contribution may be confounded by linguistic knowledge because of the nature of the speech stimuli (Boothroyd, 1997; Cole & Jakimik, 1980; Paatsch, Blamey, Sarant, Martin, & Bow, 2004) and by cognitive processes related to age (Glasberg & Moore, 1989). Furthermore, only scarce data exist on the relationship between psychoacoustic abilities and performance on tests of speech perception in young individuals with SPHL (Lamore et al., 1985).

In this study, we investigated the relationship between frequency and temporal resolution and performance on clinically used tests of speech perception. Speech perception and psychoacoustic abilities were examined for adolescents with SPHL and for young adults with normal hearing. Considering the possibility that poor auditory performance by profoundly hearing-impaired listeners results from low sensation levels (Boothroyd, 1996; Buus & Florentine, 1985; Glasberg & Moore, 1989), auditory performance was obtained from normal-hearing cohorts at both low and high levels of presentation. Frequency and temporal resolution were assessed using psychoacoustic-tuning curves (PTCs), frequency discrimination, and gap detection (GD) tasks. Speech perception was assessed by presenting words in closed-set format differing in spectral cues and by either gross or fine temporal cues. It has been suggested that closed-set tasks that include items familiar to the participant and that are acoustically/phonetically similar promote sensory or bottom-up processing (Kirk et al., 1997, p. 104). Because such closed-set tests (in comparison to open-set tasks) reduce the a priori bias to more familiar items and increase the difficulty of identifying the target on the basis of a conceptually generated gestalt, participants need to base their decision making on sensory, analytical information (Kirk et al., 1997, p. 104). Thus, using such tests helps in reducing factors associated with different levels of linguistic knowledge that influence the responses of the participants. We chose clinically used tests to obtain information regarding the contribution of basic psychoacoustic abilities to the perception of speech, information that may be applicable and of interest to professional personnel involved in the habilitation process of young individuals with SPHL.

Method

Participants

Two groups of listeners participated in this study. The first group included 12 adolescents (5 males and 7 females) with severe-to-profound congenital or prelingual hearing loss with a mean age of 17.5 years (range: 16;1 [years;months]–18;4, *SD* = 0.57). The mean unaided pure-tone average (PTA) at 0.5, 1.0, and 2.0 KHz was 91.4 dB HL (range: 85–101 dB HL, *SD* = 5.11). Individual audiometric characteristics are summarized in Table 1. Note that all participants, with the exception of Participants 2 and 5, had residual hearing through 6.0 KHz. It was important to select participants with residual hearing in the mid- to upper frequencies to reduce the possibility that lack of audibility will influence performance on the speech perception tests instead of spectral and temporal resolution abilities. All participants were born to parents with normal hearing and were native speakers of the Hebrew language. The participants with hearing loss were binaural hearing aid users but were tested unaided in order to estimate their speech perception and psychoacoustic capabilities without the confounding influence of different hearing aids. All were educated in a program for the hearing impaired in a regular high school and received auditory training once a week by an audiologist. A speech-language pathologist performed a linguistic analysis of oral and written language for all the participants with hearing loss and found them to have age-appropriate language performance. Their teachers reported them as having good scholastic achievements. Thus, the high-level functioning of these adolescents with hearing loss allowed them to attend a regular high school and to study with normal-hearing peers.

The second group included 12 young adults (5 males and 7 females) with normal hearing with a mean age of 23;7 (range: 15;0–30;0, *SD* = 4.3). The mean PTA at 0.5, 1.0, and 2.0 KHz was 7.5 dB HL (range: 5–10 dB HL, *SD* = 1.4). All were native speakers of the Hebrew language and had no known speech and language problems. It should be noted that the inclusion of participants with normal hearing who were not matched by age to those with hearing loss was based on evidence showing that children 12 to 13 years of age (and older) exhibit adult-like performance on spectral and temporal resolution tasks that reflect peripheral processing, as well as on tasks that reflect processing efficiency that are attributed to the central auditory system (Hall & Grose, 1991; Hill, Hartley, Glasberg, Moore, & Moore, 2004; Quaranta, Salonna, & Bellomo, 1992; Soderquist, 1993; Stuart, 2005; Veloso, Hall, & Grose, 1990). Similarly, children 12 to 13 years of age (and older) performed as well as adults on open-set speech perception tests of monosyllabic words (Stuart, 2005), and 6-year-olds performed as well as adults on the perception of significant phonological contrasts in a closed-set paradigm (Kishon-Rabin et al., 2002). Thus, we believe that the differences that emerged between the two groups in this study reflect the effect of the hearing loss and were not due to developmental differences.

Speech Perception Tests

Hebrew Early Speech Perception test. The Hebrew Early Speech Perception (HESP) test (Kishon-Rabin et al., 2000) was adapted into Hebrew from the Early

Table 1. Audiometric characteristics of participants with hearing loss.

Participant	Age (yr;mo)	Tested ear	Hearing thresholds at better ear (dB HL)			Unaided PTA (dB HL)	Highest frequency with residual hearing	
			0.5kHz	1kHz	2KHz		kHz	Threshold
1	16;10	R	95	105	105	101.7	6	100
2	18;3	R	85	95	110	96.7	3	110
3	17;10	L	95	90	90	91.7	8	80
4	17;3	L	75	85	95	85.0	8	85
5	18;4	R	75	85	95	85.0	4	105
6	17;2	R	85	95	95	91.7	6	110
7	17;3	R	85	95	95	91.7	8	80
8	17;5	L	70	105	105	93.3	6	110
9	16;10	R	70	85	95	83.3	6	110
10	16;10	R	85	95	100	93.3	6	110
11	18;3	R	85	90	95	90.0	8	90
12	17;2	L	90	100	100	96.7	6	110

Note. See ANSI, 1996. yr = years; mo = months; PTA = pure-tone average; R = right; L = left.

Speech Perception test (Moog & Geers, 1990). The test requires identification of words and includes three subtests: (a) Pattern Perception, (b) 2-Syllable Word Identification, and (c) 1-Syllable Word Identification. The Pattern Perception subtest includes 12 words of three different durational stress patterns: (a) four 1-syllable (e.g., /kof/ [*monkey*]), (b) four 2-syllable (e.g., /kaftor/ [*button*]), and (c) four 3-syllable (/aviron/ [*airplane*]). A word was counted correct if it matched the number of syllables of the target word (even if it did not match the target word, per se). It is assumed that if the participants perform well on this subtest but not on the 1- and 2-Syllable Word Identification subtests of the Early Speech Perception test, they base their performance on durational cues or number of syllables alone (Moog & Geers, 1990). Because each target has four possible correct answers, chance performance for the pattern perception subtest is 33% (4/12).

The second subtest of the HESP, the 2-Syllable Word Identification subtest, includes twelve 2-syllable spondee words with equal stress on both syllables. This ensures that participants are identifying words on the basis of spectral cues of vowels and not durational or amplitude stress differences. All of the Hebrew words chosen for this subtest differ in their vowel combination (e.g., /kaftor/ [*button*], /axbar/ [*mouse*], /shulxan/ [*table*], /karit/ [*pillow*], etc.). Only correct identification of the segmental information results in correct identification of the target word. It is assumed that identification of words in this subtest highly depends on relatively gross spectral cues (of the vowels) and fine spectral cues (of the consonants), as well as linguistic knowledge (phonologic and lexical). In this subtest, the word needs to be correctly identified to be scored as correct. Therefore, chance performance is 8.3% (1/12).

The third subtest of the HESP, the 1-Syllable Word Identification subtest, includes twelve 1-syllable words all beginning with the voiced plosive /b/ (e.g., /ben/ [*boy*], /but/ [*girl*], /bor/ [*hole in the ground*], etc.). In this subtest, the correct identification of the target word depends primarily on the participant's ability to perceive the final consonant and the vowel. This identification is based on the individual's hearing capabilities for detecting fine and gross spectral and temporal cues, as well as on phonetic and phonological knowledge. Only correct identification is scored. Therefore, chance performance is 8.3% (1/12).

In this study, for each of the subtests, words were presented on 33-cm × 44-cm grid picture cards in both written and illustrative forms. All words were familiar to children with and without hearing loss and have been presented routinely in hearing evaluation protocols in children as young as 3 years (Taitelbaum-Swead et al., 2005). Prior to testing, the tester confirmed that all words were known and familiar to the participants. At testing, participants were required to point at the picture/card that corresponded to the word they heard. Performance was based on two repetitions of each recorded subtest, for a total of 24 items per subtest.

Hebrew Speech Pattern Contrast test. The Hebrew Speech Pattern Contrast (HESPAC) test (Kishon-Rabin et al., 2000) was adapted into Hebrew from the Speech Pattern Contrast test (Boothroyd, 1984). The test requires identification of words and includes three subtests: (a) Vowel Height, (b) Vowel Place, and (c) Final Voicing. Each of the HESPAC subtests consists of different pairs of CVC 1-syllable words that differ by a single phonetic contrast. The resulting score is an estimate of the probability that the individual would correctly perceive the contrast that is being tested in many contexts within which it can occur (Boothroyd, 1991). Note that the phonemic inventory of basic Modern Hebrew differs from that of English (Kishon-Rabin, Taitelbaum, Tobin, & Hildesheimer, 1999). While a simplified view of the American English phonemic inventory includes 12 basic vowels (not including diphthongs; Boothroyd, 1986), modern Hebrew is limited to five vowels /i, e, a, o, u/ and does not include the tense–lax distinction as a distinctive feature, nor does it have low front, low back, or central vowels. Therefore, only contrasting pairs /i/ and /e/ and /o/ and /u/ are used in the Vowel Height subtest, and /i/ and /u/ and /e/ and /o/ are used in the Vowel Place subtest. The vowel /a/ was excluded from this test because in Hebrew, /a/ was found to differ from other vowels in both first and second formants (Most, Amir, & Tobin, 2000). In other words, contrasting the /a/ with one of the other vowels would have violated one of the criteria of the Speech Pattern Contrast test: that each subtest evaluates the perception of only one phonetic contrast (Boothroyd, 1984).

In the Final Voicing subtest, each CVC word pair differs only by the voicing of the final consonant. The perception of this contrast was also evaluated in varying phonetic contexts. It should be noted that the inventory of the consonants in Hebrew is not the same as in English (although the same features classify them all: voicing, place of articulation, and manner). Although the two languages share 16 consonant phonemes /p, b, f, v, m, t, d, s, z, l, n, ʃ, j, k, g, h/, Hebrew has the consonants /ts, x, γ/, and English has the consonants /w, θ, ð, ʒ, tʃ, ʤ, r, ŋ/. Thus, the Hebrew version of the final voicing subtest includes the contrasting word pairs ending with /x, γ/ but does not include the word pairs ending with /f, v/, /θ, ð/, and /tʃ, ʤ/. It should also be noted that, unlike English, in which the perception of final voicing is mediated by temporal cues—specifically, the duration of the vowel that precedes the consonant (Raphael, 1972)—final voicing in Hebrew is not perceived on the basis of such cues (Kishon-Rabin & Henkin, 2000; Kishon-Rabin & Nir-Dankner, 1999). Thus, the correct identification of the final voicing contrast in Hebrew requires the perception of fine temporal and spectral detail.

Two different versions were constructed for each subtest (contrast). Each version included 12 different pairs of words. Performance was therefore based on a total of 24 different items per contrast. The words within each pair differed only by the contrast being tested. In this study, the tester confirmed that the words were familiar to the participants prior to testing. At testing, participants were instructed to hear the recorded words and to circle one of two possible words presented in writing. They were instructed to guess if they were not sure. Feedback on performance was withheld. Because these tests used a two-alternative forced-choice paradigm, chance performance was 50%.

Speech Recording

All speech stimuli were recorded by a female speaker. Recordings were made in a sound-treated room onto a cassette tape recorder (Sony TM 500).The speaker used a volume unit (VU) meter to control recording volume. These speech stimuli were analyzed using a commercial speech analysis program, SS1 (Sensimetric Speech Station, 1989; Version 2.1; Ariel Corp., Mount Vernon, OH) to ensure that the number of gross-amplitude changes corresponded to the number of syllables in the one-, two-, and three-syllable words of the HESP test; there was equal duration and equal gross-amplitude changes of the two syllables in the two-syllable words; there were minimal amplitude differences between stimuli (less than 2 dB); and the stimuli within each test (excluding the Pattern Perception subtest) did not vary in duration. Controlling these parameters minimized the possibility that participants responded on the basis of cues other than the ones on which we based our hypotheses.

Psychoacoustic Tests

The psychoacoustic tests included GD, difference limen for frequency (DLF), and PTCs to measure temporal resolution, frequency discrimination, and frequency selectivity, respectively.

Gap detection. The experimental paradigm for GD was a three-interval, three-alternative, forced-choice procedure. Two standard stimuli (no gap) were presented along with a third stimulus containing the gap. The participants were instructed to choose the interval that they thought contained the gap. Stimuli were low-pass noise signals with a cutoff frequency of 1000 Hz. The duration of the standard stimuli was 1,600 ms. The test stimulus consisted of an 800-ms noise signal, a variable silent gap (6 ms–60 ms), and a trailing noise signal that, together with the silent gap, was 800 ms. The interstimulus interval was 700 ms, and the interval between trials was 3 s. All gating was with 10-ms cosinusoidal rise/fall times. The stimuli were generated using commercially available array-processing software (DaDisp; DSP Development Corp., 1990). A low-pass, finite-impulse response filter was created with a cutoff frequency of 1000 Hz and a stop-band attenuation of 100 dB. Several white noise signals were synthesized and passed through this filter to obtain a set of band-limited random noise signals. The use of more than one band-limited noise signal was necessary for minimizing the effects of frozen[1] noise (von Klitzing & Kohlrausch, 1994).

After digital-to-analog conversion, the stimuli were recorded with an audiocassette tape recorder (Sony TCM 500 AV). Gap threshold was determined using the method of constant stimuli. The participants with normal hearing were tested with six gaps (6, 8, 11, 13, 15, and 20 ms), and those with hearing loss were tested with seven gaps (10, 20, 25, 30, 35, 40, and 60 ms). These particular gap durations were selected on the basis of previous studies (Florentine & Buus, 1984; Rosen et al., 1990). For each gap duration, 60 three-interval stimuli were presented. Thus, each of the participants with normal hearing and each of the participants with hearing loss were presented with a total of 360 and 420 three-interval stimuli, respectively. The percentage-correct responses were calculated and fitted by best fit functions using the least-squares fitting technique. These functions were mostly sigmoidal (cumulative Gaussian), which are typical curves obtained with the method of constant stimuli in sensory systems, auditory included (Coren, Ward, & Enns, 1999; Kidd, Watson, & Gygi, 2007). Threshold was defined as the gap value that corresponded to 75% correct.

Difference limen for frequency. The DLF was determined using the same–different procedure. Participants were presented with two tones—standard and comparison—and were required to determine whether they were the same or different (Spiegel & Watson, 1984). The standard frequency was a 1000-Hz pure tone, and the comparison stimuli were 1005-, 1010-, 1015-, 1020-, 1030-, 1040-, 1050-, and 1070-Hz pure tones. These frequencies were selected on the basis of Gengel's (1969) research, which used the method of constant stimuli for testing children and adolescents (10–17 years of age) with SPHL. Each comparison tone was paired with the

[1]*Frozen* or *reproducible noise* refers to a same sample of noise that is consistently used in consecutive trials. This practice is not recommended for the following reasons. Statistically, noise has a certain power spectrum. This is an average property, but it fluctuates over small windows. Thus, when noise is added to transient signals, the latter may coincide by chance with a window that has a power spectrum that is not quite representative. It also appears that listeners learn the properties of the frozen noise presented over time and use this information to improve detection and recognition in noise. To reduce these effects, it is best to use a set of synthesized noise signals instead of just one.

standard tone 30 times. In 15 of the trials the standard tone was presented before the comparison, and the remaining trials were presented in the reverse order. Thus, a total of 240 pairs of different tones (standard and comparison) were recorded. To separate sensitivity from response bias, an additional 240 pairs of stimuli were recorded with identical tones within the pair. Overall, each of the participants was presented with 480 pairs of stimuli at random. The duration of each stimulus was 1,600 ms, with a rise and decay time of 20 ms. The interstimulus and intertrial intervals were 500 ms and 3 s, respectively. The same software and hardware as that used for the GD task were used for stimuli generation and recording.

Each participant was presented with a pair of stimuli: standard and comparison. He or she was instructed to respond whether the tones within a pair were same or different. The experimenter scored the participants' responses. For each participant and Δf (Δf = comparison frequency minus standard frequency), the percentage-correct responses were calculated and fitted by best fit functions using the least-squares fitting technique. These were found to be sigmoidal for most participants. Threshold, or DLF, was defined as the Δf value that corresponded to 75% correct.

PTC. The PTC method for measuring frequency resolution was based on the rationale proposed by Lutman and Wood (1985). They argued that their PTC method is preferable when testing individuals with SPHL and when minimal equipment is available for testing outside the clinic. In addition, it is a relatively simple method to interpret, and it is sensitive to the asymmetry of the hypothetical auditory filter.

The PTCs were obtained using a three-point approximation procedure (Lutman & Wood, 1985). The technique is based on a pulsed, pure-tone probe signal and three different bands of noise maskers. The pulsed signal was a 1-KHz pure tone with a 300-ms on–off cycle, a 20-ms rise time, and a 5-ms decay time. The bandpass noise maskers' cutoff frequencies were 100 to 500 Hz, 800 to 1200 Hz, and 1200 to 1600 Hz. Noise maskers were generated with a masking generator (Beltone, Model NB 103; Beltone Electronics Corp., Chicago, IL) and passed through an analog-adjustable filter (Coulbourn, Model S75-36; Coulbourn Instruments, Allentown, PA) to produce extremely steep skirts (480 dB/octave). The filtered stimuli were recorded onto an audiocassette tape (Sony, Model TC-K2A; Sony Corp., Tokyo, Japan).

The pulsed probe was derived from the oscillator within an audiometer (Beltone Model 112) and routed to an amplifier (Crown D60; Crown International, Elkhart, IN). The noise maskers also were routed from the tape recorder to the amplifier, where they were mixed with the signal.

For each participant, threshold of the pulsed probe was first determined in quiet using a standard manual audiometric procedure involving an ascending series of presentations in 5-dB steps followed by reductions in 10-dB steps (British Society of Audiology, 1981). The pulsed probe was then administered at 10 dB SL (above the measured threshold) and remained fixed. One of the maskers was then chosen from an order chart (which counterbalanced order among participants), and its level was adjusted using a 5 dB–down, 10 dB–up procedure until it just masked the tone. This was subsequently repeated for the other two masker frequencies. Note that the rationale for obtaining the level of noise that was required to mask a pure tone of 10 dB SL (and not of greater intensity) was based on the assumption that a low-level pure tone restricted the region of excitation pattern in the basilar membrane to approximately one auditory filter (Lutman & Wood, 1985; Zwicker, 1974). Furthermore, this method of PTC allowed us to set the probe tone for each listener at a level that was marginally above his or her threshold, thus limiting the masker level required (Lutman & Wood, 1985). On the other hand, the auditory filter in normal-hearing ears tends to broaden with increasing level (Weber, 1977) and to change in shape (Moore, 1989). So, when we compared the PTCs of participants with hearing loss with the PTCs of participants with normal hearing, the data were difficult to interpret because the probe tones were presented at different SPL levels to the two groups. Therefore, the PTC paradigm was repeated for normal-hearing participants with a probe tone set at 60 dB SPL. We chose not to present it at 75 dB SPL (similar to the other tests) because then the maskers could have been administered at uncomfortable levels.

Two indexes of frequency selectivity were used: (a) the low-frequency index was defined as the difference between the overall SPL of the 100- to 500-Hz and the 800- to 1200-Hz maskers, and (b) the high-frequency index was defined as the difference between the overall SPL of the 1200- to 1600-Hz and the 800- to 1200-Hz maskers.

General Procedure

For all tests, all participants (those with normal hearing and those with hearing loss) were tested individually, unaided, and in a sound-treated room that was located in the high school that the participants with the hearing loss attended. As indicated previously, the stimuli were delivered via a clinical audiometer (Beltone 112) and an amplifier (Crown D60) and were presented to the participants monaurally to the best ear through headphones (TDH-49; Telephonics Corp., Farmingdale, NY). The best ear (i.e., the ear with the lowest PTA) was tested to ensure maximum performance and maximum dynamic range for testing. The rationale for not testing the participants with hearing loss with their personal hearing aids was that some of them were fitted with more advanced hearing aids, whereas others used hearing aids with less advanced technology from a loan bank of hearing aids. Amplification via the amplifier and the audiometer provided participants with a unified signal, thus reducing possible confounding factors, such as hearing aid processing and method of hearing aid fitting. The ear with the lowest unaided PTA was selected for the presentation of the stimuli. For the participants with normal hearing, the test ear was matched to that of the participants with hearing impairment, so that in each group, 8 participants were tested in the right ear and 4 were tested in the left ear.

With the exception of the PTC measure, stimuli (speech and nonspeech) were presented to the participants with hearing loss at one level of 20 dB SL and to the normal hearing at two levels: (a) 20 dB SL and (b) 75 dB SPL. A 20-dB sensation level was chosen because most of the participants with hearing loss had relatively uniform losses as a function of frequency and because the highest intensity provided was 120 dB HL, which was approximately 20 dB above the unaided threshold at the highest frequency with residual hearing. This presentation level was similar to the one used by Glasberg and Moore (1989). Furthermore, GD is known to be negatively affected by low presentation levels (at around 20 dB SL; Moore, 1989). The high presentation level was chosen because there are data to suggest that spectral resolution is negatively affected at presentation levels greater than 75 dB SPL (Kidd et al., 2007; Moore, 1989; Weber, 1977). Therefore, to be able to compare the performance of participants with hearing loss with the performance of participants with normal hearing, both low and high presentation levels were used with the normal-hearing participants. Sensation level was determined relative to the unaided PTA (note that there was a good match between speech reception threshold [SRT] and unaided PTA values). For all participants with hearing loss, presentation levels were at comfortable levels.

The participants with hearing loss were tested in two sessions, and those with normal hearing were tested in four sessions (because their data were collected at two presentation levels). Each session included both psychoacoustic and speech perception testing. The order of testing within and between sessions was counterbalanced among the participants.

Results

Speech Perception Tests

For the purpose of comparing word identification scores on closed-set speech tests that differ in the probability for guessing, scores were corrected for chance (Boothroyd, 1988). The correction formula was:

$$S_c = [(S_u - S_g)/(100 - S_g)] \times 100,$$

where S_c = corrected score in percentage form, S_u = uncorrected score in percentage form, and S_g = mean score expected for guessing (50% for Pattern Perception; 8.3% for 2- and 1- Syllable Word Identification; and 50% for Vowel Height, Vowel Place, and Final Voicing).

The individual data obtained on the speech tests (after correction for guessing) for the participants with hearing loss and with normal hearing are shown in Table 2. Group means and standard errors are illustrated in Figure 1. Note that because all participants with normal hearing obtained scores of 100% on all speech tests at 75 dB SPL, only the data obtained at 20 dB SL are presented in Table 2. Two separate two-way repeated measures analyses of variance (ANOVAs) were conducted on the arcsined transformed data separating the effects of group (hearing loss vs. normal hearing) and speech tests ($df = 5$) for each of the presentation levels (20 dB SL and 75 dB SPL). The results of each ANOVA revealed a significant main effect of group, $F(1, 22) = 23.87, p < .01$, and $F(1, 22) = 81.97, p < .01$, for 20 dB SL and 75 dB SPL, respectively. Furthermore, a significant interaction was found for group and test for both presentation levels, $F(5, 18) = 5.37, p < .01$, and $F(5, 18) = 17.99, p < .01$, for 20 dB SL and 75 dB SPL, respectively. A series of one-way ANOVAs examined the difference between the two groups of participants for each speech test. The results showed that at the low presentation level, participants with normal hearing obtained significantly better results for 1-Syllable Word Identification, Vowel Height, Vowel Place, and Final Voicing, Fs(1, 22) = 23.6, 10.5, 27.34, and 13.2, respectively, $p < .01$. For Pattern Perception and 2-Syllable Word Identification, no significant differences were found between the two groups of participants ($p > .05$). At the 75 dB SPL presentation level, the participants with normal hearing performed significantly better than those with hearing loss on all speech tests, Fs(1, 22) = 5.24, 22.83, and 101.1 for the Pattern Perception, 2-Syllable Word Identification, and 1-Syllable Word Identification subtests, respectively, and Fs(1, 22) = 74.16, 104.1, and 27.5 for the Vowel Height, Vowel Place, and Final Voicing subtests ($p < .01$), respectively. The results of these statistical contrasts and the effect size (Cohen's d) are summarized in Table 3 and illustrated in Figure 1.

An additional mixed-model ANOVA was conducted to test the effect of presentation level (20 dB SL and 75 dB SPL) for the group of participants with normal hearing. The results revealed a significant main effect of presentation level, $F(1, 11) = 67.7, p < .01$, as well as a significant interaction between speech test and presentation

Table 2. Individual and group mean scores for the participants with hearing impairment (HI) and normal hearing (NH; in percentage correct) for each speech perception test presented at 20 dB SL.

	Early Speech Perception test						Speech Pattern Contrast test					
	Pattern Perception		2-Syllable Word Ident.		1-Syllable Word Ident.		Vowel Height		Vowel Place		Final Voicing	
Participant	HI	NH	HI	NH	HI	NH	HI	NH	HI	NH	HI	NH
1	75.0	93.8	45.4	59.0	0.0	81.8	66.7	100.0	75.0	100.0	8.3	100.0
2	31.3	100.0	31.8	100.0	22.7	100.0	25.0	100.0	8.3	100.0	−8.3	100.0
3	100.0	100.0	100.0	100.0	54.5	86.4	50.0	100.0	66.7	100.0	41.7	100.0
4	100.0	93.8	45.5	90.9	13.6	68.2	50.0	75.0	75.0	100.0	66.7	100.0
5	87.5	100.0	36.4	100.0	22.7	95.5	0	100.0	25.0	91.7	83.3	91.7
6	100.0	100.0	100.0	95.5	90.9	90.9	75.0	91.7	75.0	83.3	58.3	100.0
7	93.8	100.0	63.6	81.8	54.5	77.3	83.3	91.7	75.0	91.7	100.0	83.3
8	100.0	75.0	100.0	68.2	68.2	77.3	91.7	100.0	−8.3	100.0	100.0	91.7
9	100.0	100.0	95.5	100.0	63.6	100.0	66.7	33.3	41.7	75.0	83.3	75.0
10	100.0	81.3	77.3	86.4	40.9	86.4	91.7	100.0	50.0	100.0	91.7	100.0
11	100.0	100.0	72.7	90.9	40.9	86.4	33.3	75.0	−16.7	100.0	75.0	100.0
12	93.8	100.0	36.4	81.8	9.1	63.6	16.7	41.7	33.3	33.3	25.0	100.0
M	90.1	95.3	67.1	87.9	40.1	84.5	54.2	84.0	41.7	89.6	60.4	95.1
SD	20.0	8.5	27.4	13.3	27.3	11.5	30.3	23.7	33.7	19.5	36.3	8.3

Note. Ident. = Identification.

level, $F(5, 55) = 3.3$, $p = .01$. As part of this ANOVA, a comparison between the two presentation levels was performed for each speech test. The results showed that for all speech tests except Pattern Perception and Final Voicing, participants with normal hearing performed significantly better when stimuli were presented at 75 dB SPL than at 20 dB SL, Fs(1, 55) = 23.0, 37.5, 11.7, 6.2, and 5.02 ($p < .05$), ds = 1.3, 1.9, 0.95, and 0.75 for 2-Syllable Word Identification, 1-Syllable Word Identification, Vowel Height, and Vowel Place, respectively.

Psychoacoustic Tests

The individual data obtained on the psychoacoustic tests are shown in Table 4 for the hearing-impaired and normal-hearing cohorts. The mean GD thresholds of the two groups of participants are illustrated in Figure 2. Figure 2 shows that the mean GD threshold of participants with hearing loss ($M = 22.3$ ms) was larger than that of the normal-hearing cohort ($M = 17.1$ ms at 20 dB SL and $M = 12.9$ ms at 75 dB SPL). We conducted a series of

Figure 1. Performance on speech perception tests for participants with normal hearing at low and high presentation levels and for participants with hearing loss.

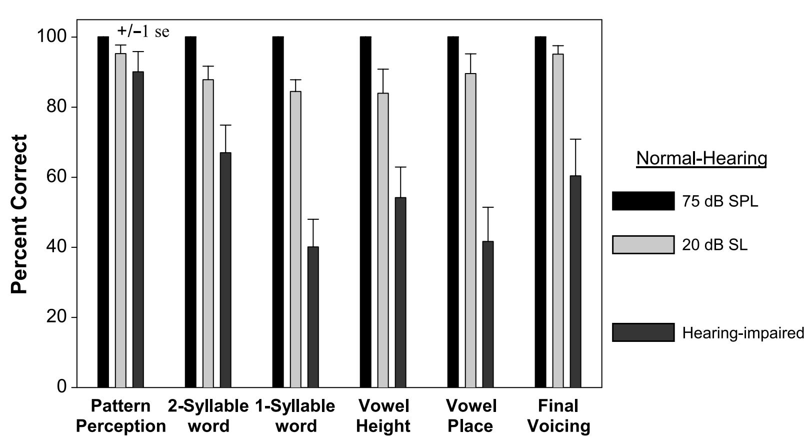


Table 3. *F* statistic values of one-way analyses of variance that compared (a) the speech perception performance of participants with hearing loss with (b) performance of normal-hearing participants on each of the speech tests.

	HESP			HESPAC		
	Pattern Perception	2-Syllable Word Ident.	1-Syllable Word Ident.	Vowel Height	Vowel Place	Final Voicing
75 dB SPL	5.2*	22.8**	101.1**	74.2**	104.1**	27.5**
Cohen's *d*	0.7	1.7	3.1	2.1	2.4	1.5
20 dB SL	*ns*	*ns*	23.6**	10.5**	27.3**	13.2**
Cohen's *d*			2.1	1.1	1.7	1.3

Note. *df* = 1, 22. HESP = Hebrew Early Speech Perception test; HESPAC = Hebrew Speech Pattern Contrast test.

*$p < .05$. **$p < .01$.

t tests for independent measures to test the difference between the two groups of participants. The results revealed that participants with normal hearing had smaller GD thresholds than those with hearing loss only when listening at high sensation levels, $t(22) = 2.5, p < .05, d = 1$. No significant differences were found when the two groups listened at 20 dB SL ($p > .05$). A one-way repeated measures ANOVA, testing the effect of presentation level for the participants with normal hearing, revealed significantly higher GD thresholds at 20 dB SL compared with 75 dB SPL, $F(1, 22) = 5.6, p < .01$.

The mean DLFs of the two groups of participants are illustrated in Figure 3. The DLF for the participants with hearing loss (DLF = 51 Hz) was approximately four times that of the normal hearing cohort (DLF = 13.8 Hz and DLF = 12.5 Hz at 75 dB SPL and 20 dB SL, respectively). Two *t* tests for independent measures confirmed that the DLF values of the participants with hearing loss were significantly greater than those of participants with normal hearing when compared at both low and high sensation levels, $t(22) = 109.2$, $p < .01$, $d = 4.3$, and $t(22) = 10.9$, $p < .01$, $d = 4.4$, respectively. An additional *t* test for dependent measures revealed no significant difference between DLF values obtained at high and low listening levels for the participants with normal hearing.

The PTCs obtained at 1000 Hz for the participants with hearing loss and the normal-hearing cohort at low and high sensation levels are shown in Figure 4. The participants with hearing loss exhibited significantly wider PTCs than the normal-hearing cohort at presentations levels of 10 dB SL and 60 dB SPL for both the left skirt, $t(22) = 7.7$, $p < .05$, $d = 3.1$, and $t(22) = 6.2$, $p < .05$, $d = 2.6$, respectively, and the right skirt, $t(22) = 9.0$, $p < .05$, $d = 3.6$, and $t(22) = 7.9$, $p < .05$, $d = 3.2$,

Table 4. Psychoacoustic thresholds for participants with hearing loss and with normal hearing.

	Hearing loss				Normal hearing at 20 dB SL				Normal hearing at 75 dB SPL			
P	GD[a]	DLF[b]	PTC1[c]	PTC2[c]	GD[a]	DLF[b]	PTC1[c]	PTC2[c]	GD[a]	DLF[b]	PTC1[c]	PTC2[c]
1	58.0	49	22.5	12.5	18.8	15	40	40.0	13.6	10	40.0	40.0
2	43.0	52	2.5	2.5	15.2	10	50	50.0	13.6	10	30.0	30.0
3	17.1	44	22.5	5.0	16.4	25	35	40.0	11.0	25	35.0	30.0
4	17.0	53	30.0	10.0	18.4	15	50	50.0	14.2	10	27.5	30.0
5	15.2	51	0.0	0.0	18.2	15	35	35.0	13.8	10	32.5	25.0
6	14.2	44	25.0	12.5	20.8	15	35	35.0	13.4	15	35.0	35.0
7	15.5	82	10.0	−10.0	18.2	15	40	40.0	8.3	15	35.0	40.0
8	14.4	47	22.5	22.5	17.8	15	40	32.5	13.3	15	35.0	40.0
9	17.1	33	20.0	25.0	14.2	10	50	45.0	12.8	10	40.0	40.0
10	20.8	48	5.0	5.0	14.5	10	35	32.5	11.9	10	32.5	32.5
11	17.1	54	10.0	−10.0	16.0	15	40	35.0	14.0	10	37.5	37.5
12	17.9	55	20.0	12.5	16.3	5	40	37.5	14.9	10	40.0	40.0
M	22.3	51	15.8	7.3	17.1	13.8	40.8	39.4	12.9	12.5	35.0	35.0
SD	13.7	11.4	9.8	10.9	1.1	4.8	6.0	6.1	1.8	4.5	4.0	5.3

Note. P = participant; GD = gap detection; DLF = difference limen for frequency; PTC = psychoacoustic-tuning curve.

[a]In milliseconds. [b]In Hz. [c]In SPL.

Figure 2. Mean gap detection thresholds of participants with hearing loss and with normal hearing at low and high presentation levels. Error bars indicate ±1 *SE*.

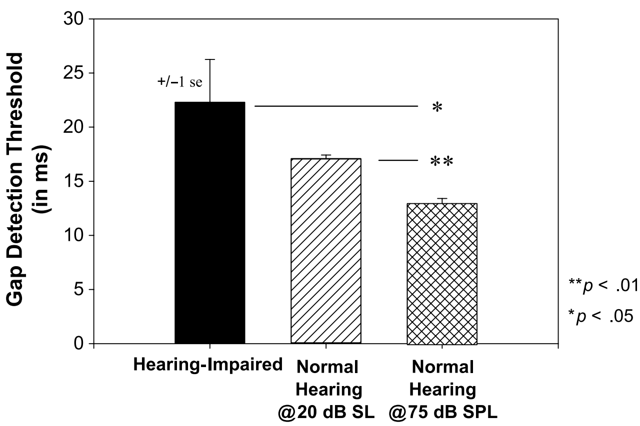


Figure 3. Mean thresholds for difference limen for frequency presented to participants with hearing loss and with normal hearing at low and high presentation levels. Δ f/f = the comparison frequency minus the standard frequency divided by the standard frequency.

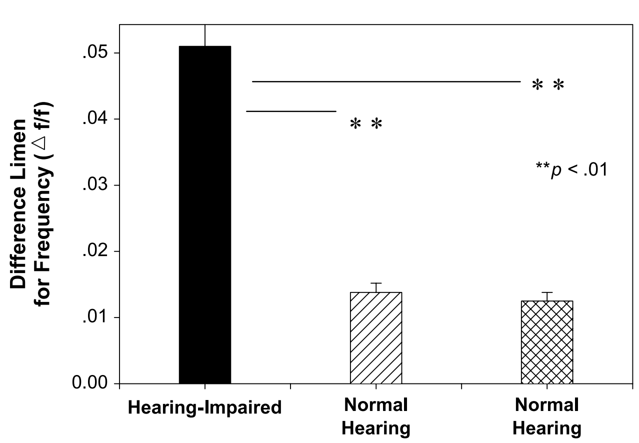
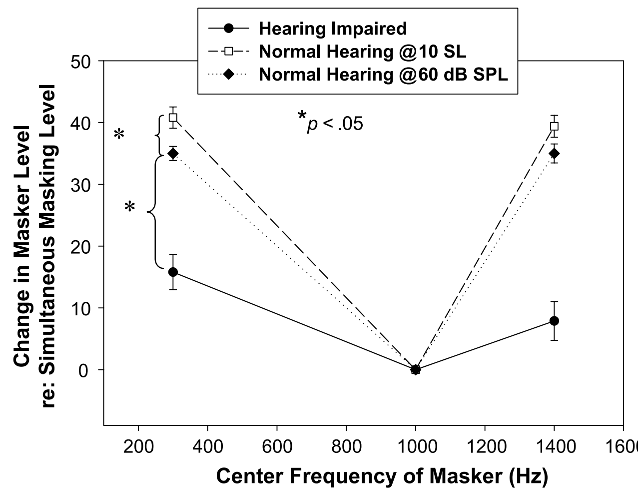


Figure 4. Mean psychoacoustic-tuning curves for participants with hearing loss and with normal hearing at low and high presentation levels.



respectively (see Figure 4). Presentation level was also found to have an effect on the width of the PTCs of participants with normal hearing; specifically, the width of the PTC was more narrowly tuned when the probe tone was presented at 10 dB SL compared with 60 dB SPL, but significantly so for the left skirt, $t(11) = 2.8$, $p < .05$.

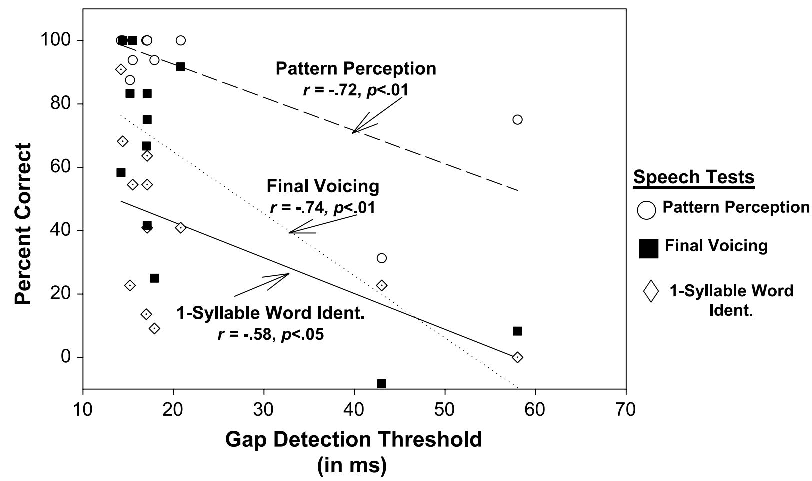
Relationship Between Speech Perception and Psychoacoustic Abilities

The relationship between performance on speech perception tests and psychoacoustic measures was studied through Pearson correlation coefficient analysis. The level of significance was set to $p < .05$. Of the possible correlations tested with the data of the group with hearing loss, only a fraction of the psychoacoustic measures showed a reliable connection with speech perception. Only GD correlated with the following measures of speech perception: Pattern Perception, $r(10) = -.72$, $p < .01$; 1-Syllable Word Identification, $r(10) = -.58$, $p < .05$; and Final Voicing, $r(10) = -.74$, $p < .01$. These correlations, illustrated in Figure 5, suggest that for these three speech tests, larger gap thresholds are associated with poorer performance. Close examination of the data shows that 2 participants with hearing loss may have influenced the outcome. Participants 1 and 2 of the group with hearing loss exhibited abnormal GD thresholds of 58 and 48 ms, respectively. However, the average GD thresholds of the participants with hearing loss, with the exclusion of Participants 1 and 2, was 16.6 ms ($SD = 1.9$). This value is comparable to the average GD thresholds of the participants with normal hearing at 20 dB SL ($M = 13.8$ ms, $SD = 4.8$). Despite their smaller GD thresholds, Participants 3 through 10 from the hearing loss group displayed substantive variability on the speech perception test (see Table 2).

Discussion

The main purpose of this study was to test the relationship between clinically used speech perception tests and the underlying psychoacoustic abilities of adolescents with SPHL. Our findings suggest two things: (a) The relationship between speech perception and psychoacoustic performance was confined to a few features, and (b) the

Figure 5. Correlations between performance on speech perception tests and gap detection thresholds for participants with hearing loss.



psychoacoustic capability least affected by SPHL was temporal resolution (GD). In the remainder of this discussion, we clarify the meaning of the absence of a strong correlation between psychoacoustics and speech perception and elaborate on the few speech–acoustic associations that were found.

Absence of a Strong Correlation Between Psychoacoustics and Speech Perception

The limited relationship between speech perception and psychoacoustic abilities was consistent with the notion that psychoacoustic abilities reflect primarily the auditory system's response to sensory information, whereas auditory speech perception reflects linguistic knowledge and mastery of complex skills in addition to psychoacoustic abilities (Boothroyd, 1997; Cole & Jakimik, 1980). In models of speech perception, psychoacoustic abilities are required for initial spectral and temporal analyses of the incoming speech signal. Linguistic rules operate on the outcome of these analyses. If the spectro-temporal analysis is impaired, then missing or distorted information is processed at the higher levels. This would predict poor speech perception performance. If, on the other hand, the acoustic analysis is of high fidelity, appropriate acoustic information enters higher levels of processing. There is no guarantee, however, that these higher levels are not impaired. Therefore, one cannot predict speech perception performance simply on the basis of psychoacoustic analyses.

The results of this study show that adolescents with hearing loss and with very poor frequency selectivity (Participants 2 and 5) and temporal resolution (Participants 1 and 2) also exhibited the poorest performance on Vowel Height and Vowel Place contrasts, and the Final Voicing contrast and 1-Syllable Word Identification, respectively. However, these psychoacoustic measures were not associated with speech perception performance for the other participants with hearing loss. Therefore, this study supports the notion that, as long as the psychoacoustic thresholds were within those required for speech perception, performance was dependent on factors other than psychoacoustic ability. Only when psychoacoustic thresholds exceeded levels required for speech did they appear to affect speech perception (Festen & Plomp, 1983; Lutman & Clark, 1986; Moore, 1987). These findings also may be partially explained by the fact that a unique group of hearing-impaired individuals participated in this study; all were high-functioning adolescents with profound hearing impairment. It is possible that their high academic and communicative achievements may be related to that fact that for most of them, basic sensory information was available. In this selected group, only a small number of individuals showed reduced psychoacoustic abilities. These also were the poorer performers on the speech perception tests. Investigating the associations between psychoacoustic abilities and speech perception in a less homogeneous group may reveal stronger correlations.

Gap Detection and Speech Perception

Of the three psychoacoustic measures tested in this study (DLF, PTC, and GD), only temporal resolution thresholds were comparable across the two groups of participants at similar sensation levels. Our result of an association between GD and speech recognition is in keeping with the assertion that it is the "most widely cited finding in support for a relationship between speech and non-speech processing abilities observed in hearing impaired and the elderly" (Kidd et al., 2007, p. 420).

The finding that participants with extremely poor GD (greater than 40 ms) performed poorly on Pattern Perception, Final Voicing contrast, and 1-Syllable Word Identification is consistent with the hypothesis that temporal cues underlie speech perception (Kishon-Rabin & Nir-Dankner, 1999; Turner, Souza, & Forget, 1995; Van Tasell, Soli, Kirby, & Widen, 1987). Pattern perception (number of syllables) is cued by gross duration differences and slow changes of amplitude over time (between 2Hz and 50 Hz; Erber, 1979; Moore, 1989; Rosen, 1992). Thus, poor temporal resolution might affect pattern perception, as the results of Participants 1 and 2 indicate. The perception of final voicing is also known to be mediated by temporal cues. In English, vowel durations are considerably longer when they precede an unvoiced consonant (Raphael, 1972). This temporal cue is so pronounced that voicing of English consonants in the final position was found to be perceived via speechreading (Hnath-Chisolm & Kishon-Rabin, 1988). In Hebrew, however, preliminary data collected prior to this study showed that vowels preceding voiced plosives were only 27 ms longer than those occurring before voiceless plosives. Moreover, a study that investigated speechreading of speech contrasts in Hebrew revealed that any temporal cues for final voicing cannot be perceived by the visual modality (Kishon-Rabin & Henkin, 2000). This supports the notion that the temporal cues of final voicing in Hebrew are subtle. The data reported here suggest that the 2 participants with hearing loss, Participants 1 and 2, might have lacked the ability to detect such small changes, thus performing poorly on the Final Voicing subtest. In addition, the speech waveform conveys fine structure information related to the consonants, which includes fluctuation rates of 150 to 500 Hz for the voiced segments and higher fluctuation rates of 600 to 10000 Hz for the unvoiced ones. This information is only partially accessible to listeners. Therefore, poor ability to detect and follow those fine temporal changes can be related to poor word intelligibility, as demonstrated by Participants 1 and 2 (Turner et al., 1995; Van Tassell et al., 1987).

Nelson et al. (1995) suggested that, with greater auditory experience, listeners with hearing loss learn to use the less ambiguous acoustic cues for speech perception. It is possible that the participants in the present study used temporal cues, rather than spectral cues, even for the perception of 1-syllable words, which is usually supported by spectral changes (e.g., Erber, 1979; Moog & Geers, 1990). Whether these participants would be able to shift the weighting of these cues with auditory training and/or different sensory devices requires further investigation.

Frequency Resolution and Speech Perception

Although GD was found to substantively correlate with speech perception in participants with SPHL, there was some evidence that very poor frequency resolution also affects the perception of vowels. The finding that participants with no frequency selectivity (less than 2.5 dB on both sides) performed poorest on the Vowel Height and Vowel Place subtests supports the hypothesis that spectral information underlies perception of these tests. The perception of vowel height is mediated by changes in the first formant, whereas perception of vowel place is mediated by changes in the second formant (Borden, Harris, & Raphael, 1994). According to Moore and Glasberg's (1986, cited in Rosen & Fourcin, 1986) model of pitch perception for complex tones, the auditory filters of individuals with hearing loss are wider than the interharmonic spacing, causing the intensities of specific harmonics to be averaged within the auditory filter. This results in a compressed spectrum of the vowels, thereby making their cues for perception less salient. The fact that only the 2 participants with poor frequency selectivity had difficulty perceiving the vowel contrasts suggests again that speech perception was affected in cases in which psychoacoustic thresholds were particularly poor.

Effect of Presentation Level on Speech Perception and Psychoacoustic Performance

We presented the group with normal hearing with stimuli at both low and high intensity levels. For some tests (Pattern Perception, 2-Syllable Word Identification, and GD), the differences between the performance of participants with hearing loss and those with normal hearing were reduced when stimuli were presented to the normal-hearing participants at low sensation levels; in other words, reduced audibility of speech resulted in comparable performance of both groups of participants for only two speech tests. This suggests that performance of the participants with hearing loss on the remainder of the speech tests was limited by other factors (e.g., spectral and temporal resolution) in addition to audibility (Glasberg & Moore, 1989).

The finding that GD thresholds increased with reduced stimulus level is in accord with previous findings (e.g., Moore, 1989) and suggests that some of the poor temporal resolution of participants with hearing loss can be attributed to poor sensitivity. Finally, elevating the presentation level widened the PTCs of participants with normal hearing, but not to values found for the participants with hearing loss. This is in keeping with previous data that showed that the auditory filter in normal-hearing ears (reflected by the PTC) tended to broaden with increasing level, thus predicting poorer frequency resolution at higher levels (Moore, 1989; Weber, 1977). The results of even wider PTCs of the participants with hearing loss as found in this study may be related to the fact that they were presented with stimuli of very high (yet comfortable) intensity levels that were inappropriate to present to the group with normal hearing. It also is possible that presentation level can only partially explain the results and that the broad PTC of the participants with hearing loss was the result of their pathology, explaining their poor frequency resolution (Dubno & Schaefer, 1992).

In summary, the present data suggest that only extremely impaired psychoacoustic abilities were associated with impaired speech perception. Although these data do not necessarily imply a cause–effect relationship, they do suggest that extremely impaired psychoacoustic abilities may be a useful predictor of performance on the more complex task of perceiving speech; specifically, poor frequency resolution (as measured by a flat PTC) resulted in poor vowel height and place (information mediated by spectral cues of formant change). Similarly, poor temporal resolution (GD threshold greater than 40 ms) resulted in poor voicing, pattern perception, and 1-syllable word identification (information mediated by temporal-envelope cues). Note that our conclusions pertain to the specific tests used and are affected, to a large extent, by a small number of individuals with profound hearing loss.

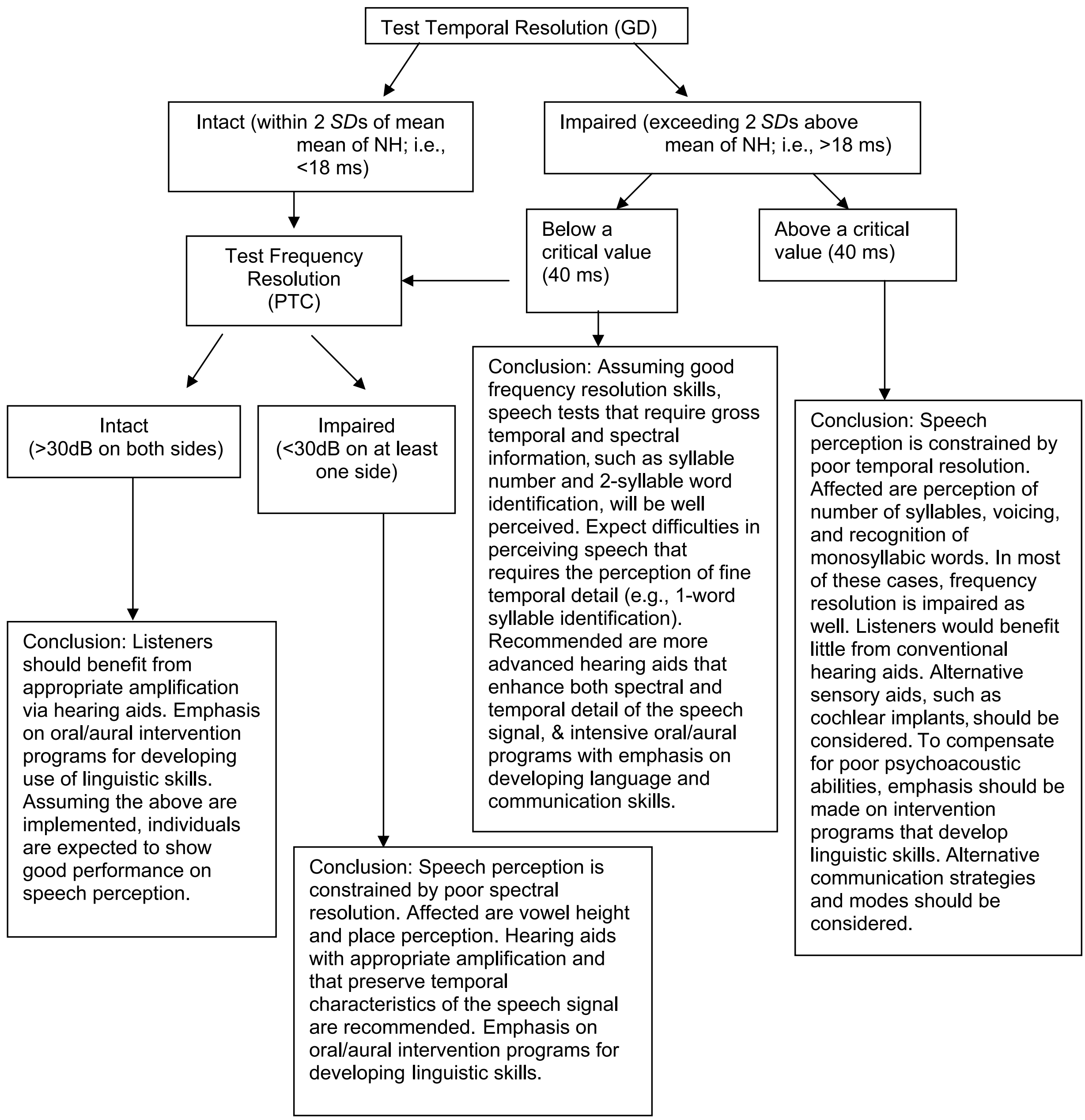
Implications for Practice and Theory

The flow chart in Figure 6 is based on the results of this study and the observed associations among psychoacoustic measures and performance on speech perception in individuals with SPHL. We suggest that performance on speech perception tests of individuals with hearing loss and subsequent intervention can be predicted from GD thresholds. We divided GD thresholds into two categories: (a) intact or (b) impaired. We chose the criterion of "impaired" for GD thresholds that were 2 *SD*s above the mean of the participants with normal hearing. The results of this study, as well as others, showed that normative thresholds of GD at 1 KHz were in the range of 12 to 14 ms (Buus & Florentine, 1985; Green & Forrest, 1989; Shailer & Moore, 1983), although some were as low as 7 to 8 ms, depending on the methods used, such as the bandwidth of the noise maskers and signal-to-noise ratio in the gaps (Fitzgibbons & Wightman, 1982; Shailer & Moore, 1983, 1985). Furthermore, *SD*s of the group with normal hearing were considerably small (e.g., 1.78 ms in this study). Thus, we suggest that at 1 KHz, GD thresholds that exceed 18 ms are outside the normative range and are termed *impaired,* whereas those that are within the normative range are termed *intact*. We hypothesized that significantly reduced temporal resolution would restrict speech perception. Indeed, our data showed that for those participants for which GD thresholds exceeded 40 ms, speech perception (i.e., number of syllables, voicing and recognition of words) was poor. We also predicted that individuals who exhibit poor temporal resolution also will have degraded frequency resolution (because frequency resolution is often negatively affected by hearing loss and is less resistant to impairment than temporal resolution). Therefore, for individuals with impaired temporal resolution, linear amplification provided by conventional hearing aids may not compensate for reductions in the ability to discriminate sounds that are well above threshold (Glasberg & Moore, 1989). Other sensory aids, such as advanced digital hearing aids or cochlear implants, should therefore be considered. Cochlear implants, for example, bypass the impaired inner ear (including damaged or absent hair cells) and stimulate directly surviving neurons in the auditory nerve. Limitations imposed by the absent or nonfunctional hair cells, such as reduced frequency resolution, are therefore bypassed and do not influence the perception of auditory stimuli when transmitted via the cochlear implant (Papsin & Gordon, 2007; Wilson, 2000). Furthermore, much emphasis should be placed on use of linguistic knowledge to compensate for the loss of acoustic–sensory information.

For individuals whose GD thresholds are outside the normative range but below 40 ms, frequency resolution could be intact or impaired, and speech perception would depend on the extent to which the sensory information is accessible in concert with the listener's linguistic skill. One would assume that within this category are individuals with hearing loss who may have relatively poor auditory skills but who, with appropriate intervention and intensive auditory and spoken language programs, could exhibit good communication.

The flow chart in Figure 6 also suggests that individuals with hearing loss who show normative GD thresholds can be divided into two categories: those who have (a) intact versus (b) impaired frequency resolution. Our study, as well as others, found that when the PTC paradigm is used as a measure of frequency resolution, the difference in signal threshold between the target and adjacent frequencies exceeded 30 dB in normal-hearing listeners (Lutman & Wood, 1985; Stelmachowicz & Jesteadt, 1984; Tyler et al., 1982). In contrast, for participants with hearing loss, this value was reduced to less than 30 dB and usually is no more than 10 to 15 dB for one of the adjacent frequencies. Therefore, speech features that require spectral information would be difficult to perceive. For these individuals, sensory aids that preserve the temporal detail in the speech signal would be

Figure 6. A summary of the associations among psychoacoustic measures and performance on speech perception in individuals with severe-to-profound hearing loss on the basis of this study. Implications to habilitation programs are indicated (see text for explanation). GD = gap detection; NH = normal hearing; PTC = psychoacoustic-tuning curve.



recommended—or, alternatively, aids that provide spectral information and that are not limited by the frequency-resolving capabilities of the cochlea, such as cochlear implants. Finally, for individuals with SPHL who show both normative values of GD and PTC thresholds, it is assumed that the spectral–temporal information in the speech signal is available and accessible to them as long as the speech is amplified to their dynamic range of hearing. These individuals are expected to communicate very well if they are in appropriate intervention programs.

When evaluating the results of this study, one should consider its limitations. The impact of a small number of individuals on the results, the less-than-perfect matching of age, and the absence of standardized tests in Hebrew on aspects of linguistic skills in adolescents somewhat constrain the generalization of the conclusions. Furthermore, the homogeneity and intact linguistic and cognitive skills of the adolescents with hearing loss might interfere with application of the results to the larger deaf and hard-of-hearing population. Nevertheless, the current results may reflect performance in optimal conditions (reducing the effects of linguistic and cognitive factors on intersubject variability) and are of value in view of the limited studies evaluating the impact of psychoacoustic impairment on speech perception.

We argue that psychoacoustic capabilities may be related to speech perception for individuals with profound hearing loss. Such information may help clinicians realize whether speech perception is limited by basic psychoacoustic capabilities or by further linguistic–cognitive stages of processing. This distinction is important for diagnosis and intervention processes and can assist in emphasizing the relative importance of acoustic cues (spectral, temporal, or both) available to the listener. Finally, despite its empirical bases, the recommended flow chart should be tested and validated with larger and heterogeneous groups of individuals with hearing loss.

Acknowledgments

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