J Am Acad Audiol 1:217-226 (1990)

Revising the Routine Audiologic Test Battery To Examine Sources of Interpatient Variability

Marleen T. Ochs

Abstract

The current audiologic test battery does not explain individual differences in performance in patients with similar degrees of sensorineural hearing loss. These patients can differ in perceived handicap and satisfaction with amplification, as well as in word-recognition ability in quiet and in noise. This article discusses several perceptual tasks that may reveal important interpatient differences. Each procedure is examined as a potential addition to the routine audiologic test battery in terms of three questions: does the procedure elicit novel information, are the results relevant to the speech perceptual process, and is the technique clinically practical?

Key Words: Hearing disorders, psychoacoustics, central auditory processing disorder, interpatient variability

Ten years ago, Tyler (1979) suggested that including suprathreshold psychoacoustic measures in the clinical test battery may allow audiologists to make subtle distinctions between patients with similar audiograms (see also Lutman, 1983; Lutman and Wood, 1985; Haggard et al, 1986; Glasberg and Moore, 1989). Tyler envisioned a psychoacoustic profile for each patient, including assessment of frequency selectivity and temporal resolution, as well as discrimination of speech-like sounds. This is technically feasible today. Most personal computers can produce and/or store the stimuli needed for these measures. In addition, many psychoacoustic phenomena can be reliably examined within the time constraints of the clinical setting (Lutman, 1983; Hazan and Fourcin, 1985; Lutman and Wood, 1985; Davidson and Melnick, 1988).

Criteria for New Test Selection

In spite of substantial technologic and methodologic advances, today's "air, bone, and speech" test battery is basically the same as it was in the earliest days of the profession (Martin and Morris, 1989). The desire to discriminate between patients with similar audiograms has remained strong. It is not clear, however, whether psychoacoustic tests are the best choice, or if other measures are more appropriate. If a new behavioral procedure is to become part of the routine audiologic test battery, it must meet several criteria. First, it must assess auditory perceptual skills that are not predictable from the audiogram or other current tests. Second, it must contribute to an analysis of speech perceptual strategy at the word and sentence level. The goal of amplification is accurate and effortless comprehension of verbal messages. Therefore, clinical tests should provide information relevant to this process. Third, new clinical tests must require minimal administration time and patient practice. In view of these

Assistant Professor, Division of Hearing and Speech Sciences, Vanderbilt University School of Medicine and The Bill Wilkerson Center, Nashville, Tennessee

Portions of the material in this paper were presented at the first annual meeting of the American Academy of Audiology, Kiawah Island, South Carolina, April, 1989.

Reprint requests: Marleen T. Ochs, Ph.D., Division of Hearing and Speech Sciences School of Medicine, Vanderbilt University, Nashville, TN 37232

requirements, it is not surprising that we continue to rely on traditional procedures.

Sources of Interpatient Variability

Selecting meaningful additions to the clinical test battery is made more difficult because it is not clear which aspects of auditory perception are disrupted in a "typical" sensorineural hearing loss. Hearing-impaired patients who are similar in age and have similar audiograms can differ in several ways, including speech-recognition ability (e.g., Plomp and Mimpen, 1979; Yoshioka and Thornton, 1980; Walden et al, 1981; Preminger and Wiley, 1985; Walden et al, 1986), satisfaction with amplification (Walden et al, 1984), perceived handicap (Weinstein and Ventry, 1983), and tolerance of background noise (Plomp and Mimpen, 1979; Duquesnoy, 1983). This interpatient variability has been interpreted in several ways, as discussed below.

1. **Cochlear Distortion**

Plomp (1978, 1986) has suggested that at least part of the interpatient variability observed clinically is due to varying degrees of suprathreshold cochlear "distortion" in addition to simple sound attenuation. Patients exhibiting such distortion presumably would have communication difficulties even if the speech signal were appropriately amplified. The suprathreshold distortion concept has encouraged study of relationships among psychoacoustic ability, cochlear pathology, and speech perception in hearing-impaired subjects. The logical outcome of this work has been a search for new ways to alter speech to overcome underlying psychoacoustic limitations (e.g., Revoile et al, 1986; Gordon-Salant, 1987; Revoile et al, 1987; Montgomery and Edge, 1988; Freyman and Nerbonne, 1989; Picheny et al, 1989; Williamson and Punch, 1990).

2. **Central Auditory Processing Disorder**

Other authors have attributed interpatient variability to differences in central auditory processing ability, especially in the case of elderly patients (e.g., Stach et al, 1985; Jerger et al, 1989; Jerger et al, 1990). Patients suspected of having significant central auditory pathology in addition to a peripheral hearing loss may exhibit a number of deficits, including: significantly poorer speech-recognition performance in background noise than in quiet, an abnormally poor score on the Synthetic Sentence Index (SSI) (Jerger et al, 1968; Yellin et al, 1989), deterioration of speech-recognition performance at high stimulus presentation levels, and/or abnormal absolute or difference scores on the Dichotic Sentence Identification (DSI) test (Fifer et al, 1983).

3. **Audibility Model**

Several investigators have suggested that if the entire speech signal is made audible to a hearing-impaired listener at usable sensation levels, most consonant confusions can be eliminated, without the need for a suprathreshold cochlear distortion hypothesis. One basis for this view is the Articulation Index (AI) (French and Steinberg, 1947), a way of predicting the speech-understanding ability of normally hearing subjects listening in less than optimal environments. Various modifications of the AI have been applied to hearing-impaired subjects with moderate success, although some patients have more difficulty understanding speech than would be predicted by this index (Walden et al, 1981; Pavlovic, 1984; Kamm et al, 1985; Fabry and Van Tasell, 1986; Humes et al, 1986; Walden et al, 1986; Humes et al, 1987; Turner and Robb, 1987; Zurek and Delhorne, 1987; Dubno et al, 1989). If audibility is confirmed to be the major factor in consonant perception, then the role of the audiogram in disability prediction will be enhanced. Within this model, any interpatient variability that remains after the signal is appropriately amplified, is presumably due to differences in information processing at central sites in the nervous system.

The selection of new tests for the clinical battery depends on which model of sensorineural hearing loss is most applicable. The cochlear distortion model would support psychoacoustic measures using relatively simple stimuli or speech-like stimuli. The audibility model, on the other hand, would focus on the impact of linguistic and cognitive function on auditory perception. The central auditory disorder model has resulted in several test protocols, but these will not be covered here. The following discussion will examine measures that might be considered for an expanded clinical test battery, in light of the various views of sensorineural hearing loss.

CLINICAL MEASURES OF INTERPATIENT VARIABILITY

Frequency Resolution

It has been suggested that frequency resolution, the ability to select out a signal at one frequency in the presence of energy at other frequencies, is an impaired process in cochlear pathology. Many studies indicate that frequency resolution is poorer in hearing-impaired subjects than in subjects with normal audiograms (see Tyler, 1986, for review). Moreover, much of the data suggest that frequency-resolution ability is important for accurate phoneme recognition (Dreschler and Plomp, 1980; Patterson et al, 1982; Festen and Plomp, 1983; Stelmachowicz et al, 1985; but see Dubno and Dorman, 1987; and Leek et al, 1987). Perhaps the most important finding for this discussion, is that frequency resolution is highly correlated to degree of sensorineural hearing loss (Dreschler and Plomp, 1980, 1985; Florentine et al, 1980; Glasberg and Moore, 1986; Glasberg and Moore, 1989). This relationship between spectral resolution and the audiogram implies that measurement of frequency selectivity may be redundant in the context of the clinical test battery (van Rooij et al, 1989).

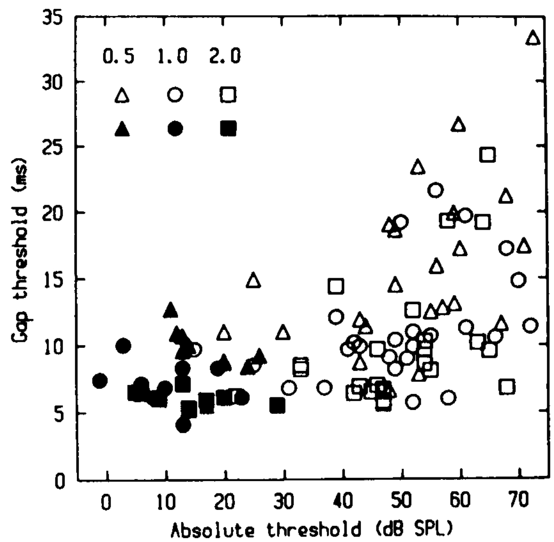

Figure 1 Gap detection thresholds as a function of absolute threshold at the test frequency, either 0.5 kHz (triangles), 1.0 kHz (*circles*), or 2.0 kHz (*squares*). Filled symbols show results for the normally hearing ears of subjects with unilateral cochlear impairments. Open symbols show results from the impaired ears. (Adapted with permission from Glasberg BR, Moore BCJ, Bacon SP. (1987). Gap detection and masking in hearing-impaired and normal-hearing subjects. *J Acoust Soc Am* 81:1546–1556.)

Temporal Resolution

Some measures of temporal resolution may hold promise as additions to the test battery. As previously mentioned, in order to be considered for routine use, the test should provide novel information, be relevant to speech perception, and be simple to implement. Gap detection, the ability to detect a brief period of silence between two bursts of noise, satisfies at least two of these three criteria. Gap detection is attractive as a clinical test because it can be measured quickly and with minimal practice, using a Bekesy tracking technique (Fitzgibbons, 1984). Further, it appears that gap-detection ability is poorly predicted by the audiogram, whether because of cochlear or central auditory processing factors (e.g., Glasberg et al, 1987; Moore and Glasberg, 1988, but see Dreschler and Leeuw, 1990). As shown in Figure 1, subjects with the same degree of hearing loss exhibit a substantial range of gap-detection thresholds. In addition, the range increases as the degree of sensorineural hearing loss increases. The weak correlation between cochlear status and gap-detection ability is also supported by data collected on subjects with multiple-electrode cochlear implants (Moore and Glasberg, 1988; Shannon, 1989). At comparable loudness levels, implant subjects and normally hearing listeners have similar gap detection thresholds, despite total loss of cochlear function in the case of implant subjects. This dissociation between gap-detection ability and degree of hearing loss is further supported by the finding that some hearing-impaired subjects exhibit more dramatic temporal resolution difficulties than do normally hearing subjects who have been masked to simulate hearing loss (Florentine and Buus, 1984; Humes et al, 1988; but see Humes, 1990).

A gap-detection task, then, may provide information not available from the present clinical test battery in a time-efficient manner. Whether gap-detection ability is important for accurate perception of speech, however, is more controversial. There is no doubt that silent intervals in continuous speech can have linguistic importance. For example, introduction of a period of silence between the [s] and [l] in the word "slit" results in perception of the word "split" (Bastian et al, 1961; Marcus, 1978). Relative duration of the silent interval is also important. One of the cues to voicing in intervocalic stops (e.g, rapid-rabid) is duration of the closure for the stop consonant (Lisker, 1957). Finally, an increase in the duration of the silent interval in the middle of the word "topic" produces the two-word phrase "top pick" (Pickett and Decker, 1960). The question, therefore, is not whether periods of silence are linguistically important but, rather, whether gap detection thresholds are so elevated in hearing-impaired listeners that these silent periods are poorly perceived (Dorman et al, 1985). Typically, the silent interval preceding an intervocalic stop consonant ranges from 35 to 90 ms, depending on voicing and speaking rate. The distinction between "slit" and "split" is evoked with a pause of at least 30 to 45 ms. The poorest gap-detection threshold shown in Figure 1 is approximately 35 ms, and most of the hearing-impaired subjects in that study exhibited even better resolution. Therefore, linguistically relevant silent periods in speech should be easily perceived by these hearing-impaired subjects.

The relationship between temporal resolution and speech perception has been widely studied using multivariate correlation analyses. Several investigations reveal significant correlations between gap detection and speech-recognition ability (especially in noise) even when audiometric threshold is factored out (Tyler and Summerfield, 1980; Tyler et al, 1982; Dreschler and Plomp, 1985; Glasberg et al, 1987; Glasberg and Moore, 1989). Other studies, however, find no significant correlation between these factors (Festen and Plomp, 1983; Dorman et al, 1985; Lutman and Clark, 1986; van Rooij et al, 1989). This discrepancy may be due to stimulus or procedural variables. Spectrum of the stimulus, off-frequency listening regions, and sensation level are all known to be important for temporal resolution tasks in hearing-impaired subjects (Fitzgibbons and Wightman, 1982; Bacon and Viemeister, 1985), and these factors have not always been controlled. Another possible explanation involves the redundancy of the acoustic characteristics of speech. Deficient performance on a single measure of temporal processing ability cannot be expected to account for all consonant confusions. Listeners may be able to use alternate cues if they are hampered by poor temporal resolution.

Speech Recognition in Background Noise

Difficulty understanding speech in the presence of background noise is one of the most common complaints of hearing-impaired patients. Many patients who communicate easily in quiet have great difficulty in noisy or reverberant environments. There are several possible explanations for this difficulty, including central auditory processing disorder (Jerger et al, 1989) and cochlear distortion (Plomp, 1978, 1986).

Currently, speech perceptual difficulty in noise can be evaluated clinically using the Synthetic Sentence Index (SSI) at various message-to-competition ratios, or by administering a conventional phonemically balanced (PB) word-recognition test in the presence of background noise. The adaptive speech-reception threshold (SRT) technique is another way of quantifying degree of difficulty in noisy situations (Plomp, 1978). In this procedure, the signal-to-noise ratio (SNR) is varied until the subject achieves a speech-recognition score of 50 percent for words or short sentences. This is accomplished either by keeping the level of the noise constant and adaptively varying the level of the signal (e.g, Plomp, 1978; Plomp and Mimpen, 1979; Duquesnoy, 1983; Plomp, 1986; Van Tasell et al, 1987), or by holding the signal level constant and varying the background noise level (Dirks et al, 1982; Dubno et al, 1984).

Plomp and colleagues have compared the SNR required for 50 percent performance in the presence of high-level speech spectrum noise, with the signal level required for this performance level in quiet, to arrive at a numerical estimate of the deleterious effects of the noise for an individual subject. The data shown in Figure 2 are from 133 elderly subjects whose hearing loss is attributed to presbycusis. In this figure, the speech presentation level required for 50 percent performance in quiet is shown on the horizontal axis, and the SNR required for 50 percent recognition in noise is shown on the or-

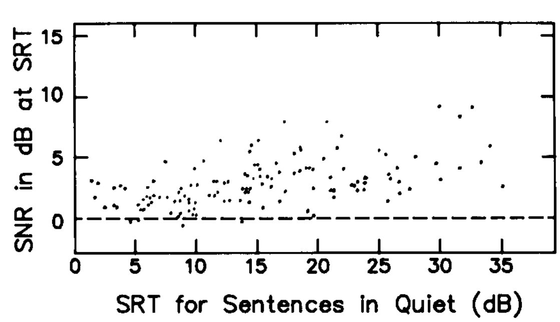

Figure 2 Signal-to-noise ratio (SNR) required for Speech Reception Threshold (SRT) as a function of SRT in quiet for the better ear of 133 elderly listeners. (Adapted with permission from Plomp R. (1986). A signal-to-noise ratio model for the speech-reception threshold of the hearing impaired. *J Speech Hear Res* 29:146–154.)

dinate. Subjects who require large SNRs (i.e, less noise) to achieve 50 percent recognition are presumed to have cochlear distortion or central auditory pathology in addition to their pure-tone loss. Note the substantial range of SNRs needed to maintain 50 percent performance in the noise condition for a given degree of hearing loss in quiet. These data suggest that more routine use of a test of speech perception in noise may improve our ability to discriminate between patients who are alike in their speech-recognition ability in quiet.

The SRT-in-noise procedure satisfies most of the test selection criteria previously stated. The test can be done quickly, with little or no patient practice. The information provided is clearly relevant to speech perception, since background noise is disruptive for so many patients. Duquesnoy (1983) notes that a 1 dB change in the SNR required for the SRT corresponds to a 17 to 20 percent change in more conventional measures of speech understanding (e.g., PB word scores).

The question remaining is whether the SRT-in-noise technique provides information that is unavailable in the conventional test battery. Once again, the issue of audibility and its effect on performance must be considered, especially in the case of high-frequency sloping hearing loss. In order to reach SRT, normally hearing subjects require a more favorable SNR when they listen to low-pass filtered speech in noise than when they listen to unfiltered speech in noise (Plomp, 1986; Humes et al, 1988). This implies that the cochlear or central "distortion" component thought to be present in some sensorineurally hearing-impaired patients may in fact be due to degree of threshold elevation in the high frequencies. If this is true, audiometric thresholds for the high frequencies may explain much of the variability observed in Figure 2. Development of normative data bases for different degrees and configurations of hearing loss, as has begun for the SSI (Yellin, et al, 1989), may clarify this issue for the clinician.

Measurement of speech-recognition ability in noise provides different information than assessment of frequency or temporal resolution. Psychoacoustic tests are designed to explain the mechanism(s) underlying disordered speech perception, and perhaps to suggest a solution. A measure of speech recognition in noise, on the other hand, quantifies the presence of such difficulty but does not explain the phenomenon.

Variation in Auditory Perception in "Normals"

When dealing with sensorineural hearing-impaired subjects, it is tempting to attribute all auditory perceptual deficits to the cochlear pathology. This is an oversimplification, however, because even people with normal audiograms can differ in their suprathreshold auditory abilities. For example, in frequency-discrimination and tonal sequence-discrimination tasks, there is a substantial range of performance. Some experienced subjects with normal audiograms have discrimination thresholds as much as 2.0 standard deviations poorer than the mean (Johnson et al, 1987). Phoneme-boundary experiments using synthetic speech can also reveal auditory perceptual differences

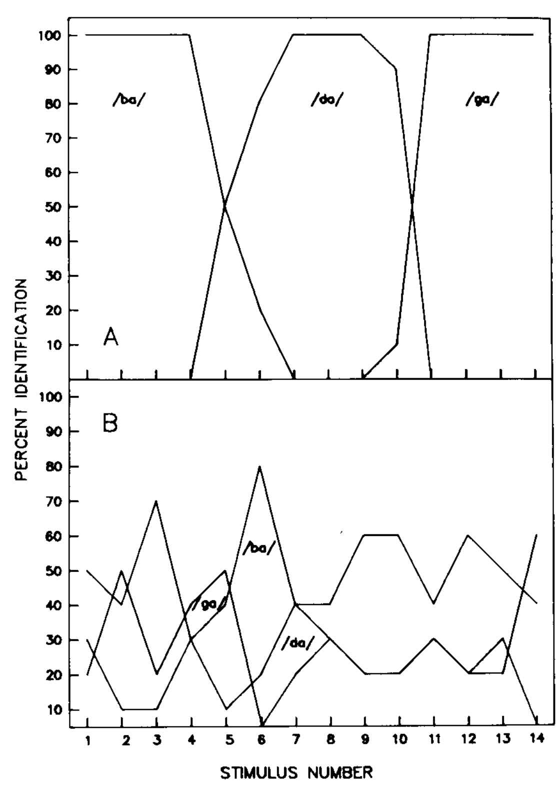

Figure 3 Percent phoneme labeling as a function of stimulus number along a five-formant synthetic stop-consonant continuum. Both panels represent individual data from young adult subjects with normal audiometric thresholds and excellent word-recognition ability in the test ear as measured with naturally produced monosyllables. (Adapted with permission from Walden BE, Montgomery AA, Prosek RA. (1986). Phoneme boundaries in normal and hearing-impaired ears. *J Acoust Soc Am* 79:1101–1112.)

between people with normal audiograms. In these experiments, the acoustic characteristics of a syllable are progressively altered to create a continuum. The stimuli at either end of the series are easily identified, and belong to two different phonemic classes. In most normally hearing subjects, the boundary between phoneme categories is sharp, as shown in Panel A of Figure 3. If the subject has difficulty identifying the syllables in the continuum, the function may be disorganized, as shown in Panel B. Such functions are often seen in hearing-impaired subjects, and the abnormal shape is attributed to the hearing loss. In fact, however, the identification function shown in Panel B is that of a subject with a normal audiogram and functionally normal communication skills (Walden et al, 1986). This subject's perceptual deviation, observed here with synthetic speech, would not be detected by our current clinical techniques. This example reminds us that "normal" hearers, like hearing-impaired subjects, may differ from each other in ways unrelated to their cochlear status. It seems likely that performance on such tasks is affected by central processing in the auditory and/or cognitive domain.

The identification and discrimination tasks discussed by Johnson et al (1987) and Walden et al (1986) involve perceptual phenomena that can be disturbed even in the presence of normal thresholds. The tasks thereby satisfy the criteria that a potential test must provide information different from the audiogram. Another criteria, however, is that of practicality. Measures of frequency discrimination and tonal sequence discrimination require substantial periods of practice by a patient before the results can be considered valid estimates of ability (Johnson et al, 1987). This tends to preclude their use in a clinical test battery. The synthetic speech continuum task, on the other hand, is easy and quick to administer and requires little patient training (Hazan and Fourcin, 1985). Further work is needed to determine whether this task advances our understanding of interpatient differences.

To satisfy the final criterion, the proposed test must be relevant to speech perception. Subjects who have normal audiograms but "abnormal" perception on these identification and discrimination tasks typically report no auditory difficulties in natural settings. It is tempting, therefore, to conclude that these measures are unimportant for speech perception. We know, however, that even substantial central auditory disorders are not observed unless the speech signal is degraded by filtering or by the presence of a competing noise. It may be that these subtle auditory perceptual abnormalities become more important when the redundancy of speech is reduced by loss of hearing, or by background noise and reverberation. Perhaps these individuals experience more dramatic difficulties as they age than subjects with superior auditory perceptual abilities. Most audiologists have seen some patients who have auditory complaints in the presence of normal hearing sensitivity. Saunders and Haggard (1989) suggest that the perceived disability in these cases may be due to an interaction of auditory, linguistic, and psychological difficulties. If these patients subsequently develop a cochlear hearing loss and are fitted with a hearing aid, will they be the ones who complain that speech is loud enough, but still difficult to understand? These issues certainly warrant continuing investigation.

Role of Linguistic and Cognitive Factors

Even with an optimal hearing aid fitting, sensorineurally hearing-impaired people frequently misunderstand words or phrases in conversation. To avoid asking for a repetition, the listener must use linguistic knowledge and have adequate cognitive ability to fill in the gaps. For example, the listener's knowledge of syntax limits the possibilities to words that are in appropriate grammatical classes. Good semantic and cognitive processing further limits the choices to those that would fit into the context of the conversation. Finally, the listener must be able to quickly think of a pool of words that would satisfy these constraints, and select the most appropriate one. Interpatient differences in any of these areas might affect their relative communication success. Assessment of these skills may reveal differences between patients that are not obvious from the audiogram.

1. Speech-Perception-in-Noise (SPIN) Test

The Speech-Perception-In-Noise (SPIN) test has been suggested as a way of examining semantic context effects in hearing-impaired patients. The test compares final-word recognition in sentences with and without semantic cues (Kalikow et al, 1977; Morgan et al, 1981; Bilger et al, 1984), called high-probability and low-probability items, respectively. The difference between the word-recognition score for high- and low-probability items is often considered a measure of the patient's use of semantic context. In hearing-impaired subjects, however, the difference score is also related to degree of hearing loss and signal-to-noise ratio (Owen, 1981; Bilger et al, 1984). For example, if a few key words in the sentence are misunderstood, semantic context is altered. If the patient then uses the *perceived* semantic cues, and responds with a word consistent with this altered context, an error may occur on that test item. Such errors minimize the difference score, which is interpreted as poor use of semantic cues. This problem could be circumvented by presenting the test in written form, or by presenting the context auditorily and visually, followed by an auditory-only presentation of the stimulus word in noise (Theodoridis et al, 1985; Theodoridis and Schoeny, 1988). The patient could also be presented with SPIN sentences and asked to provide as many appropriate endings as possible, in a fixed amount of time. While these techniques are clinically feasible, it is not clear whether such measures of linguistic competence would be valuable in predicting degree of hearing disability in real-world settings.

2. **Cohort Model of Word Recognition**

Recent advances in our understanding of the word-recognition process in normally hearing subjects may produce new clinically useful paradigms for the assessment of hearing-impaired patients. For example, the Cohort model of word recognition proposes that when asked to identify a word presented auditorily, listeners use acoustic-phonetic information at the beginning of the word to establish a set of possible words or cohorts (Marslen-Wilson and Welsh, 1978). Often the listener correctly identifies the word after hearing only the initial portion of the word. Acoustic information occurring after this point is presumably ignored. This phenomenon has been studied using a technique called gating (Grosjean, 1980). In this procedure, the target word is digitally edited into a series of progressively longer segments, starting at the beginning of the word. By the end of the series, the whole word is presented. The listener is asked to guess at the word after each segment. The segment duration required for correct identification is considered a measure of the efficiency of the subject's word-recognition process. When the target word segment is presented in a semantic context, the initial set of cohorts is smaller, and the target word is often recognized with a shorter segment duration.

The gating technique has been used to compare word-recognition strategy in young children, teenagers, and elderly adults (Elliott et al, 1987). In this study, both children and teenagers had normal audiograms, but teenagers required a shorter segment duration to correctly identify monosyllables. The elderly subjects tended to require longer segments before they could correctly identify the items. Many of the elderly subjects had some high-frequency hearing loss, therefore the reduced acoustic-phonetic information available to them may have increased the stimulus duration required.

The gating technique could be easily administered within the equipment and time constraints of the audiology clinic. Because it is a direct estimate of word recognition under conditions of reduced redundancy, the task is relevant to speech perception. To minimize the effect of peripheral hearing loss, the test would presumably be administered after the patient was optimally fitted with amplification.

Role of Visual Cues

The extent to which a patient relies on, and benefits from, visual cues to enhance word recognition is not currently assessed by most audiologists. Some patients benefit more from visual information than do others (Walden et al, 1974). This intersubject variability, and the importance of visual cues in poor listening environments, support the need for routine audiovisual assessment of speech-recognition ability. At the simplest level, auditory and audio-visual recognition of speech can be compared using standard speech materials.

Recent work on the perceptual integration of auditory and visual speech stimuli may lead to the development of new clinical techniques (Massaro, 1987; Walden et al, 1990). For example, when /ba/ is presented auditorily at the same time that a speaker's face is conveying visual information consistent with /ga/, subjects typically perceive /da/ (McGurk and MacDonald, 1976). This intersensory biasing, which has become known as the McGurk effect, is even more dramatic in hearing-impaired subjects than in normal hearers (Walden et al, 1990). It may be that degree of intersensory biasing is a measure of the subject's reliance on visual versus auditory cues. If this is true, the McGurk technique may provide a quick, global assessment of the patient's audiovisual perception without requiring testing of many phonemic combinations.

CONCLUSIONS

In the past, certain changes in the clinical test battery have had a substantial impact on patient care and on the profession. For example, consider the effect of immittance audiometry on the diagnostic process for conductive hearing loss. Prior to the introduction of immittance audiometry, audiologists could evaluate the magnitude of a conductive hearing loss, but could not distinguish between pathologies that produced similar air- and bone-conduction thresholds. In addition, before audiologists assessed auditory evoked potentials, acoustic stapedial reflexes, and high-level word recognition, lesions of the auditory nerve could not be distinguished from a pure cochlear disorder.

Self-assessment scales of hearing disability (Ventry and Weinstein, 1982; Schow and Nerbonne, 1982; Weinstein and Ventry, 1983; Demorest and Erdman, 1987; Lutman et al, 1987; Owens and Raggio, 1988; Bess et al, 1989) reveal significant interpatient variability within the current diagnostic category of "sensorineural" hearing loss. This suggests that further differential diagnosis may be possible for this group of patients. Pure-tone sensitivity and speech-recognition ability account for less than 50 percent of the variance in disability scores (Weinstein and Ventry, 1983). If we are to more completely explain the sources of this variance we must examine a broad range of skills that underlie the speech perceptual process. This review suggests measurement of temporal resolution or word-recognition ability under various types of signal degradation. It also seems reasonable to assess the impact of linguistic context and visual cues on word-recognition ability. It will be necessary to determine which perceptual skills distinguish between patients, and which can be tested in a reliable and efficient way.

Acknowledgement. Special thanks are due to Jay Hall, Larry Humes, Carol Sammeth, and Christy Woodall for their helpful comments on an earlier draft of this manuscript.

REFERENCES

Bacon SP, Viemeister NF. (1985). Temporal modulation transfer functions in normal-hearing and hearing-impaired listeners. *Audiology* 24:117–134.

Bastian J, Eimas PD, Liberman AM. (1961). Identification and discrimination of a phonemic contrast induced by a silent interval. *J Acoust Soc Am* 33(Suppl):s842.

Bess FH, Lichtenstein MJ, Logan SA, Burger MC, Nelson E. (1989). Hearing impairment as a determinant of function in the elderly. *J Am Geriatr Soc* 37:123–128.

Bilger RC, Nuetzel JM, Rabinowitz EM, Rzeczkowski C. (1984). Standardization of a test of speech perception in noise. *J Speech Hear Res* 27:32–48.

Davidson S, Melnick W. (1988). A clinically feasible method for determining frequency resolution. *J Speech Hear Res* 31:299–303.

Demorest ME, Erdman SA. (1987). Development of the communication profile for the hearing impaired. *J Speech Hear Disord* 52:129–143.

Dirks DD, Morgan DE, Dubno JR. (1982). A procedure for quantifying the effects of noise on speech recognition. *J Speech Hear Disord* 47:114–123.

Dorman MF, Marton K, Hannley MT, Lindholm JM. (1985). Phonetic identification by elderly normal and hearing-impaired listeners. *J Acoust Soc Am* 77:664–670.

Dreschler WA, Plomp R. (1980). Relations between psychophysical data and speech perception for hearing-impaired subjects, I. *J Acoust Soc Am* 68:1608–1615.

Dreschler WA, Plomp R. (1985). Relations between psychoacoustic data and speech perception for hearing-impaired subjects, II. *J Acoust Soc Am* 78:1261–1270.

Dreschler WA, Leeuw AR. (1990). Speech reception in reverberation related to temporal resolution. *J Speech Hear Res* 33:181–187.

Dubno JR, Dirks DD, Morgan DE. (1984). Effects of age and mild hearing loss on speech recognition in noise. *J Acoust Soc Am* 76:87–96.

Dubno JR, Dorman MF. (1987). Effects of spectral flattening on vowel identification. *J Acoust Soc Am* 82:1503–1511.

Dubno JR, Dirks DD, Schaefer AB. (1989). Stop-consonant recognition for normal-hearing listeners and listeners with high-frequency hearing loss, II. Articulation Index predictions. *J Acoust Soc Am* 85:355–364.

Duquesnoy AJ. (1983). The intelligibility of sentences in quiet and in noise in aged listeners. *J Acoust Soc Am* 74:1136–1144.

Elliott LL, Hammer MA, Evan KE. (1987). Perception of gated, highly familiar spoken monosyllabic nouns by children, teenagers, and older adults. *Percept Psychophys* 42:150–157.

Fabry DA, Van Tasell DJ. (1986). Masked and filtered simulation of hearing loss: effects on consonant recognition. *J Speech Hear Res* 29:170–178.

Festen JM, Plomp R. (1983). Relations between auditory functions in impaired hearing. *J Acoust Soc Am* 73:652–662.

Fifer RC, Jerger JF, Berlin CI, Tobey EA, Campbell JC. (1983). Development of a dichotic sentence identification test for hearing-impaired adults. *Ear Hear* 4:300–305.

Fitzgibbons P, Wightman FL. (1982). Gap detection in normal and hearing-impaired listeners. *J Acoust Soc Am* 72:761–765.

Fitzgibbons P. (1984). Temporal gap resolution in narrowband noises with center frequencies from 6000–14000 Hz. *J Acoust Soc Am* 75:566–569.

Florentine M, Buus S, Scharf B, Zwicker E. (1980). Frequency selectivity in normally hearing and hearing-impaired observers. *J Speech Hear Res* 23:646–669.

Florentine M, Buus S. (1984). Temporal gap detection in sensorineural and simulated hearing impairment. *J Speech Hear Res* 27:449–455.

French NR, Steinberg JC. (1947). Factors governing the intelligibility of speech sounds. *J Acoust Soc Am* 19:90–119.

Freyman RL, Nerbonne GP. (1989). The importance of consonant-vowel intensity ratio in the intelligibility of voiceless consonants. *J Speech Hear Res* 32:524–536.

Glasberg BR, Moore BCJ. (1989). Psychoacoustic abilities of subjects with unilateral and bilateral cochlear hearing impairments and their relationship to the ability to understand speech. *Scand Audiol* 32(Suppl):1–25.

Glasberg BR, Moore BCJ. (1986). Auditory filter shapes in subjects with unilateral and bilateral cochlear impairments. *J Acoust Soc Am* 79:1020–1033.

Glasberg BR, Moore BCJ, Bacon SP. (1987). Gap detection and masking in hearing-impaired and normal-hearing subjects. *J Acoust Soc Am* 81:1546–1556.

Gordon-Salant S. (1987). Effects of acoustic modification on consonant recognition by elderly hearing-impaired subjects. *J Acoust Soc Am* 81:1199–1202.

Grosjean F. (1980). Spoken word recognition processes and the gating paradigm. *Percept Psychophys* 28:267–283.

Haggard MP, Lindblad AC, Foster JR. (1986). Psychoacoustical and audiometric prediction of auditory disability for different frequency responses at listener-adjusted presentation levels. *Audiology* 25:277–298.

Hazan V, Fourcin AJ. (1985). Microprocessor-controlled speech pattern audiometry. *Audiology* 24:325–335.

Humes LE, Dirks DD, Bell TS, Ahlstrom C, Kincaid GE. (1986). Application of the Articulation Index and the Speech Transmission Index to the recognition of speech by normal-hearing and hearing-impaired listeners. *J Speech Hear Res* 29:447–462.

Humes LE, Dirks DD, Bell TS, Kincaid G. (1987). Recognition of nonsense syllables by hearing-impaired listeners and by noise-masked normal hearers. *J Acoust Soc Am* 81:765–773.

Humes LE, Espinoza-Varas B, Watson CS. (1988). Modeling sensorineural hearing loss I. Model and retrospective evaluation. *J Acoust Soc Am* 83:188–202.

Humes LE. (1990). Masking of tone bursts by modulated noise in normal, noise-masked normal, and hearing-impaired listeners. *J Speech Hear Res* 33:3–8.

Jerger J, Speaks C, Trammel J. (1968). A new approach to speech audiometry. *J Speech Hear Disord* 33:318–327.

Jerger J, Jerger S, Oliver T, Pirozzolo F. (1989). Speech understanding in the elderly. *Ear Hear* 10:79–89.

Jerger J, Oliver TA, Pirozzolo F. (1990). Impact of central auditory processing disorder and cognitive deficit on the self-assessment of hearing handicap in the elderly. *J Am Acad Audiol* 1:75–80.

Johnson DM, Watson CS, Jensen JK. (1987). Individual differences in auditory capabilities. *J Acoust Soc Am* 81:427–438.

Kalikow DN, Stevens KN, Elliott LL. (1977). Development of a test of speech intelligibility in noise using sentence materials with controlled word predictability. *J Acoust Soc Am* 61:1337–1351.

Kamm CA, Dirks DD, Bell TS. (1985). Speech recognition and the Articulation Index for normal and hearing-impaired listeners. *J Acoust Soc Am* 77:281–288.

Leek MR, Dorman MF, Summerfield Q. (1987). Minimum spectral contrast for vowel identification by normal-hearing and hearing-impaired listeners. *J Acoust Soc Am* 81:148–154.

Lisker L. (1957). Closure duration and the intervocalic voiced-voiceless distinction in English. *Language* 33:42–49.

Lutman ME. (1983). Microcomputer-controlled psychoacoustics in clinical audiology. *Br J Audiol* 17:109–114.

Lutman ME, Wood EJ. (1985). A simple clinical measure of frequency resolution. *Br J Audiol* 19:1–8.

Lutman ME, Clark J. (1986). Speech identification under simulated hearing-aid frequency response characteristics in relation to sensitivity, frequency resolution, and temporal resolution. *J Acoust Soc Am* 80:1030–1040.

Lutman ME, Brown EJ, Coles RRA. (1987). Self-reported disability and handicap in the population in relation to pure-tone threshold, age, sex and type of hearing loss. *Br J Audiol* 21:45–58.

Marcus SM. (1978). Distinguishing "slit" and "split"—an invariant timing cue in speech perception. *Percept Psychophys* 23:58–60.

Marslen-Wilson W, Welsh A. (1978). Processing interactions and lexical access during word recognition in continuous speech. *Cognit Psych* 10:29–63.

Martin FN, Morris LJ. (1989). Current audiologic practices in the United States. *Hear J* 42:25–44.

Massaro DW. (1987). *Speech Perception by Ear and Eye: A Paradigm for Psychological Inquiry.* Hillsdale, NJ: Erlbaum.

McGurk H, MacDonald J. (1976). Hearing lips and seeing voices. *Nature* 264:746–748.

Montgomery AA, Edge RA. (1988). Evaluation of two speech enhancement techniques to improve intelligibility for hearing-impaired adults. *J Speech Hear Res* 31:386–393.

Moore BCJ, Glasberg BR. (1988). Gap detection with sinusoids and noise in normal, impaired, and electrically stimulated ears. *J Acoust Soc Am* 83:1093–1101.

Morgan DE, Kamm CA, Velde TM. (1981). Form equivalence of the speech perception in noise (SPIN) test. *J Acoust Soc Am* 69:1791–1798.

Owen JH. (1981). Influence of acoustical and linguistic factors on the SPIN test difference score. *J Acoust Soc Am* 70:678–682.

Owens E, Raggio M. (1988). Performance inventory for profound and severe loss (PIPSL). *J Speech Hear Disord* 53:42–56.

Patterson RD, Nimmo-Smith I, Weber DL, Milroy R. (1982). The deterioration of hearing with age: frequency selectivity, the critical ratio, the audiogram and speech threshold. *J Acoust Soc Am* 72:1788–1803.

Pavlovic CV. (1984). Use of the Articulation Index for assessing residual auditory function in listeners with sensorineural hearing impairment. *J Acoust Soc Am* 75:1253–1258.

Picheny MA, Durlach NI, Braida LD. (1989). Speaking clearly for the hard of hearing, III. An attempt to determine the contribution of speaking rate to differences in intelligibility between clear and conversational speech. *J Speech Hear Res* 32:600–603.

Pickett JM, Decker LR. (1960). Time factors in the perception of a double consonant. *Lang Speech* 3:11–17.

Plomp R. (1978). Auditory handicap of hearing impairment and the limited benefit of hearing aids. *J Acoust Soc Am* 63:533–549.

Plomp R, Mimpen AM. (1979). Speech-reception threshold for sentences as a function of age and noise level. *J Acoust Soc Am* 66:1333–1342.

Plomp R. (1986). A signal-to-noise ratio model for the speech-reception threshold of the hearing impaired. *J Speech Hear Res* 29:146–154.

Preminger J, Wiley TL. (1985). Frequency selectivity and consonant intelligibility in sensorineural hearing loss. *J Speech Hear Res* 28:197–206.

Revoile SG, Holden-Pitt L, Pickett JM, Brandt F. (1986). Speech cue enhancement for the hearing impaired: I. Altered vowel durations for the perception of final fricative voicing. *J Speech Hear Res* 29:240–255.

Revoile SG, Holden-Pitt L, Edward D, Pickett JM, Brandt F. (1987). Speech cue enhancement for the hearing impaired: amplification of burst/murmur cues for improved perception of final stop voicing. *J Rehabil Res Dev* 24:207–216.

Saunders GH, Haggard MP. (1989). The clinical assessment of obscure auditory dysfunction—I. Auditory and psychological factors. *Ear Hear* 10:200–208.

Schow RL, Nerbonne MA. (1982). Communication Screening Profile: use with elderly clients. *Ear Hear* 3:135–147.

Shannon RV. (1989). Detection of gaps in sinusoids and pulse trains by patients with cochlear implants. *J Acoust Soc Am* 85:2587–2592.

Stach BA, Jerger JF, Fleming KA. (1985). Central presbyacusis: a longitudinal case study. *Ear Hear* 6:304–306.

Stelmachowicz PG, Jesteadt W, Gorga MP, Mott J. (1985). Speech perception ability and psychophysical tuning curves in hearing-impaired listeners. *J Acoust Soc Am* 77:620–627.

Theodoridis GC, Schoeny ZG. (1988). Comparison of various modes of presenting sentence materials in tests of speech perception in noise. *J Acoust Soc Am* 84:2270–2272.

Theodoridis GC, Schoeny ZG, Anne A. (1985). Measuring the contribution of printed context information to acoustical word recognition by normal subjects. *Audiology* 24:104–116.

Turner CW, Robb MP. (1987). Audibility and recognition of stop consonants in normal and hearing-impaired subjects. *J Acoust Soc Am* 81:1566–1573.

Tyler RS. (1979). Measuring hearing loss in the future. *Br J Audiol* 13 (Suppl #2):29–40.

Tyler RS, Summerfield Q. (1980). Psychoacoustical and phonetic measures of temporal processing in normal and hearing-impaired listeners. In: van den Brink G, Bilsen FA, eds. *Psychophysical, Physiological and Behavioral Studies in Hearing.* Delft, the Netherlands: Delft University Press, 458–465.

Tyler RS, Summerfield Q, Wood EJ, Fernandes MA. (1982). Psychoacoustic and phonetic temporal processing in normal and hearing-impaired listeners. *J Acoust Soc Am* 72:740–752.

Tyler RS. (1986). Frequency resolution in hearing-impaired listeners. In: Moore BCJ, ed. *Frequency Selectivity in Hearing.* London: Academic Press.

van Rooij JCGM, Plomp R, Orlebeke JF. (1989). Auditive and cognitive factors in speech perception by elderly listeners. I: Development of a test battery. *J Acoust Soc Am* 86:1294–1309.

Van Tasell DJ, Yanz JL. (1987). Speech recognition threshold in noise: effects of hearing loss, frequency response, and speech material. *J Speech Hear Res* 30:377–386.

Ventry IM, Weinstein BE. (1982). The hearing handicap inventory for the elderly: a new tool. *Ear Hear* 3:128–134.

Walden B, Prosek R, Worthington DW. (1974). Predicting audiovisual consonant recognition performance of hearing-impaired adults. *J Speech Hear Res* 17:270–278.

Walden B, Schwartz D, Montgomery A, Prosek R. (1981). A comparison of the effects of hearing impairment and acoustic filtering on consonant recognition. *J Speech Hear Res* 24:32–43.

Walden BE, Demorest ME, Hepler EL. (1984). Self-report approach to assessing benefit derived from amplification. *J Speech Hear Res* 27:49–56.

Walden BE, Montgomery AA, Prosek RA. (1986). Phoneme boundaries in normal and hearing-impaired ears. *J Acoust Soc Am* 79:1101–1112.

Walden BE, Montgomery AA, Prosek RA, Hawkins DB. (1990). Visual biasing of normal and impaired auditory speech perception. *J Speech Hear Res* 33:163–173.

Weinstein BE, Ventry IM. (1983). Audiometric correlates of the Hearing Handicap Inventory for the Elderly. *J Speech Hear Disord* 48:379–384.

Williamson MJ, Punch JL. (1990). Speech enhancement in digital hearing aids. *Semin Hear* 11:68–78.

Yellin MW, Jerger J, Fifer RC. (1989). Norms for disproportionate loss in speech intelligibility. *Ear Hear* 10:231–234.

Yoshioka P, Thornton AR. (1980). Predicting speech discrimination from the audiometric thresholds. *J Speech Hear Res* 23:814–827.

Zurek PM, Delhorne LA. (1987). Consonant reception in noise by listeners with mild and moderate sensorineural hearing impairment. *J Acoust Soc Am* 82:1548–1559.