ON THE PREDICTION OF PHONEME RECOGNITION BY THE HEARING IMPAIRED

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ABSTRACT

A review of recent research on psychoacoustic correlates of subnormal speech recognition by hearing-impaired listeners reveals a confusing diversity of results. This may be due partly to the use of recognition measures that derive only an overall score of percent phonemes correct or a signal level for a criterion percent correct phonemes. A set of studies is described in which this problem is approached by scoring the correctness of perception of specific consonant features, such as voicing or manner, for correlation with related psychoacoustic capacities, such as discrimination of vowel duration, discrimination of the rate of formant transition, and modulation detection. The availability of cues to consonant features is controlled by processing to degrade selected cues in the test syllables and/or by selection of listeners with limited cue reception. Fairly useful correlations were found from the point of view of predicting feature perception differences among individuals.

INTRODUCTION

The past decade has witnessed increasing interest in the relation between impaired speech recognition and basic psychoacoustic performance, such as auditory resolution of intensity, frequency, and time. Knowledge of such relations could contribute to our understanding of speech processing at the cochlear level; when substantial speech/psychoacoustic relations are found, the similarities between the psychoacoustic assessments and analogous physiological measures of audition enable inferences to be drawn about the auditory analysis of speech. A more practical intent of these studies is to identify measures that might predict speech recognition performance more effectively than traditional and current audiological techniques. However, whether for predictive purposes or to gain more basic knowledge, relations between speech/psychoacoustic performances have yet to be firmly established due in part to the diversity of findings throughout investigations thus far. The variability in results is apparent among some of the more recent studies.

Haggard et al. (1986)[1] found that the predictiveness of psychoacoustic tuning curves (PTC) and pure tone sensitivity for speech performance in noise was affected by the frequency response used for speech presentation. For a flat response, tone thresholds and abbreviated PTC measurements (Lutman and Wood, 1985[2]) at 2 kHz were each similarly effective in predicting speech performance. For a rising response, adequate predictions for speech performance required both tone thresholds and PTCs. The speech measure was a speech identification test from which an overall score was obtained for correct consonant recognition.

Of the audiometric and psychoacoustic variables measured by Lutman and Clark (1986)[3], threshold sensitivity at 2 kHz was the best predictor of, although only moderately related to, speech performance in noise of 23 hearing-impaired subjects ranging in age from 44 to 72. Subject age also showed some predictive value for speech performance. While frequency resolution and gap detection at 2 kHz were moderately related to speech performance via simple correlations, they lacked uniqueness as predictors of speech performance via multiple regression. The index of speech performance was the signal-to-noise ratio, determined adaptively, that yielded about 70% correct word identification.

Using a similar speech performance index Stelmachowitz et al. (1985)[4] measured recognition of monosyllabic words in noise and correlated the S/N ratio for 75% correct with impaired subjects' frequency selectivity, as indicated from psychoacoustic tuning curves. (These curves plot the levels, as a function of frequency, of narrow-band remote maskers that just mask a probe tone, of 2000 Hz in this study). Frequency selectivity values derived from the curves were found to predict the speech recognition level with correlations on the order of .65 in the broad-band noise and .70 in the low-pass noise; combining various selectivity parameters accounted for 68% and 54% of the variance, respectively.

Lamore et al. (1985)[5] tested 32 severely/profoundly hearing-impaired adolescents for audiometric and psychoacoustic performances, which were analyzed relative to the speech reception threshold (SRT) and maximum word discrimination scores in quiet. (SRT is the lowest speech level or speech-to-noise ratio at which the listener judges meaningful speech to be at least 50% correct.) Between the two speech measures, the SRT showed somewhat better relations to the auditory measures than did the word discrimination scores. Of course, the SRT showed the highest relations to pure tone threshold sensitivity (.83 to .92). At least moderate relations were seen between the SRT vs DL for frequency and for critical ratios measured with low and mid frequency tones (correlations were .57 to .76). These same auditory measures yielded the highest correlations to word discrimination scores in quiet. Measures of amplitude modulation for white noise and temporal integration generally manifested poor relations to the speech performances.

Dreschler and Plomp (1985)[6] related various audiometric and psychoacoustic variables to speech perception in quiet and in noise for 21 hearing-impaired subjects from 13 to 20 years of age. The measure of speech perception was the SRT for sentences (Plomp and Mimpen, 1979)[7]. Speech perception in quiet was best predicted by the amount of loss, as represented generally by the mean audiometric tone thresholds, and specifically by the 500-Hz threshold. In contrast, audiometric variables had little power for predicting speech perception in noise, which was best predicted by measures of gap detection and the critical ratio--believed to reflect indirectly the frequency resolution capabilities of the ear. These psychoacoustic measures accounted for about 70% of the variance among the subjects' hearing for speech in noise.

Preminger and Wiley (1985)[8] tested consonant recognition in quiet and PTCs for 3 pairs of two subjects each matched for audiograms showing either flat, low-, or high-frequency losses. Within either subject pair of low- or high-frequency losses, the subject with poorer consonant recognition manifested a more abnormal PTC in the frequency region where the loss was greatest. Hence, pure tone threshold sensitivity appeared to show less association with consonant recognition than did frequency resolution.

Dorman et al. (1985)[9] related identification for synthetic, burstless /ga/ in a /ba, da, ga/ continuum to 2 kHz tone thresholds and frequency selectivity of aged listeners who generally showed reduced perception for /ga/. The optimal tokens of /ga/ contained F2 starting frequencies near 2 kHz. While a moderate relation to /ga/ identification was found for 2 kHz tone thresholds, a lower relation occurred for the measure of 2 kHz frequency selectivity versus /ga/ identification.

With few exceptions (e.g., Dorman, 1985[9]; Preminger and Wiley, 1985[8]), a common element among these studies of psychoacoustic versus speech performance is the representation of speech recognition by a total performance score, which is then analyzed for its relation to psychoacoustic performance. Such global scores are gross measures of speech recognition and do not reveal the particular acoustic patterns in speech that may be imperceptible for a hearing-impaired listener. Among the temporal and spectral cues available for use in recognition of phonemes, the hearing-impaired listener may rely exclusively on one type of cue, because other cues are imperceptible. For example, in distinctions of final consonant voicing, some of our listeners seemed to depend primarily on the vowel duration cue since their reception was reduced for consonant constriction cues or spectral cues in the vowel offset (Revoile et al., 1982[10], 1985[11]). If a listener's speech perception is limited to use of only certain cues, such information would seem relevant to correlational analyses of speech and psychoacoustic performances.

Underlying the effort to relate psychoacoustic performance and speech recognition is the assumption that psychoacoustic discrimination for a particular type of stimulus is associated with a similar mode of auditory processing for speech recognition. Yet few attempts have been made to examine given auditory abilities in relation to the use of particular types of acoustic patterns involved in speech recognition. The speech/psychoacoustic relations may be more easily determined if speech recognition is measured according to each of several classes of cues that contribute to phoneme distinctions, for example, temporal cues, dynamic spectral cues, or static spectral cues. Relative to these classes, then psychoacoustic performances for analogous stimuli could be examined (as well as for the more traditional types of psychoacoustic stimuli used for this purpose). The psychoacoustic performances found to relate most highly with the speech measures may be those that used acoustic stimuli resembling the critical speech-cue patterns.

A study modeled after this approach would test consonant recognition according to articulatory features using stimuli altered to contain only one type of cue per feature category. Thus, recognition of a test consonant would depend only on the perceptibility for the listener of the single available cue per stimulus. The stimuli used to test psychoacoustic performance would be selected according to the dominant acoustical domain of the critical cue. For example, in a study of VOT use for voicing perception of initial stop consonants, a temporal measure of psychoacoustic performance would be indicated.

In our investigations of speech perception by the hearing impaired we have employed cue-degraded spoken stimuli to determine the cues used by hearing-impaired listeners for consonant recognition. Listeners are tested with different conditions of cue degraded nonsense syllables, among which the different redundant cues have been progressively eliminated. When a listener's performance declines significantly for a given condition of cue deletion, then it is apparent that the absent cue is important to perception.

The following text describes three experiments in which the relations were examined between psychoacoustic performance and consonant recognition, where both were measured by stimuli thought to require similar types of auditory processing.

VOWEL DURATION DISCRIMINATION VS USE FOR CONSONANT VOICING IDENTIFICATION

Some hearing-impaired listeners with severe/profound losses may rely predominantly on the vowel duration cue to distinguish voicing perception for word-final consonants (Revoile et al., 1982[10], 1985[11]). In an experiment on enhancement of the vowel duration cue (Revoile et al., 1986[12]), we used stimuli representing a range of vowel durations to test recognition of final fricative voicing for severely/profoundly hearing-impaired listeners (N=25).

Method. For each of the syllables /bæs/, /bæz/, /bæf/, /bæv/, ten different spoken utterances were selected from a larger pool of stimuli to vary systematically in vowel duration. The vowels of the /bæs/-/bæf/ utterances ranged from 214 to 298 ms, and of /bæz/-/bæv/, from 277 to 412 ms.

Identification of the utterances was tested via single-interval trials in which a listener chose a response from among the 4 syllables plus /bæ/, displayed on an answer box. No feedback of correct responses was given. Voicing perception was scored across all four fricatives (errors for place of articulation were ignored), yielding a percent correct score for each of two blocks of 40 utterances. These tests were administered at the end of the experiment on vowel duration cue enhancement.

The stimuli used to test vowel duration discrimination ranged from 200 to 475 ms, in steps averaging 10 ms. The stimuli were composed of iterations of a single pitch period that had been extracted from a typical test syllable. Duration discrimination thresholds were measured adaptively via 2A/3IFC trials in which listeners chose the longer stimulus relative to two identical reference stimuli of 197 ms, each. Correct-answer feedback followed each trial. About 42 trials were presented to reach threshold, which was taken as the smallest duration difference yielding 70% correct responses. About 5 threshold measurements of vowel duration discrimination were obtained per listener throughout the experiment.

All stimuli were presented to each listener's better ear at a comfortable level, established via an adaptive procedure at the beginning of each test session. A computer controlled all procedures. Stimulus events during trials were signalled to the listener by flashing lights on an answer box.

Results. Final fricative voicing perception for the listener group averaged 68% (S.D.=17.3) and ranged from 35% to 98% among the listeners. For discrimination of vowel duration, the listeners' mean jnd was 36 ms (S.D. = 24.5) relative to a 197-ms reference vowel. Among the listeners the jnds ranged from 17 to 89 ms, however about 3/4 of the group obtained jnds smaller than the mean.

A multiple regression analysis was carried out to examine the relations of various auditory measures, including vowel duration discrimination, to final fricative voicing perception. While the zero-order correlation (simple r) of vowel duration discrimination versus fricative voicing was modest (-.41) relative to the other variables analyzed, the third-order partial correlation (-.37) re vowel duration discrimination equaled that of the 250 Hz tone threshold, which showed the highest zero-order relation to the fricative voicing scores (-.87).

The similarity among listeners for discrimination of vowel duration may account for the barely moderate relation of this measure to final fricative voicing perception, for which a fairly continuous distribution of scores was found. This continuous distribution was partly due to the inclusion of some listeners who could use cues in the vowel onset to distinguish final consonant voicing, in the absence of the vowel duration cue.

It is possible that the relation between vowel duration discrimination and use of the vowel duration cue for final consonant voicing perception is too categorical to be well described by a regression model. That is, some criterion level of vowel duration discrimination may be necessary to support the use of the vowel duration cue. However, discrimination ability beyond that criterion level may be unrelated to cue use. Supporting this idea is our finding that 4 of the 5 listeners who performed at chance level [<55%] for voicing perception, were also those who showed the poorest vowel duration discrimination (jnd >57 ms) among the listeners overall.

TRANSITION DISCRIMINATION VERSUS USE FOR GLIDE MANNER PERCEPTION

For many persons with hearing impairments, the difficulties they encounter in speech recognition may be related to deficient reception for formant transitions in speech. There seems to be no research that has attempted to test a given group of subjects for their ability to discriminate transitions, as well as for their use of transitions for consonant perception. In this study we examined hearing-impaired listeners both for their use of transitions for consonant perception and for their discrimination of transitions that were generated to simulate those present in the spoken syllables containing the test consonants.

Method. Perception was assessed for the initial phonemes of the syllables /wæk, jæk, bæk, gæk, dæk, æk/. For each syllable, 6 different utterances (male talker) were tested. A block of 36 utterances was tested at least 5 times for each listener, according to the procedure described above for the study of vowel duration cue use.

The listeners were 21 impaired- and 6 normal-hearing students at Gallaudet. The mean .5, 1, 2 kHz threshold average was 84 dB HL for the impaired group, and ranged from 64 to 105 dB HL. All listening was done monaurally (better ear) with the stimuli presented at the listeners' comfortable levels. The normal-hearing listeners were presented the stimuli at 75 dB SPL.

Among the other measures obtained were discrimination thresholds for different continua of synthetic transitions that varied in either frequency extent or duration. The stimuli were two-formant signals (parallel resonance synthesis) designed to resemble the transition characteristics of the velar glide and stop consonants in the /jæk/ and /gæk/ syllables. Thresholds were assessed using 2A/3IFC trials, with subsequent feedback, in an adaptive procedure. In tests for discrimination of transition duration, the transition frequency extent was held constant; the duration threshold obtained corresponded to the just-longer duration of transition that could be discriminated relative to a reference stimulus with a stop-like duration of the transition. For discrimination of transition frequency extent, the threshold was the minimum transition frequency extent that could be discriminated relative to a steady state formant.

Results. Results are reported here for one measure each of transition duration discrimination and of transition frequency extent discrimination. For both transition frequency extent and transition duration discrimination, performance by the hearing-impaired group was poorer than that seen for the normal group. In the test for transition duration discrimination, the hearing-impaired group required a transition that was 123 ms in duration in order to distinguish the difference relative to the 70 ms reference stimulus. In comparison, the normal group could discriminate a shorter duration transition of about 100 ms relative to the 70 ms reference.

Transition frequency extent was discriminated relative to a steady state reference. The hearing-impaired group required an F1 transition of over 100 Hz to discriminate its presence relative to a steady state stimulus. The normal-hearing listeners discriminated an F1 transition of less than 50 Hz relative to the steady state.

Percent correct perception is reported only for the glides of each repetition of a block of utterances, per listener. Mean perception of glide manner (place errors ignored) for the hearing-impaired group averaged 73%, while mean phoneme perception was about 60%. (Note that the normal-hearing group perceived /wæk/ and /jæk/ syllables with 100% accuracy.)

The results for glide manner perception for the /jæk/ and /wæk/ syllables were analyzed relative to the discrimination results for transition duration and transition frequency extent. Pearson product moment correlations for /wæk/ versus discrimination of frequency extent and of transition duration, respectively, were -.27 and -.23, and for /jæk/, -.46 and -.59 ($p<.05$). The direction of the correlations was negative for each analysis indicating generally that the higher the glide manner score, the smaller the frequency extent or duration of transition that could be discriminated.

The size of the coefficients obtained between transition discrimination and /jæk/ perception, both greater than -.40, reveals that transition discrimination was moderately related to manner perception for the velar glides. In other words, the discrimination ability for the transition stimuli tended to indicate how well a listener would perceive manner perception for the velar glides. This suggests that the listeners' abilities to use transitions for velar glide manner perception appears somewhat related to their ability to discriminate glide-like synthetic transitions.

AMPLITUDE MODULATION VS INTERVOCALIC CONSONANT IDENTIFICATION

Finally, as an adjunct to several speech perception studies, we have obtained some data on the detection of amplitude modulation at very low rates by our hearing-impaired listeners, an interest stimulated in part by the work of Festen and Plomp (1983)[13]. Within the context of a continuous utterance, relatively rapid spectral and temporal variations must presumably be processed to support consonant perception. For instance, static spectral shape cues to stop consonant identity (Blumstein and Stevens, 1979)[14] which are usually present for initial consonants in CV or CVC syllables spoken in isolation, can be absent or less salient for intervocalic stops in longer utterances. This places a greater burden on the listener to process transition and/or spectral change cues to consonant identity. Thus, the rationale for these studies was the possibility that a measure like the amplitude modulation threshold, because it involves processing amplitude variations in time, might be more representative of a listener's ability to perceive intervocalic consonants than more static sensitivity measures.

While prior work has used modulated broadband noise (e.g., Bacon and Viemeister, 1985[15]; Formby, 1985[16]; Lamore, et al., 1985[5]), we have used AM tones, sometimes in a tone complex, and have concentrated on modulation rates between 4 and 12 Hz. These very low rates are of interest both because they fall within the area of maximal sensitivity to sinusoidal amplitude modulation, and because they correspond to the region of temporal variation most associated with dynamic speech events (Plomp, 1984[17]). Four Hertz is a typical syllable rate for conversational speech; a rate of twelve Hertz falls in the range of more rapid fluctuations that may be associated with the detection of formant transitions. That is, the rapid rise and fall of amplitude within a single auditory "channel" as a formant passes across that channel is similar in wavelength to a 12-Hz modulation rate.

Method. These data were obtained from 9 listeners who, with other subjects, were involved in a study of speech enhancement that required identification of stop consonants in LPC vocoded speech. The speech stimuli were three-syllable nonsense utterances of the form /əCVlə/ and /əlVCə/ in which V = (/i/, /a/, /u/), and C = (/p/, /t/, /k/, /b/, /d/, /g/). The tokens, originally produced by a male talker, were analyzed and then resynthesized with an LPC vocoder program. They were identified in separate listening tests for the voiced and voiceless stops. In addition to the standard identification tasks, the listeners' modulation thresholds were measured for detecting several AM stimuli. Four AM conditions were used, all with a carrier frequency of 1024 Hz. For three conditions, the carrier was modulated at a rate of 4 Hz, and for the fourth condition the modulation rate was 12 Hz. Two of the 4-Hz modulated tones were modulated sinusoidally, but differed in duration (500 ms versus 1000 ms). For the third 4-Hz modulation condition, the carrier was modulated by a square wave. In the following, these conditions are labeled SN4 (4-Hz sinusoidal modulation), SQ4 (4-Hz square wave modulation), SN4X (4-Hz sine modulation extended in duration from 500 to 1000 ms), and SN12 (12-Hz sinusoidal modulation).

The procedure was a 3-interval task, similar to those described above, in which depth of modulation was varied adaptively in discrete logarithmic steps to locate the listener's threshold for detecting the presence of modulation.

Results. Table I presents the thresholds obtained from each listener for the various stimulus conditions, three-frequency pure tone threshold averages (PTA), and average percent correct stop consonant identification (ID) scores for consonants in either stressed syllable Initial, or Final position, and Combined.

The modulation thresholds varied over a range of about 25 dB and were generally well correlated with both the pure tone thresholds and with the identification scores. For example, the correlation between PTA and SN4X was -.636 while the correlation between PTA and combined ID score was .572. The measure most strongly related to consonant ID score (r=.840) for these 9 listeners was their threshold for detecting 4-Hz sinusoidal modulation in the extended-duration AM stimulus (SN4X). Under regression analysis, the relationship between SN4X threshold and Combined identification score was significant [$F(1,7)$ = 16.81; p=.0046]. Once this variable was included in the regression equation, no other variable produced a significant improvement in the prediction.

These results suggest a moderately strong relationship between AM detection thresholds and intervocalic consonant identification, however, they must be considered with caution. First, it is clear from the regression analysis that variance associated with AM threshold is not independent of that associated with the three frequency averages. Secondly, the correlations here benefit from the small number of listeners and relatively wide range of hearing loss they exhibit: had our population of listeners been less diverse, or our population of sentences more diverse, weaker correlations would likely have obtained. Finally, it is worth mentioning that the LPC vocoding process used in this experiment may be thought of as adding noise to the speech. Consequently, the identification measure here is actually similar to a speech-in-noise test.

SUMMARY

Prediction of speech recognition abilities on the basis of auditory discrimination capacities should be tested using stimuli that represent the speech features which are cued by the particular acoustic differentials of the psychoacoustic discrimination tests. The potential application of this approach was tested in three studies using psychoacoustic measures of 1) duration discrimination, 2) rate of formant transition, and 3) detection of amplitude modulation to be correlated with recognition, respectively, of stop voicing, glide consonants, and intervocalic stops. The results yielded generally modest correlations suggesting that much additional research is required prior to the successful development of a predictive relational model between psychoacoustic characteristics of impaired hearing and phoneme perception.

Table I. Three-frequency (.5, 1.0, 2.0 kHz) Pure Tone Averages (PTA), Modulation Detection Thresholds (dB re 100 percent modulation), and percent correct consonant identification scores in syllable Initial position, syllable Final position, and Combined. See text for modulation conditions.

Subject	PTA	SN12	SN4	SQ4	SN4X	Initial	Final	Combined
BT	72	-28.0	-16.9	-39.9	-22.1	43.68	39.17	41.42
BK	65	-25.3	-23.8	-29.0	-27.8	50.99	62.63	56.81
CD	70	-41.1	-28.1	-33.2	-34.0	78.56	73.05	75.81
HJ	60	-28.4	-25.7	-28.6	-29.4	63.52	74.13	68.82
HK	57	-25.6	-20.4	-34.3	-24.8	72.43	65.63	69.03
HE	60	-28.3	-24.5	-29.6	-25.7	45.08	35.01	40.05
MM	75	-16.2	-12.7	-23.8	-15.4	36.06	34.82	35.44
PC	43	-32.7	-22.1	-32.8	-32.9	73.04	69.55	71.30
RD	76	-20.8	-16.9	-19.6	-18.8	45.78	43.89	44.80
Mean	64.2	-27.4	-21.2	-30.1	-25.7	56.57	55.32	55.95
S.D.	10.5	7.0	5.0	6.0	6.2	15.50	16.79	15.72

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