Stimulus factors influencing the identification of voiced stop consonants by normal-hearing and hearing-impaired adults

Julie Mapes Lindholm  
Department of Psychology, Arizona State University, Tempe, Arizona 85287

Michael Dorman and Bonnie Ellen Taylor  
Department of Speech and Hearing Science, Arizona State University, Tempe, Arizona 85287

Maureen T. Hannley  
Audiology Clinic, Stanford University Medical Center, Palo Alto, California 94305

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The effects of mild-to-moderate hearing impairment on the perceptual importance of three acoustic correlates of stop consonant place of articulation were examined. Normal-hearing and hearing-impaired adults identified a stimulus set comprising all possible combinations of the levels of three factors: formant transition type (three levels), spectral tilt type (three levels), and abruptness of frequency change (two levels). The levels of these factors correspond to those appropriate for /b/, /d/, and /g/ in the /ae/ environment. Normal-hearing subjects responded primarily in accord with the place of articulation specified by the formant transitions. Hearing-impaired subjects showed less-than-normal reliance on formant transitions and greater-than-normal reliance on spectral tilt and abruptness of frequency change. These results suggest that hearing impairment affects the perceptual importance of cues to stop consonant identity, increasing the importance of information provided by both temporal characteristics and gross spectral shape and decreasing the importance of information provided by the formant transitions.

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INTRODUCTION

Our aim in conducting this research was to assess the effects of spectral tilt at signal onset, abruptness of frequency change following onset, and formant transitions on the identification of voiced stop consonants by normal-hearing and hearing-impaired listeners. The rationale for studying these three stimulus attributes is that they are a set of the distributed (in time) acoustic consequences of stop consonant production and, as such, are potential cues to place of articulation. The rationale for comparing normal-hearing and hearing-impaired listeners is that poor frequency resolution, poor temporal resolution, and spectral amplitude distortion commonly coexist with cochlear hearing impairment and may alter the perceptual importance of one or more of the potential cues to stop identity.

A. Cues for place of articulation

As noted above, formant transitions (e.g., Fant, 1973), spectral tilt at signal onset (Blumstein and Stevens, 1979), and abruptness of frequency change following onset (Kewley-Port, 1983) vary systematically with place of articulation. Moreover, each of these attributes can be shown to have an effect on stop consonant identification. The influence of formant frequency information on identification has been known for more than 30 years (e.g., Liberman et al., 1954), whereas that of spectral tilt at signal onset (Blumstein et al., 1982) or, alternatively, of the change in the distribution of spectral energy from burst onset to voicing onset (Lahiri et al., 1984) has been demonstrated more recently.
place of articulation. For one set, they adjusted the spectral shape of the burst; for the other set, they adjusted the spectral shape at the onset of voicing.

Despite the differences between the types of stimuli used, both Blumstein et al. (1982) and Walley and Carrell (1983) found that formant frequency information was the primary determinant of identification responses. In contrast, Lahiri et al. (1984) found that subjects responded in accord with the relative change in the distribution of spectral energy. Lahiri et al. suggested that an explanation for the discrepancy between their results and those of Blumstein et al. (1982) and Walley and Carrell (1983) "lies in the fact that, in both [of the former] studies, it was only the spectral tilt at onset that was manipulated, not the distribution of spectral energy at onset relative to what followed" (Lahiri et al., 1984, p. 402). The Walley and Carrell (1983) stimuli were, however, characterized by a dynamic change in spectral shape over time, albeit the initial shape was maintained longer (25 ms as opposed to 15 ms) than in the Lahiri et al. stimuli, and the change over time was gradual (25 ms) rather than abrupt. An alternative explanation lies in the apparently impoverished information regarding stop identity in the Lahiri et al. stimuli. Forty percent of their listeners were unable to reliably ( > 70% correct for each stop for three of the five vowels) identify the prototypical stimuli. The authors suggest that this difficulty may have been due to the relatively small formant-frequency excursions that characterized their stimuli. Although they indicate that this "flatness" was particularly characteristic of their labial stimuli, the degree that it characterized both stops, the stimuli within a given vowel environment must have also had relatively similar formant starting frequencies. In this regard, Lahiri et al. found that identification of /da/, the syllable with the largest transitions (and presumably with the most distinctive starting frequencies), was not affected by their spectral shape manipulations. Taken together, then, these three studies suggest that, when not impoverished, formant information is the primary determinant of stop identification.

B. Distortions in auditory processing caused by cochlear damage

Hearing-impaired listeners commonly show poor frequency resolution (e.g., Pick et al., 1977; Wightman et al. 1977). One consequence is that spectral peaks above F1 appear to be poorly defined in the internal representation of speech (Bacon and Brandt, 1982; Leek et al., 1987; Sidwell and Summerfield, 1985). It is not surprising then to find that some hearing-impaired listeners experience difficulty identifying stop consonants when the cues to place of articulation are limited to the onset frequencies and transitions of F2 and F3 (Dorman et al., 1985b; Turek et al., 1980; Summerfield et al., 1985). If the large effect of spectral tilt in the Lahiri et al. study was due to reduced formant information, then we might expect that hearing-impaired listeners, for whom formant representations may be poor, would be influenced more than normal-hearing listeners by spectral tilt. On the other hand, for hearing-impaired listeners whose sensitivity loss varies with frequency, tilt information is presumably distorted, with the nature of the distortion a function of signal level. From this perspective, we might expect that tilt would not be a useful cue for hearing-impaired listeners.

When there are multiple acoustic cues to phonetic identity, neutralization of the primary cue(s) allows other cues to influence categorization (e.g., Lisker, 1978). Therefore, in the context of the present experiment, the impoverished formant information available to hearing-impaired listeners could result in abruptness of frequency change (as well as spectral tilt) affecting the identification responses of these listeners more than it affects the identification responses of normal-hearing listeners. Although hearing-impaired listeners may evidence poorer-than-normal temporal resolution (Buus and Florentine, 1985; Tyler et al., 1982), this deficiency appears to have little effect on the use of temporal cues to phonetic identity. The performance of individuals with mild-to-moderately severe sensitivity losses is generally not impaired on identification tasks in which phonetic contrasts are based on voice onset time, vowel duration, fricative noise duration, or silent interval duration (Dorman et al., 1985b; Revoile et al., 1982; Johnson et al., 1984; Parady et al., 1981).

I. METHODS

A. Subjects

Two groups of adults, normal-hearing and hearing-impaired, participated in this experiment. The 20 subjects in the normal-hearing group ranged in age from 19 to 40 years, with a mean age of 23 years. Normal hearing was defined by pure-tone thresholds of less than 20 dB HL at octave frequencies between 0.25 and 4 kHz as well as normal findings on tests of immittance and acoustic-reflex thresholds. All of the 24 hearing-impaired subjects were clients of the Audiology Service at Arizona State University. The selection criterion was a 1-kHz threshold of at least 20 dB HL and a 4-kHz threshold of no worse than 70 dB HL, with normal findings on tests of immittance and acoustic-reflex thresholds. (One of the subjects had a 90-dB threshold at 4 kHz.) Speech audiometry results were consistent with peripheral auditory impairment. All subjects experienced post-lingual onset of hearing loss and all had normal speech and language development. Six of the hearing-impaired subjects were excluded from the data analyses because they labeled most (> 95% for at least one presentation level) of the stimuli with a single response. Of these six, five were over the age of 60 years. The remaining 18 subjects ranged in age from 23 to 73 years, with a mean age of 56 years. The unaided pure-tone thresholds for this group are shown in Fig. 1.

B. Stimuli

We used the Kewley-Port modification of the all-parallel branch of the Klatt (1980) software speech synthesizer to generate a set of 18 CV syllables. This branch of the synthesizer allows control over the relative amplitudes of the formants. The sampling rate of the synthesizer was 10 kHz, and control parameters were updated every 5 ms.

The stimuli were synthesized on a PDP 11/23, output through a 12-bit D/A converter at 10 kHz, and low-pass...
stimuli with nonabrupt frequency change were created by declaration always differed from those of the first frame. The set, the parameter values of the second 5-ms frame of the /dae/, and 1990 and 2230 Hz for /gae/. Formant amplitudes able.
acterize the onset spectra varied with the abruptness vari-
duration of the long steady state was somewhat arbitrary. We wanted to use a duration appropriate for velar stops without obviously distorting labial and alveolar stops. It appeared to us that steady states longer than 20 ms created such distortion.

Initial spectral tilt parameters were held constant for 15 ms for signals with abrupt frequency change and for 30 ms for signals with nonabrupt frequency change. For both signal types, the tilt changed to values appropriate for the following vowel over 30 ms. Total signal duration was 250 ms for stimuli with the abrupt frequency change following onset and 265 ms for stimuli with the nonabrupt frequency change.

Signals with conflicting transitions and tilts were created by adjusting the formant amplitudes of the given transition type to correspond to the formant amplitudes of the prototypical stimulus with the desired tilt. This required few arbitrary decisions for b and d tilts. For g tilts, however, there was a question as to how to create the midfrequency peak. We chose to elevate F2. This resulted in a not unreasonable peak location for stimuli with d transitions. For stimuli with b transitions, however, the frequency of the peak was much lower than that in the prototype (although still in the frequency range of possible peaks for a velar stop). Elevation of F3 would have resulted in a peak location more similar to that of the prototype.

The onset spectra for the nine combinations of formant transitions and spectral tilt types are shown in Fig. 2. The spectra were obtained from linear prediction analyses, without preemphasis, using a 25.6-ms Hamming window centered at signal onset.

C. Procedure

Subjects were tested individually in an IAC booth. Hearing-impaired listeners, who used hearing aids, were tested without the aids.

The signals were reproduced on a Nakamichi 550 tape deck, routed through a Madsen OB 803 audiometer, and delivered via TDH 49 headphones mounted in MX41/AR cushions. The signals were presented monaurally at two levels: 82 and 92 dB SPL. Each level was associated with one of the test lists. The order of presentation of the two levels was counterbalanced within each group.

The subjects read a set of written instructions at the beginning of the experimental session. Prior to each test list, they listened to a practice list consisting of five repetitions of the tokens of /bae/, /dae/, and /gae/, whose parameter values corresponded most closely to those of natural speech. The identities of the practice items were indicated on the answer sheet. For the test sequences, the subjects were instructed to respond by writing "b," "d," or "g" to all stimuli.

II. RESULTS

We determined the confusion matrix for each subject for each presentation level. These data, averaged over presentation levels and subjects within a group, are shown in Table I.

![Graph](FIG. 1. Means and standard deviations (shown by brackets) of pure-tone thresholds for hearing-impaired listeners.)

filtered at 4.97 kHz. Two randomized test lists, each of which contained ten tokens of each stimulus, were recorded on audiotape.

The parameter values for the stimuli were derived from analysis of typical tokens of /be/, /de/, and /ge/, as spoken by the second author. The 18 stimuli represented all possible combinations of the levels of three stimulus factors: formant transition type (three levels; appropriate for /b/, /d/, and /g/), spectral tilt (three levels; appropriate for /b/, /d/, and /g/), and abruptness of frequency change following onset [two levels; abrupt (5 ms; appropriate for /b/ and /d/) and nonabrupt (20 ms; appropriate for /g/)].

We constructed the stimuli without noise-excited bursts. The following parameter values were used for all tokens: F1 started at 220 Hz and reached a steady state of 620 Hz; F2 steady state was 1550 Hz; F3 steady state was 2430 Hz; F4 was 3300 Hz; F5 was 4500 Hz; F1, F2, and F3 transition durations were 20, 30, and 40 ms, respectively; formant bandwidths were 90 Hz; signal amplitude rose 10 dB over the initial 30 ms of the formant transitions and fell 20 dB over the final 100 ms of the utterance; and the fundamental frequency increased from 105 to 120 Hz over the initial 30 ms of the formant transitions and decreased from 120 to 100 Hz over the final 150 ms of the utterance.

The starting frequencies for F2 and F3, respectively, were 1100 and 2150 Hz for /be/, 1550 and 2650 Hz for /de/, and 1990 and 2230 Hz for /ge/. Formant amplitudes during the onset and transition periods depended upon the desired spectral tilt, and the number of frames used to characterize the onset spectra varied with the abruptness variable.

For stimuli with abrupt frequency change following onset, the parameter values of the second 5-ms frame of the declaration always differed from those of the first frame. The stimuli with nonabrupt frequency change were created by holding the stimulus parameters constant for the first four frames, creating a "steady state" of 20 ms. The decision as to the duration of the long steady state was somewhat arbitrary. It appeared to us that steady states longer than 20 ms created such distortion.

Initial spectral tilt parameters were held constant for 15 ms for signals with abrupt frequency change and for 30 ms for signals with nonabrupt frequency change. For both signal types, the tilt changed to values appropriate for the following vowel over 30 ms. Total signal duration was 250 ms for stimuli with the abrupt frequency change following onset and 265 ms for stimuli with the nonabrupt frequency change.

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II. RESULTS

We determined the confusion matrix for each subject for each presentation level. These data, averaged over presentation levels and subjects within a group, are shown in Table I.
Inspection of this table reveals that the normal-hearing listeners tended to respond to a given stimulus in a highly consistent manner, in accord with formant frequency type. All of the confusion-matrix cell values for the normal-hearing listeners were greater than 70% or less than 20%. In contrast, the hearing-impaired listeners, as a group, were both less consistent in their identification responses (with over half of the cells showing values between 20% and 70%) and,

TABLE I. Mean stop identification over two presentation levels as a function of stimulus factors and hearing status.

<table>
<thead>
<tr>
<th>Hearing status</th>
<th>Response</th>
<th>Impaired</th>
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<tr>
<td>Normal</td>
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<tr>
<td>Transitions</td>
<td>Tilt</td>
<td>Abruptness</td>
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apparently, more influenced by spectral tilt and abruptness of frequency change. Inspection of the individual data revealed that some hearing-impaired listeners were highly consistent in their labeling of most of the stimuli, whereas others responded inconsistently to the majority of stimuli. Moreover, some of these subjects responded primarily in accord with the place of articulation specified by one of the stimuli attributes, whereas the identification responses of other subjects were determined by specific combinations of stimulus attributes. Finally, the response patterns of some of the hearing-impaired subjects varied appreciably with presentation level.

For purposes of analysis, we treated formant transitions as the primary cue to stop consonant identity; that is, the type of formant transition defined the "correct" response to each stimulus, while abruptness of frequency change following onset and spectral tilt were treated as variables that could affect the probability that a correct response was given. We conducted a 1 between X 4 within analysis of variance with hearing status as the between-subjects variable and formant type, spectral tilt, abruptness of frequency change, and presentation level as the within-subjects variables. The dependent variable was the percentage of "b" responses for b-type formants, "d" responses for d-type formants, and "g" responses for g-type formants.

The mean performance of the hearing-impaired group (59.1%) was significantly lower than the mean performance of the normal-hearing group (84.4%), F(1,36) = 40.47, p < 0.0001. Significant interactions involving hearing status indicated, however, that the magnitude of this performance decrement varied as a function of the stimulus variables.

The main effects of transition type and spectral tilt were both significant, F(2,72) = 17.97, p < 0.0001, and F(2,72) = 5.79, p < 0.005, respectively, as well as their interaction F(4,144) = 17.17, p < 0.0001, and the three-way interaction of group X transition type X spectral tilt, F(4,144) = 3.38, p < 0.02. As shown in Fig. 3, the forms of the transition X tilt effects were similar for the two groups, but the effect was larger for the hearing-impaired listeners than for the normal-hearing listeners. Identification accuracy for b-transition stimuli was highest when they had a b tilt and lowest when they had a d tilt, whereas identification accuracy for d-transition stimuli was highest when they had a d tilt and lowest when they had a g tilt. Performance on g identification, which was comparable for stimuli with d and g tilts, was relatively low for stimuli with a b tilt. Analyses of the simple effect of tilt for each transition by group indicated that (a) for the normal-hearing listeners, tilt had a significant effect on the identification accuracy of both d-transition and g-transition stimuli, F(2,38) = 14.27, p < 0.001, and F(2,38) = 3.70, p < 0.05, respectively, and (b) for hearing-impaired listeners, tilt had a significant effect on the identification of all three transition types: F(2,34) = 7.17, p < 0.01 for b; F(2,34) = 7.86, p < 0.01 for d; and F(2,34) = 7.21, p < 0.01 for g.

Although the main effect of abruptness of frequency change following onset was not significant, both the transition X abruptness and the transition X abruptness X group interactions were significant, F(2,72) = 10.65, p < 0.0001 and F(2,72) = 8.51, p < 0.001, respectively. The three-way interaction is shown in Fig. 4. Analyses of the simple effect of abruptness for each transition by group indicated that, for the normal-hearing listeners, only d-identification accuracy was affected by abruptness, with 9% lower accuracy for the nonabrupt stimuli, F(1,19) = 5.62, p < 0.05. The hearing-impaired listeners showed a comparable, albeit nonsignificant, F(1,17) = 2.97, p < 0.11, mean difference (11%) in d-identification accuracy for the two levels of abruptness. In addition, for the hearing-impaired listeners, b identification was poorer, F(1,17) = 8.09, p < 0.02, and g identification was better, F(1,17) = 13.87, p < 0.01, for the nonabrupt than for the abrupt stimuli.

Neither the main effect of presentation level nor the level X group effect was significant. However, the interactions of level and tilt, F(2,72) = 4.71, p < 0.02, level, formant, and tilt, F(4,144) = 4.01, p < 0.01, and level, formant, tilt, and group, F(4,144) = 3.08, p < 0.02, were all significant. The forms of these interactions were complex and not readily interpretable. The largest effect of presentation level (a 17% difference in favor of the lower level) was shown by the hearing-impaired listeners for d-formant stimuli with a d tilt. At the higher presentation level, the hearing-impaired group tended to misidentify these stimuli as "b." Finally, although small and irregular, the abruptness X tilt X group, F(2,72) = 4.63, p < 0.02, and the abruptness X transition

Fig. 3. Identification accuracy as a function of type of spectral tilt, type of formant transition, and group.

Fig. 4. Identification accuracy as a function of abruptness of frequency change following onset, type of formant transition, and group.
The hearing-impaired listeners in this study were older than the normal-hearing listeners, and some of the differences in performance that have been attributed to hearing impairment may have resulted from age-related differences in speech processing (e.g., Hayes and Jerger, 1979). As a partial test of the importance of age, the data for the hearing-impaired listeners were reanalyzed with age \(< 60\) years \((n = 10)\) vs \(> 60\) years \((n = 8)\) as a grouping variable. None of the effects involving age was significant in these analyses.

In a recent study of stop consonant recognition, Dubno et al. (1987) categorized their hearing-impaired listeners with respect to audiometric configuration: flat, gradually sloping, and steeply sloping. They found that accuracy was lower for the steeply sloping group than for the other two hearing-impaired groups. In order to determine whether some of the within-group variability in our experiment could be accounted for by the steepness of hearing loss, we analyzed the data for the hearing-impaired listeners with audiometric configuration \((\text{steep} \quad (n = 7)\) and not steep \((n = 11)\) as a grouping variable. The effects involving configuration were all nonsignificant in this analysis.

### III. DISCUSSION

The results indicate that hearing status affects the relative perceptual importance of cues to stop consonant identification. In accord with previous results reported by Blumstein et al. (1982) and Walley and Carrell (1983), formant information was the dominant factor in determining the identification responses of normal-hearing listeners. Although spectral tilt at signal onset had a significant effect on identification performance, the effect was small. Similarly, abruptness of frequency change following onset had little effect on the identification responses of normal-hearing listeners: Only \(d\)-formant identification was affected, with slightly higher performance for the abrupt frequency change.

The tilt effects for the hearing-impaired listeners were larger than those for the normal-hearing listeners. As shown in Fig. 3, however, the transition \(\times\) tilt interactions for the two groups differed little in form, suggesting that the effect of tilt on hearing-impaired listeners differs quantitatively but not qualitatively from the effect of tilt on normal-hearing listeners. There was no evidence that the tilt manipulation functioned merely to change the audibility of certain parts of the spectrum. Were this the case, identification accuracy for all of the formant types would presumably have increased with the rising \(d\) tilt.

Abruptness of frequency change, like tilt, had a greater effect on the identification performance of hearing-impaired listeners than on the identification performance of normal-hearing listeners, although in this case the form of the interaction varied with hearing status. For normal-hearing listeners, the abruptness effect was limited to \(d\)-formant stimuli. In contrast, for hearing-impaired listeners, abruptness affected the identification accuracy of all three formant types. A long, spectral steady-state onset increased the number of \(g\) responses to stimuli with \(b\) and \(d\) transitions and was necessary to elicit a large number of \(g\) responses to stimuli with \(g\) transitions. The latter effect is consistent with the poor identification of \(/g/\) by hearing-impaired listeners in our previous experiments, for which stops were synthesized without a long spectral steady state following signal onset (see Dorman et al., 1985a; Hannley and Dorman, 1983; Turek et al., 1980).

We suppose that the diminished influence of formant information on the identification responses of hearing-impaired listeners was due to the effects of poor frequency resolution and poor temporal resolution, acting independently or in concert. As we noted earlier, poor frequency resolution may alter formant information by reducing the auditory definition of spectral peaks associated with \(F2\) and \(F3\). In addition, poor temporal resolution may alter formant information by blurring the auditory representation of the distribution of spectral energy over time (Summerfield et al., 1985). The greater-than-normal influence of tilt and abruptness may have been a consequence of the diminished effect of formant information. As we noted in the Introduction, when there are multiple potential cues for phonetic categorization, and the primary cue is made ambiguous or is insufficient to support phonetic categorization, then secondary cues may determine phonetic categorization.

In natural speech, information about spectral tilt and abruptness of frequency change is carried by portions of the signal that are of relatively low amplitude. Even low levels of noise could mask this information. To the degree that hearing-impaired listeners rely disproportionately on these cues, they would need a better signal-to-noise ratio than that needed by normal-hearing listeners to achieve a given level of performance (e.g., Dirks et al., 1982). Finally, if spectral tilt and abruptness of frequency change are particularly important for hearing-impaired listeners, then prosthetic devices should process signal onsets with very high fidelity.

### ACKNOWLEDGMENTS

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1 We chose to construct the stimuli without noise excited bursts because \(/b/\) stimuli with a nonabrupt onset of 20-ms duration, if constructed with a noise excited burst, would have sounded voiceless. It is important to note, however, that the spectral peaks of the voiced onsets were similar in amplitude to those of a noise excited burst.

2 The 92-dB SPL level was chosen so that both low- and high-frequency components of the signals would be suprathreshold for the hearing-impaired listeners. The 82-dB level was chosen because in other research we had found, for some hearing-impaired listeners, better identification of synthetic stops at SPLs lower than 90 dB SPL (Dorman et al., 1985a).

3 Preliminary analyses, by hearing status group, indicated that the order in which the two presentation levels were administered did not have a significant effect upon performance. Therefore, this factor was not included in the main analyses.
