Auditory Evoked Potential Correlates of Speech Sound Discrimination

Michael F. Dorman
Haskins Laboratories, New Haven

Numerous studies have indicated that the sounds of speech enjoy a special mode of perception, distinct from that of nonspeech signals (Liberman, 1970; Liberman, Cooper, Shankweiler, and Studdert-Kennedy, 1967). One set of investigations supporting this view has examined the relationship between identification and discrimination of speech and nonspeech signals. Listeners can discriminate many more nonspeech stimuli than they can identify absolutely (Miller, 1956; Pollack, 1952). However, certain speech sounds, the stop consonants [b,d,g,p,t,k], tend to be discriminated no better than they can be identified (Pisoni, 1971; Studdert-Kennedy, Liberman, Harris, and Cooper, 1970). This unique relationship between identification and discrimination is termed "categorical perception."

In a typical experiment, Lisker and Abramson (1970) presented to Ss for identification and discrimination a series of computer-synthesized stop consonants which differed solely along the physical continuum of voice onset time (VOT). Listeners identified these stimuli exclusively as members of the phonetic category [ba] or [pa]. Ss discriminated almost perfectly between stimuli which were assigned to different phonetic categories. However, when physically different stimuli were drawn from the same phonetic category, discrimination was only slightly better than chance. Thus, equal acoustic differences (for example, 20 msec) along the VOT were not equally discriminable. Only when

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+Currently Herbert Lehman College of the City University of New York.

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1VOT refers to the relative timing of the release of supraglottal closure and the onset of laryngeal pulsation or "voicing." Abramson and Lisker (1970) have argued that the acoustic features of explosion energy, amount of aspiration, and first-formant intensity may all be derived from the single articulatory variable of VOT. In sound spectrograms VOT is reflected by the onset of the first formant relative to the second and third formants and, for stop consonants with a delayed onset of the first formant, the presence of aspiration in the upper formants in the period preceding the onset of voicing.
stimuli were drawn from different phonetic categories could listeners discriminate accurately between physically different stimuli.

In contrast to the categorical perception of the stop consonants, nonspeech signals and steady-state vowels are perceived "continuously." Signals drawn from the same nonspeech or vowel category are discriminated equally well or poorly as signals drawn from different categories (Mattingly, Liberman, Syrdal, and Halwes, 1971).

The purpose of the present study was to determine whether components of the human cortical averaged auditory evoked response (AER) would reflect the categorical perception of different stop consonant signals or the equal physical differences between the different signals.

Very few studies have explored AERs to speech stimuli (Cohen, 1971; Greenberg and Graham, 1970; Wood, Goff, and Day, 1971). However, previous studies have indicated that when an auditory stimulus, a click or tone, is detected as different in a discrimination task, the amplitude of the N1-P2 component of the AER at the vertex is larger than it is in response to an undetected stimulus difference (Davis, 1964; Karlin, 1970; Sheatz and Chapman, 1969). If the vertex AER responds to the discrimination of speech stimuli in a manner similar to nonspeech, and if the detection of differences between speech stimuli is made task relevant, then the N1-P2 response to discriminally different stop consonant signals should be larger than the corresponding response to signals which are not discriminally different.

The use of the AER technique has another purpose which bears directly on the nature of categorical perception and its interpretation. It is possible that a listener may hear two physically distinct stimuli from within the same phonetic category as slightly different. However, because the listener knows that the two stimuli are both labeled the same in conventional speech and orthography, he may respond that the two stimuli are the same.

In the context of the present study, an estimate of the time necessary to code the acoustic signal into a categorized phonetic description can be made by assessing whether the N1-P2 component of the AER reflects continuous or categorical perception. If the N1-P2 component reflects a categorical response, i.e., a larger response to the stimuli from a different phonemic category than to the stimuli from the same phonemic category, then within 100-200 msec after stimulus onset the acoustic signal has been recoded into a phonetic representation. This would suggest that a categorized phonetic coding is an immediate and obligatory transformation of the acoustic signal.

**METHOD**

**Subjects.** Fifty undergraduate students at the University of Connecticut served as Ss. No S had previously participated in research involving synthetic speech or electroencephalographic (EEG) recording.

**Apparatus.** The Ss sat in a comfortable chair within a dimly lit, electrically shielded room and listened to tape-recorded stimuli presented via stereo headphones (Koss 600A). The sound level at the headphones was 65 db SPL.

Recording of the EEG was made from the scalp using a single silver-disk electrode located at the vertex (Jasper, 1958) which was referenced to the right
earlobe. Resistance between electrodes was always less than 5K Ohms.

The EEG signals were transmitted by telemetry (Narco FM-1100-E3) to an AC preamplifier (W-P Instruments DAM 6) and oscilloscope amplifier (Tektronic RM 502A) which also served to monitor the EEG. The frequency response of the system after amplification was flat, between 2.0 and 30 Hz. The amplified EEG was stored for later analysis using a Vetter FM Adapter (FM-3) and a Sony 355 tape deck.

The extraction of the evokedresponse from the EEG was carried out both on- and off-line by a computer of average transients (Fabri-Tek 1072). The sweep duration was one second. The averaging cycle of the computer was triggered by a pulse from the second channel of the stimulus presentation tape. The onsets of the cuing pulses and the synthetic speech stimuli were simultaneous. The AER records were written out on an X-Y plotter (Hewlett-Packard 7035b).

Stimuli. The three synthetic, stop consonant-vowel syllables used in this study are shown in Figure 1. These stimuli were generated on the Haskins Laboratories computer-controlled parallel-resonance synthesizer (Cooper and Mattingly, 1969).

The three stimuli differed solely along the VOT continuum: 0 msec VOT (0 VOT); 20 msec VOT (20 VOT); and 40 msec VOT (40 VOT). Stimulus duration was 250 msec. For stimulus 0 VOT, the onsets of the first (F1), second (F2), and third (F3) formants were simultaneous; for stimulus 20 VOT, F1 began 20 msec after F2 and F3; for stimulus 40 VOT, F1 began 40 msec after F2 and F3. Aspiration was added to the upper formant frequencies during the period of F1 delay for stimuli 20 and 40 VOT. Thus, each adjacent pair of stimuli along the VOT continuum differed by exactly 20 msec VOT (i.e., 20-0 VOT and 20-40 VOT). Previous identification studies have indicated that stimuli with 0 and 20 VOT are identified as members of the phonetic category [ba] and that stimulus 40 VOT is identified as a member of the phonetic category [pa] (Lisker and Abramson, 1970). Discrimination tests have indicated that the pair 20-40 VOT is discriminated essentially perfectly. The pair 20-0 VOT is discriminated just slightly better than chance (Abramson and Lisker, 1970). In the following account, stimulus 20 VOT will be termed the "standard" stimulus, stimulus 0 VOT the "within-category" shift stimulus, and stimulus 40 VOT the "across-category" shift stimulus.

Preparation of the stimulus tapes. With the aid of the computer-controlled synthesizer four stimulus sequences were recorded on audio tape. Two of the stimulus sequences were composed of varying length runs of standard stimuli (20 VOT), separated by pairs of either within- or across-category shift stimuli. There were a total of 154 standard stimuli and sixteen pairs of shift stimuli in each sequence. The pairs of shift stimuli occurred on the average once every ten successive standard stimuli (range 6-14). In one sequence the pairs of

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2The three synthetic speech stimuli used in this study were slight modifications of the stimuli used by Lisker and Abramson (1970). Informal listening tests by the author and his colleagues indicated that the 20 VOT stimulus used in the present study was labeled more consistently as a [ba] than the 20 VOT stimulus used by Lisker and Abramson. These tests also indicated that the 20 VOT stimulus was discriminated less often from the 0 VOT stimulus than was the corresponding stimulus used by Lisker and Abramson.
Figure 1: Sound spectrograms of the speech stimuli 0 VOT [ba], 20 VOT [ba], and 40 VOT [pa].
shift stimuli were within-category stimuli; in the other, across-category stimuli. A third stimulus tape consisted of a single sequence of 186 standard stimuli.

The fourth stimulus sequence contained an alternating sequence of blocks of ten within-category stimuli and ten across-category stimuli separated by 30–sec interblock intervals. There were three blocks of each shift category. The interstimulus interval (onset to onset) for all sequences was 2 sec.

**Design.** The Ss were assigned to five groups (ten Ss per group). The groups were run successively. The experimental task for the Ss in Groups 1, 2, 3, and 4 was to detect the occurrence of shift stimuli embedded in the sequence of standard stimuli.

The Ss in Group 1 listened first to the within-category shift sequence (20–0 VOT), then, on the following day, to the across-category shift sequence (20–40 VOT). The Ss in Group 2 also listened to both sequences on successive days, but in the reverse order.

Group 3 was given twenty practice trials with both the standard and within-category stimuli before listening to the within-category shift sequence. Pretraining consisted of twenty presentations of a group of four stimuli; two standard stimuli followed by two within-category stimuli. The interval between the groups was 5 sec. The Ss were told the order of the different stimuli and were instructed to try to detect any difference between the sounds. The within-category shift sequence was begun immediately after pretraining. These Ss were given pretraining to determine whether increased familiarity with the "unfamiliar" nonphonemic distinction would improve performance.

In a no-shift condition (Group 4) the Ss listened to the tape which contained all standard stimuli. The purpose of this control was to establish a baseline from which to assess the effects of the different shift conditions. In the other control condition (Group 5) the Ss listened to the randomized sequence of blocks of within- and across-category stimuli (the fourth stimulus sequence). The purpose of this control was to determine the amplitude of the AER to the across- and within-category stimuli in a setting unrelated to the discrimination tasks and thus to assess the "inherent" amplitude of the AERs to the 0 and 40 VOT stimuli.

Groups 3, 4, and 5 were tested in a single session. The session duration was approximately 7 minutes.

**Analysis of the evoked potentials.** The amplitude differences between the N1 and P2 responses was determined from the X-Y plots by measuring the difference in millimeters between the maximum wave of negativity between 75 and 125 msec after stimulus onset (N1) and the maximum wave of positivity between 175 and 225 msec (P2).

Each AER was the sum of sixteen individual responses. Responses to the standard and shift stimuli were averaged separately in all conditions. A separate AER was accumulated for each member of the shift pairs. The AER to the last standard stimulus before the shift pair was designated as the AER to the standard stimulus. In the no-shift condition (Group 4) evoked responses were accumulated for the stimuli which occurred in the same positions as the standard and shift stimuli in the shift conditions. For the stimulus control condition (Group 5) separate evoked responses were accumulated for the within- and across-category stimuli by summing over blocks of trials.
Procedure. All Ss were instructed to remain as motionless as possible during the experiment and to fixate on a point in front of them. The Ss in Groups 1, 2, 3, and 4 were instructed to "listen for" the occurrence of "any change" from the standard stimuli. The Ss were not told which pair of shift stimuli would occur in a given test sequence. The Ss in Group 3, after practice with the within-category and standard stimuli, were told to "listen for" the same changes in the test sequence as they had listened to in the practice sessions. The Ss in Group 5 were told that they would hear separate blocks of [pa] and [ba] and were instructed simply to listen to the stimuli.

RESULTS

Amplitude of N1-P2. For each S, the amplitude scores for both shift stimuli were expressed as the ratio of the shift stimulus amplitude to the standard stimulus amplitude. A ratio score of 1.0 indicated that the amplitudes of the standard and shift stimuli were identical. A ratio score greater than 1.0 indicated a larger shift stimulus amplitude than standard stimulus amplitude. For the Ss in Group 1 (across shift then within shift) and Group 2 (within shift then across shift) separate ratio scores were computed for the within- and across-category shift conditions. The ratio scores for Groups 1-4 collapsed across Ss are shown in Table 1.

<table>
<thead>
<tr>
<th>Shift Category</th>
<th>Position in Shift Pair</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st</td>
</tr>
<tr>
<td>Group 1</td>
<td></td>
</tr>
<tr>
<td>Across</td>
<td>1.36</td>
</tr>
<tr>
<td>Within</td>
<td>0.92</td>
</tr>
<tr>
<td>Group 2</td>
<td></td>
</tr>
<tr>
<td>Within</td>
<td>0.95</td>
</tr>
<tr>
<td>Across</td>
<td>1.35</td>
</tr>
<tr>
<td>Group 3</td>
<td></td>
</tr>
<tr>
<td>Pretrained Within</td>
<td>0.92</td>
</tr>
<tr>
<td>Group 4</td>
<td></td>
</tr>
<tr>
<td>No Shift</td>
<td>0.95</td>
</tr>
</tbody>
</table>

For Groups 1 and 2, the effects of presentation order (within shift then across shift vs. across shift then within shift), shift type (within vs. across), and location in the shift pair (first vs. second) were compared in an analysis of variance. A reliable main effect due to shift type was obtained.
\[ F_{1,18} = 25.00, \ p < .01; X (\text{within shift}) = .91, X (\text{between shift}) = 1.45 \]. No other main effects were significant. A shift type x location interaction was also obtained \( F_{1,18} = 4.66, \ p < .05 \).

The difference in N1-P2 amplitude to the within- and across-category shifts is illustrated for a representative S in Figure 2. In the across-category shift, the amplitude of both members of the shift pair (BS1 and BS2) exceeded that of the standard stimulus (S). For the within-category shift, neither member of the shift pair was larger than the standard stimulus.

Since the analysis of variance showed no significant effect due to presentation order, the data for the within- and across-category shifts were pooled over Groups 1 and 2. Two additional analyses of variance were then computed with the pooled data.

The first analysis compared the pooled across-category shift condition from Groups 1 and 2 with Group 3 (pretrained within-category shift) and Group 4 (no shift). In the groups x location analysis of variance only the groups effect was significant \( F_{2,37} = 13.16, \ p < .01 \). Post hoc comparisons according to Scheffe revealed that the pooled across-category shift condition \( X = 1.46 \) differed from both the pretrained within-category condition \( X = .91 \) and the no-shift condition \( X = .92 \) at the .05 level. A second analysis of variance compared the pooled within-category shift condition from Groups 1 and 2 with Groups 3 and 4. The analysis of variance showed no reliable effects.

For Group 5, the absolute (N1-P2) amplitude difference of the AERs to the within-category stimulus (0 VOT) and to the across-category stimulus (40 VOT) were compared by a correlated t-test. The amplitudes of the two stimuli were not significantly different \( t_{9} = 1.01, \text{n.s.} \).

**DISCUSSION**

The comparison of the within- and across-category shift conditions demonstrated that the across-category shift (20-40 VOT) elicited a larger N1-P2 response than the within-category shift (20-0 VOT). The difference in N1-P2 amplitude in the two shift conditions cannot be attributed to an "inherently" larger N1-P2 response to the across-category stimulus (40 VOT) than to the within-category stimulus (0 VOT), since in the stimulus control condition (Group 5) the amplitude of the N1-P2 response to 0 VOT [ba] and to 40 VOT [pa] did not differ. This outcome suggests that the difference in N1-P2 amplitude in the within- and across-category shift conditions was due to the difference in discriminability of the two types of shift.

The comparison involving the within-category shift group and the no-shift control (Group 4) revealed that the N1-P2 response in the two conditions did not differ. Furthermore, pretraining with the within-category and standard stimuli (Group 3) did not alter the amplitude of the N1-P2 response in the within-category shift situation.

Thus, the behavior of the N1-P2 component of the AER, under the conditions of the present study, mirrored the relative discriminability of the stop consonant pairs.
Figure 2: Auditory evoked responses to the within- and across-category shifts for a representative S. The standard stimuli are labeled S. The within- and across-category shift pairs are labeled WS and AS respectively.
Auditory to phonetic recoding. The "categorical" response of the N1-P2 component of the AER suggests that within 100-200 msec after the onset of a stop consonant, the finely detailed acoustic stimulus has been recoded into a categorized phonetic representation. The data from the present study do not support the suggestion that a categorical response is generated at a "long" interval after stimulus onset as a function of an arbitrary labeling of two discriminably different stimuli as belonging to the same phonetic category.

This interpretation of the data bears directly on the nature of the processing of the highly encoded stop consonants. After a stop consonant has been recoded into a categorized phonetic representation, a listener knows very little about the detailed acoustic structure of the auditory signal (e.g., VOT). The processing mechanism for the stop consonants appears to act like a "digitizing" device, accepting as input a highly variable and finely detailed auditory signal and then rapidly recoding it into a quantized phonetic representation (Mattingly et al., 1971). After recoding, the detailed auditory information does not seem to be stored in any accessible form.

This interpretation of the data is supported by two recent studies exploring differences in the processing of stop consonants and steady-state vowels. Crowder (1971) using a serial recall task found that if the vowel portions of CV syllables were varied in a serial list, then a large recency effect was obtained during recall. If, however, the consonant portions of the syllables were varied in the lists, then no recency effect was obtained. If the recency effect is contingent upon an "echoic" or "precategorical" acoustic memory store of 2-3 sec duration, as Crowder and Morton (1969) have suggested, then the representation of a stop consonant does not persist 2-3 sec in "precategorical" auditory memory.

The life span of auditory memory for stop consonants has also been studied using recognition memory tasks. In one of a series of studies, Pisoni (1971) varied the interval (0, .25, .50, 1.0, 2.0 sec) between vowel pairs and stop consonant-vowel pairs in an A-X discrimination paradigm. The discrimination of vowel stimuli was markedly affected by the A-X interval, with longer intervals producing poorer discrimination. Stop consonant discrimination, however, was relatively unaffected by A-X interval. Pisoni concluded that "information other than a binding phonetic categorization is unavailable for use in discrimination [of stop consonants]." The results of the present study are in complete agreement with those of Pisoni (1971) and Crowder (1971) and further reinforce the notion of a special mode of processing for the stop consonants characterized by the absence of a persistent noncategorical auditory image.

REFERENCES


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