A "labial" feature analyzer in speech perception*

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A selective adaptation experiment was conducted to determine the ability of various adapting stimuli to alter the perception of a series of 13 synthetic speech syllables. The synthetic test syllables, which varied acoustically in the starting frequency and direction of second- and third-formant transitions, included stop consonant distinctions of *place of articulation* for the syllable types [bæ], [dæ], and [gæ]. A systematic adaptation effect was produced in the locus of the bæ-dæ phonetic boundary for these stimuli after repetitive listening to each of the following adapting syllables: [bæ], [p^hæ], [mæ], and [væ], indicating that perception of *place* distinctions among the stop consonants can be altered even by repetitive listening to certain speech sounds not belonging to the stop-consonant class.

Recent studies in the perception of speech suggest that man analyzes speech sounds into sets of distinctive features at some stage of the listening process. The evidence for this feature analysis is derived in part from investigations concerning the nature of perceptual confusions among phonemes (Miller & Nicely, 1955; Singh, 1966, 1970), subjective judgments of phoneme similarity (Greenberg & Jenkins, 1964), and errors and speed of phoneme recognition and discrimination under conditions of dichotic listening (Studdert-Kennedy & Shankweiler, 1970; Blumstein & Cooper, 1972; Cole & Scott, 1972; Blumstein¹).

The feature processing of speech sounds has also been studied recently using a selective adaptation procedure (Eimas & Corbit, 1973; Eimas, Cooper, & Corbit, 1973; Cooper, 1973). With this procedure, an attempt is made to systematically alter listeners' perception along a single feature dimension. Initial work with the technique has focused on two consonant feature dimensions—*voicing*, which in English serves to minimally distinguish voiced from voiceless stop consonants (i.e., [b] from [p]; [d] from [t]; [g] from [k]), and *place of articulation*, which serves to distinguish among the stop consonants [b], [d], [g] and [p], [t], [k].

To permit a quantitative assessment of perception along a single feature dimension, continua of synthetically produced speech syllables have been used as test stimuli in the selective adaptation experiments. These synthetic syllables consist of sets of stimuli

varying from one another in small steps to produce phonetic distinctions along a feature dimension.

In the studies concerning the feature *voicing* (Eimas & Corbit, 1973; Eimas et al, 1973), two series of synthetic test stimuli were used predominantly, each of these two series containing 14 syllables that varied acoustically in voice onset time (VOT). VOT is defined as the interval between the onset of the release burst of the stop consonant and the onset of voicing. This cue was employed because variations in VOT sufficiently distinguish voiced from voiceless stop consonants in word-initial position within many natural languages (cf. Lisker & Abramson, 1970). Each of the test series contained some consonant stimuli that were normally perceived as voiced, some normally perceived as voiceless, and some whose categorization as either voiced or voiceless was potentially ambiguous. A group of listeners were instructed to identify the synthetic syllables as either [ba] or [p^ha] (bilabial test series) or as either [da] or [t^ha] (alveolar test series) in both the unadapted state and after a period of repetitive listening to voiced or voiceless stop consonants that had been selected from the extreme ends of the two VOT series.

After repetitive listening to the voiced bilabial stop [b], a shift was produced in the locus of the phonetic boundary for a VOT series consisting of either bilabial ([ba]-[p^ha]) or alveolar ([da]-[t^ha]) stop consonants. The shift for each series was in the direction toward the voiced end of the VOT continuum, signifying that listeners assigned a greater percentage of their identification responses to the voiceless mode after adaptation. These results, as well as the results obtained in a test using a response measure of discrimination, indicated that a selective adaptation effect could indeed be produced along a single linguistic feature dimension. The results suggested, furthermore, that a major component of the adaptation effect was feature-specific

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in nature and not a function of adaptation of the consonant sound as a unit. It was reasoned that if the adaptation effect was being produced primarily at the level of the consonant as a whole, then repetitive listening to [ba], for example, would not have produced an adaptation effect along the [da]-[tʰa] synthetic test series.

The presence of such crossed-consonant shifts also indicated that the effect could not be readily accounted for by a simple response contrast interpretation. The contrast interpretation would attempt to explain the adaptation effect in terms of the Ss' response tendency to identify sounds as belonging to a category other than the category assigned to the adapting stimulus. The data suggested to the contrary that the adaptation effect reflects the fatiguing of a feature analyzing mechanism. More recent data reported by Sawusch and Pisoni (1973) add support to this interpretation.

In the study of *place of articulation* (Cooper, 1973), which served as a basis for the present investigation, the test stimuli were a series of 13 synthetic speech syllables varying acoustically in the starting frequency and direction of the second- and third-formant transitions. These acoustic variations were sufficient to produce distinctions among the syllable types [bæ], [dæ], and [gæ]. It was found that a selective adaptation effect could be produced for *place* in a manner analogous to *voicing*. Repetitive listening to the voiced bilabial stop [b], for example, produced a shift in the locus of the b-d phonetic boundary such that fewer identification responses were made to the [b] category after adaptation.

While the b-d phonetic boundary shifted in the direction toward the [b] category after adaptation with [bæ], the d-g phonetic boundary locus remained virtually fixed. This finding, corroborated in the same study using a discrimination response, provided new information about the nature of perceptual shifts produced by the selective adaptation technique. In the two-category response situation of the *voicing* identification tests (e.g., "b" or "p"), a decrease in the listeners' response to one category necessarily implied an increase in response to the other category. In the three-category response situation for *place*, this dependency relation of course did not hold. As a result, we were able to better evaluate the effects of adaptation on the shifting of the response distributions. It was found, for example, that after adaptation with [bæ], the decrease in the percentage of [b] responses was accompanied by an increase in the percentage of [d] responses, whereas the percentage of [g] responses remained stable. After adaptation with [gæ], a decrease in the percentage of [g] responses was accompanied by an increase in the percentage of [d] responses, whereas the percentage of [b] responses remained relatively fixed. Finally, after adaptation with [dæ], a decrease in the percentage of [d] responses was accompanied by increases in the percentages of both [b] and [g] responses.

These results provided support for an analyzing mechanism of *place* having a particular organizational structure. The analyzing mechanism was thought to decode *place* information along a single feature dimension of analysis, in terms of three separate analyzer modes. The three modes, which were presumed to detect the presence of bilabial, alveolar, and velar stop consonants, respectively, were arranged in a particular order: bilabial-alveolar-velar, with the adjacent modes, bilabial-alveolar and alveolar-velar, having partially overlapping ranges of sensitivity to *place* stimulus values. It was argued that the locus of a phonetic boundary corresponds to the *place* stimulus value to which two adjacent analyzer modes respond with equal strength. During selective adaptation, the analyzer mode most sensitive to the *place* value of the adapting stimulus is fatigued such that sensitivity across its entire response range is decreased. Consequently, certain stimuli formerly detected by the adapted mode are detected more readily by an adjacent analyzer mode, producing a shift in the locus of the phonetic boundary.

This system of analysis, which generally accounted for the obtained adaptation effects for *place*, was in contrast to a system that would decode *place* information in terms of two or more separate dimensions of analysis, each dimension having two analyzer modes. The latter type of system has as its theoretical basis the linguistic feature descriptions for *place* provided by Jakobson, Fant, and Halle (1963) and by Chomsky and Halle (1968). Because adaptation with the syllable [gæ], for example, did not produce a shift in the b-d phonetic boundary in a direction predicted by the two- or multidimensional systems, it was concluded that the unidimensional system provided a better explanation of the adaptation effects.²

Similar to the findings for the feature *voicing*, the results for *place* indicated that the adaptation effect was in part feature-specific. Support for this claim was derived from the finding that an adaptation effect was obtained along the bæ-dæ-gæ series after adaptation with the syllable [pʰæ] as well as with [bæ]. In addition, adaptation along the bæ-dæ-gæ dimension was obtained after repetitive listening to the syllable [bi], a syllable whose second- and third-formant transitions differed considerably in frequency from the transition values of the [bæ] members of the bæ-dæ-gæ test series. Real speech syllables were also found to be effective in altering the perception of the synthetic test syllables. These various results suggested that the adaptation effect taps feature analyzers which operate in a fairly complex fashion. These analyzers operate in one of three ways: by (a) extracting acoustic *pattern* information from the speech signal, the acoustic pattern for *place* probably being formant transitions having a certain direction and also a certain range of slope steepness (cf. Stevens, 1973); by (b) matching incoming *place* information to internalized motor commands (cf. Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967); or by (c) extracting abstract

phonetic information for which there exists no single invariant acoustic pattern. The possibility of further specifying the means by which these analyzers operate is currently being studied by Ades (1973) as well as by ourselves.

In addition to this issue, the present study was directed at obtaining further information about the organizational properties of the feature analyzing mechanism. We were especially interested in determining whether the adapting stimulus must belong to the class of stop consonants in order to produce perceptual shifts along the bæ-dæ-gæ test series. This question is of particular theoretical importance. In the prior experiments with the bæ-dæ-gæ series, it was shown that the adaptation effects could be obtained when both the adapting stimulus and test stimuli were stop consonants differing in the feature *voice* (i.e., [p^hæ] and [bæ]). In this study, we wanted to test whether adaptation effects could also be obtained when the adapting and test stimuli belonged to different *manner* categories (e.g., [mæ] and [bæ]). If perceptual shifts could be obtained under such conditions, it would appear that the effects operate on analyzers that extract *place* information for consonants irrespective of the particular *manner* class of consonant to which they belong. The failure to obtain perceptual shifts after such adaptation would, on the other hand, indicate that the adaptation effects operate on analyzers of a more restricted nature, which decode *place* for each of the major consonant classes individually.

To test this characteristic of the *place* feature analyzers, we selected five different real speech syllables as adapting stimuli. The five adapting syllables included [bæ], [p^hæ], [mæ], [væ], and [wæ]. All contain a labial initial segment and thus represent likely candidates as adaptors of the [bæ] members of the bæ-dæ-gæ test series.

Attention should be paid to the rationale for our choice of the adapting syllables [mæ], [væ], and [wæ], the three adapting syllables whose initial segments do not belong to the class of stop consonants. The phonetic segment [m], a voiced nasal consonant, is articulated like [b] except that the velum is lowered to permit airflow through the nasal passages. The location at which the airflow is obstructed for both [m] and [b] is at the lips. Because this closure of the lips accompanies the production of both consonants, their place of articulation is traditionally termed "bilabial." By using [m] as an adapting consonant, we could begin to assess whether the adaptation effect along the bæ-dæ-gæ series is restricted to the class of stop consonants or whether it is more general in scope, involving both stops and nasals.

The phonetic segment [v], a voiced fricative consonant, is distinguished from both [m] and [b] by virtue of the fact that at no point in the oral cavity does a complete obstruction of airflow exist. Rather, a partial obstruction of the airflow accompanies the production

of [v], this partial closure being made by the front upper teeth and the lower lip. The place of articulation for [v] is thus termed "labio-dental," distinguishing it from bilabial consonants such as [m] and [b]. In addition to providing a further test of the scope of the adaptation effects across different consonant classes, employing [v] as an adapting stimulus was of interest here because it allowed us to test whether a strict sharing of place of articulation by the adapting and test stimulus members is a necessary condition for obtaining the adaptation effects.

In linguistic feature descriptions of the phonetic structure of English, the three consonants [b], [m], and [v] share all feature values for place of articulation. In the feature system devised by Jakobson et al (1963), these three consonants share values for the two place features, *grave* and *compact*, all three being described as [+grave] and [-compact]. In the feature system proposed by Chomsky and Halle (1968), the same consonants share feature values for each of five *place* features, being marked as [+anterior], [-coronal], [-high], [-low], and [-back].

Although the classes of stop, nasal, and fricative consonants are distinguished acoustically by the presence of noise bursts, nasal resonance bands, and frication, respectively, the syllables [bæ], [mæ], and [væ] all contain rising and sharply sloping second- and third-formant transitions. These transitions have been found to be sufficient cues for the perception of place of articulation in these consonants (cf. Cooper, Delattre, Liberman, Borst, & Gerstman, 1952; Malecot, 1956; Harris, 1958; Sharf & Hemeier, 1971). Because of the acoustic similarity in the formant transitions for [bæ], [mæ], and [væ], as well as the articulatory and abstract phonetic similarity already mentioned, it was predicted that any adaptation effects obtained for [mæ] and/or [væ] would be like the effects obtained previously for [bæ] and opposed to the effects obtained previously for either [dæ] or [gæ].

Unlike the consonants [b], [m], and [v], the phonetic segment [w] is represented linguistically as a semi-consonant. This classification reflects the fact that, in linguistic systems, [w] functions in part like a consonant and in part like a vowel (cf. Jakobson, Fant, & Halle, 1963). Despite the fact that [w] is not a consonant and contains no significant zeroes in its spectrum, [w] does share some acoustic and articulatory characteristics with the consonants [b], [m], and [v]. The production of [w] contains a bilabial component in that it is accompanied by considerable lip-rounding. In addition, [wæ] is acoustically similar to [bæ] in that both syllables contain rising second- and third-formant transitions. The difference between these two syllables is signaled by the duration and slope of the transitions (cf. Liberman, Delattre, Gerstman, & Cooper, 1956). By employing [wæ] as an adapting stimulus, we attempted to further define the extent of the adaptation effects for *place*.

Table 1
Starting Frequencies of the Second- and Third-Formant
Transitions for the Synthetic CV Stimuli

Stimulus Number	Starting Frequencies (in Hz)	
	F ₂	F ₃
1	1232	2180
2	1312	2348
3	1386	2525
4	1465	2694
5	1541	2862
6	1620	3026
7	1695	3195
8	1772	3026
9	1845	2862
10	1920	2694
11	1996	2525
12	2078	2348
13	2156	2180

Note—The fixed steady state formants were centered at 743 Hz (F₁), 1,620 Hz (F₂), and 2,862 Hz (F₃) (after Pisoni, 1971).

METHOD

Subjects

Eight paid volunteers, primarily students enrolled at Boston area universities, served as experimentally naive listeners in this study. All Ss were native speakers of American English and had no known hearing impairments. No S had had any prior experience in listening to synthetic speech.

Stimuli

The test stimuli consisted of a series of 13 synthetic CV syllables. These stimuli, the same bæ-dæ-gæ test stimuli used in the prior study of *place* adaptation (Cooper, 1973), were three formant patterns constructed using a parallel resonance synthesizer by Pisoni (1971). Stimuli differed from one another only in the starting frequency and direction of the second- and third-formant transitions. The different starting frequencies of F₂ and F₃ are displayed in Table 1, along with the steady state formant frequencies to which these transitions rose or fell.

Voicing was produced for the consonants by starting each syllable pattern with a 40-msec low-amplitude F₁ centered at 150 Hz. This voicing period was followed by the formant transitions, also lasting 40 msec. The transitions were followed by the steady state formants appropriate for the vowel [æ], yielding an overall syllable duration of 300 msec for each stimulus pattern. In sum, the test stimuli consisted of 13 synthetic CV syllables differing from one another in small steps to yield a continuum for the perceived syllable types of [bæ], [dæ], and [gæ]. Exemplars of each of these syllable types are displayed schematically in Pisoni (1971, Fig. 1). Note that the third-formant transitions are identical for [bæ] and [gæ].

Synthetic stimuli were used in the test series in order to obtain a series of syllables varying only in the second- and third-formant transitions, allowing a quantitative measure of adaptation to be obtained. The adapting stimuli, on the other hand, consisted of five real speech syllables, all produced by a male speaker of American English (W.E.C.). The five stimuli represented exemplars of the syllable types [bæ], [p^hæ], [mæ], [væ], and [wæ]. Each stimulus was judged by the authors to be a good representative of its syllable type as spoken in American English. All five syllables were edited to a duration of 300 msec, and, in addition, the peak amplitudes of the five stimuli were equalized. The starting frequency and steady state center frequency of the second and third formants for each syllable were measured spectrographically; these frequency values are presented in Table 2. Spectrographic analysis also showed that the duration of the formant transitions for [bæ],

[p^hæ], [mæ], and [væ] was approximately 30 msec, whereas for [wæ] the duration of these transitions was about 65 msec.

Procedure

Two baseline functions of identification were obtained for all listeners in the unadapted state. The first was obtained prior to the series of adaptation tests, and the second was obtained after the series of adaptation tests had been completed. In each of the baseline tests, listeners were presented randomized sequences of the 13 test syllable patterns, with an interstimulus interval of 2.5 sec. The Ss listened to the output of a Tandberg 1200X tape recorder and Advent speaker, the gain on the tape recorder being set at a fixed comfortable listening level. Each of the 13 stimuli was presented 20 times for identification in this manner. The Ss were instructed to identify each stimulus as [bæ], [dæ], or [gæ] by writing the appropriate consonant letter on answer sheets. The listeners were instructed to make their responses as soon as possible after hearing each identification stimulus.

On the day after the initial baseline test, a series of five adaptation tests was conducted, each test lasting about 1 h and taking place at approximately 24-h intervals. In order to make certain that each adaptation test was begun with the S in the unadapted state, a minimum of 20 h separated any two adaptation tests (cf. Eimas & Corbit, 1973).³ Five different adapting syllables were used, one in each test. These adapting stimuli were the real speech syllables [bæ], [p^hæ], [mæ], [væ], and [wæ]. Four of the Ss (B.S., D.D., S.T., and W.N.) were presented the five adaptation tests in the order: [bæ] adaptation, [p^hæ] adaptation, [mæ] adaptation, [væ] adaptation, and [wæ] adaptation; the remaining four Ss were presented these same tests in the reverse order.

Each of the five adaptation tests was conducted in the manner used by Cooper (1973). Listeners were first presented with 2 min (180 presentations) of the selected adapting stimulus ([bæ], [p^hæ], [mæ], [væ], or [wæ] in a given session). Each repetition of the adapting stimulus was separated by 350 msec of silence. Following this 2-min "warm-up" period of adaptation, 35 adaptation trials were administered. On each trial, the adapting stimulus was first presented for 1 min (90 presentations), followed by 1.5 sec of silence, and then four randomly selected stimuli from the series of 13 stop consonants. The Ss were instructed to identify each of these four test stimuli during a 2.5-sec silent interval separating adjacent stimuli to be identified. As in the baseline tests of identification, the listeners were instructed to respond as soon as possible after hearing each test item. After the fourth stimulus was presented for identification, 5 sec of silence intervened before the onset of the

Table 2
Frequency Values of the Second and Third Formants
for the Five Real Speech Adapting Syllables

Syllable	Starting Frequency		Steady State Center Frequency (in Hz)	
	F ₂	F ₃	F ₂	F ₃
[bæ]	1000	2000	1400	2400
[p ^h æ]	(See Note Below)		1500	2500
[mæ]	1000	1975	1500	2500
[væ]	1000	2000	1500	2400
[wæ]	800	2000	1500	2500

Note—The frequency values were estimated from wide-band spectrograms of the real speech stimuli. Since the F₂ and F₃ starting frequencies for p^hæ are not readily observable in spectrograms of real speech (due to the obscuring effect of aspiration and the weak energy of the formant transitions themselves), measurements of the starting frequencies for p^hæ were less precise than the measurements included in the table. To the best of our ability to estimate the starting frequencies for p^hæ, the values obtained were F₂ starting at 1100 Hz and F₃ starting at 2000 Hz.

Table 3
Individual and Mean Loci of Phonetic Boundaries for Each Test Condition

Ss	Without Adaptation	Adaptation With				
		[bae]	[phae]	[mae]	[vae]	[wae]
Table 3a: b-d Phonetic Boundary						
W.N.	4.85	0	4.10	2.55	4.10	5.03
A.S.	4.92	3.72	3.47	1.44	2.50	3.34
E.B.	3.32	3.32	2.48	1.72	0	2.92
B.S.	4.25	0	0	0	0	1.85
S.T.	4.19	1.02	1.96	3.29	3.73	5.43
D.D.	5.44	4.44	6.00	5.67	5.45	6.39
J.M.	3.36	3.13	4.33	4.04	2.87	2.72
Mean	4.33	2.23	3.19	2.67	2.66	3.95
Table 3b: d-g Phonetic Boundary						
W.N.	10.23	9.32	9.92	10.50	10.41	10.41
A.S.	9.33	9.11	8.34	9.65	9.54	9.07
E.B.	10.38	9.65	9.68	10.00	10.00	10.46
B.S.	10.74	10.73	10.73	11.08	9.96	10.41
S.T.	8.98	9.11	8.96	10.04	10.33	9.96
D.D.	10.47	10.55	10.61	10.46	10.45	10.20
J.M.	8.56	9.45	9.94	10.00	9.67	8.39
Mean	9.81	9.70	9.74	10.25	10.05	9.84

Note—The locus of the phonetic boundary was determined in each case by first assigning to each stimulus an arbitrary number, ranging from 1 to 13, and then performing a least mean squares analysis. The loci of the phonetic boundaries for the "without adaptation" condition are based on the pooled results of baseline functions obtained before and after adaptation testing (see text).

RESULTS

next adaptation trial. Using this method, each stimulus in the series of 13 synthetic test syllables was presented a total of 10 times within a single, hour-long adaptation session. Throughout each of the five adaptation sessions, the stimuli to be identified were placed on the Tandberg 1200X tape recorder and Advent speaker, while the adapting stimuli were played on a Tandberg 12-41 tape recorder and the same Advent speaker. The two speaker outputs were matched in peak amplitude by means of a General Radio sound-level meter (Type 1565-A). On the day after the last adaptation test, Ss were presented the second baseline test of identification.

Table 4
Individual and Mean Loci of Phonetic Boundaries
for the Two Baseline Tests

Ss	Without Adaptation	
	First Test	Second Test
Table 4a: b-d Phonetic Boundary		
W.N.	5.28	4.80
A.S.	4.93	5.28
E.B.	3.01	3.66
B.S.	4.51	4.03
S.T.	3.16	4.99
D.D.	5.03	6.11
J.M.	3.48	3.27
Mean	4.20	4.59
Table 4b: d-g Phonetic Boundary		
W.N.	9.86	10.31
A.S.	9.10	9.47
E.B.	10.83	10.24
B.S.	10.79	10.52
S.T.	9.27	9.41
D.D.	10.52	10.41
J.M.	8.36	9.33
Mean	9.82	9.96

Note—The locus of the phonetic boundary was determined in each case by first assigning to each stimulus an arbitrary number, ranging from 1 to 13, and then performing a least mean squares analysis.

The results for seven Ss appear in Table 3. The data for the eighth S, D.M., were analyzed separately on the basis of his initial baseline function, which did not show the sharply sloping contours found for all other listeners in this experiment as well as for the listeners in experiments conducted previously with the bæ-dæ-gæ test stimuli (cf. Pisoni, 1971; Cooper, 1973). For all eight Ss, the loci of the b-d and d-g phonetic boundaries were determined for each test condition by first assigning to each test stimulus a number ranging from 1 to 13, and then performing a least-mean squares analysis (Ferguson, 1959) on the transformed percentages of identification responses. The numbers assigned to the test stimuli for the purpose of this analysis correspond to the numbers assigned in Table 1.

To assess the amount of baseline variability for each S in the pre- and postadaptation baseline tests, we determined the loci of the phonetic boundaries for each of the two baseline tests separately. These results appear in Table 4. An inspection of this table reveals that the loci of both the b-d and d-g phonetic boundaries were very similar overall for the two baseline measures. A statistical test of this difference was found to be nonsignificant ($p > .20$, two-tailed t test for correlated observations) for both the b-d and d-g phonetic boundaries. It should be noted, however, that the individual baseline functions obtained before and after adaptation testing are more variable for some Ss than for others. Three of the Ss, W.N., A.S., and B.S., showed a minimal baseline disparity (less than 0.5 units) in both the b-d and d-g phonetic boundary loci.⁴

Table 5
Tests of Significance for Shifts in Phonetic Boundary Loci
Between the Unadapted Test Condition and
Each Adaptation Condition

	Adaptation With				
	[bae]*	[phae]*	[mae]*	[vae]*	[wae]*
Table 5a: b-d Phonetic Boundary					
t Value	2.82	1.72	2.40	2.67	0.76
p Value	p < .025	p > .05	p < .05	p < .025	p > .20
	Adaptation With				
	[bae]	[phae]	[mae]	[vae]	[wae]
Table 5b: d-g Phonetic Boundary					
t Value	0.47	0.24	1.85	0.83	0.19
p Value	p > .20	p > .20	p > .10	p > .20	p > .20

*Denotes one-tailed test, the direction of shift being toward the [b] category.

We reasoned that a better estimate of the Ss' baseline during the course of the study would be provided if the baseline functions obtained before and after adaptation testing were pooled than if either of these individual baseline functions was considered alone. The phonetic boundary loci for the baseline test which appear in Table 3 were thus determined for each S by pooling his responses from the pre- and postadaptation baseline tests and then performing a least-mean squares analysis on this pooled identification function.

Table 5 shows the results of statistical tests of significance (t tests for correlated observations) for shifts in the loci of the phonetic boundaries after adaptation. One-tailed tests of significance were applied in cases where the phonetic boundary bordered the category which shared its *place* mode with the adapting stimulus (i.e., the b-d phonetic boundary for [bae], [phae], [mae], [vae], and [wae] adaptation). Based on the model of the selective adaptation effect proposed by Cooper (1973), the predicted direction of the boundary shifts in these cases was toward the category having the same *place* mode as the adapting stimulus (i.e., toward the [b] category). The results of Table 5 show that, in comparison with the baseline measure of identification, a statistically significant shift occurred in the locus of the b-d phonetic boundary after adaptation with each of the syllables [bae], [mae], and [vae], the shift in each instance being directed toward the [b] category. Overall, a somewhat greater magnitude of shift was obtained after adaptation with [bae] than with [mae] or [vae], although this difference was not systematic across Ss. After adaptation with each of the three syllables [bae], [mae], and [vae], listeners made a smaller percentage of [b] responses than in the baseline test. A statistically nonsignificant shift in this same direction was obtained for the syllable [phae] (.10 > p > .05) and for the syllable [wae] (p > .20). For the d-g phonetic boundary locus, no significant shift occurred for any of the five adaptation conditions.

Figure 1 depicts the identification functions for each test condition for a single listener, B.S. For the group of seven Ss, shifts produced by selective adaptation were usually not accompanied by a decline in the steepness of the response function slopes. In addition, for each S showing a shift in the b-d phonetic boundary locus after adaptation, the decrease in the percentage of [b] responses was accompanied by an increase in the percentage of [d] responses, while the percentage of [g] responses remained virtually fixed.

The results of the eighth S, D.M., appear in Tables 6 and 7 and in Fig. 2. The shape of the baseline functions for this S (cf. Fig. 2) differs dramatically from the shape of the baseline functions obtained for B.S. (cf. Fig. 1) and for the other listeners as well. Unlike these Ss, D.M. identified only a small proportion of the 13 stimulus values as belonging to the same consonant category on all trials. Despite this marked tendency toward probabilistic, as opposed to absolute, identification, the baseline function obtained for D.M. before adaptation testing closely matches his baseline function obtained after the series of adaptation tests had been completed (cf. Table 7 and Fig. 2).

For the adaptation test conditions, D.M. showed a systematic shift in the b-d phonetic boundary. The direction of this shift was *away* from the [b] category, in contrast to the direction of shift obtained for the other seven Ss. Whereas the group of seven Ss made fewer [b] responses after adaptation with each of the syllables [bae], [phae], [mae], [vae], and [wae], D.M. made more [b] responses after adaptation with each of these syllables. For the d-g phonetic boundary, D.M. showed no systematically directed shifts in the locus of the phonetic boundary after adaptation, similar to the results obtained for the other listeners.

DISCUSSION

Ss A.S., E.B., W.N., B.S., J.M., S.T., and D.D.

The results for the group of seven listeners were very similar for the adaptation tests conducted with the adapting stimuli [bae], [phae], [mae], and [vae]. The results obtained after adaptation with the syllable [bae] replicate the findings of Cooper (1973). That is, after adaptation, the b-d phonetic boundary shifted in the direction toward the [b] category, whereas the d-g phonetic boundary remained fixed.

The results obtained with the adapting syllable [phae] are only in partial agreement with the data obtained in the earlier *place* study. For the b-d phonetic boundary, both studies showed some shift in the direction toward the [b] category, in accord with the findings obtained with the adapting syllable [bae]. For the d-g phonetic boundary, however, a discrepancy between the results of the two studies exists. In the prior study, a shift occurred in the locus of the d-g boundary toward the [g] category. This shift was unexpected on the basis of

Fig. 1. Percentages of identification responses ([b], [d], or [g]) obtained for the single listener B.S. in the unadapted state and after adaptation with [bæ], [pʰæ], [mæ], [væ], and [wæ].

the results obtained after adaptation with [bæ]. In the present study, no systematic shift occurred in the locus of this boundary, consistent with the results obtained after [bæ] adaptation. A different real speech exemplar of [pʰæ] was used in the two studies (different exemplars of [bæ] were used as well), and it is possible that an acoustic difference between the two [pʰæ] stimuli can account for the observed discrepancy. The exemplar used in the earlier study was more heavily

aspirated and had a stronger initial burst than the one used here. This heavy aspiration coupled with a high-energy burst may have rendered the former stimulus somewhat [k]-like (cf. Cooper et al, 1952), even though Ss reported hearing both stimuli unambiguously as [pʰæ].

The results obtained with the adapting stimuli [mæ] and [væ] show that both of these stimuli exert a reliable influence on the perception of certain members

Table 6
Individual Loci of Phonetic Boundaries for Each Test Condition

		Adaptation With				
S	Without Adaptation	[bae]	[phae]	[mae]	[vae]	[wae]
Table 6a: b-d Phonetic Boundary						
D.M.	4.98	5.93	5.20	6.84	6.60	6.47
Table 6b: d-g Phonetic Boundary						
D.M.	8.57	6.85	9.50	9.45	10.21	8.28

Note—The locus of the phonetic boundary was determined in each case by first assigning to each stimulus an arbitrary number, ranging from 1 to 13, and then performing a least mean squares analysis. The loci of the phonetic boundaries for the "without adaptation" condition are based on the pooled results of baseline functions obtained before and after adaptation testing (see text).

of the bæ-dæ-gæ series. For both of these syllables, significant shifts in the locus of the b-d phonetic boundary occurred, the shifts being direction toward the [b] category. For the d-g phonetic boundary, on the other hand, no significant shifts occurred. The data for the adapting stimuli [mae] and [vae] are thus akin to the results obtained with the adapting syllable [bae].

The adapting stimulus [wae] showed a slight mean shift in the b-d phonetic boundary, in the direction toward the [b] category. This stimulus was certainly less effective as an adapting syllable than any of the other adapting stimuli, however.

S D.M.

For the S showing an atypical baseline function, we found, surprisingly, that repetitive listening to each of the adapting syllables produced an effect of facilitation. Because D.M.'s systematic tendency to make a greater percentage of [b] responses after adaptation was not shared by any other S, either in this study or in the study of Cooper (1973), it is important to try to rule out any trivial explanation of D.M.'s atypical performance. Since the second baseline test function for this S was in remarkably close agreement with his first baseline function, the possibility of a general shift in baseline criterion or the possibility of random responding can be discarded as explanations of either the unusual baseline function or the facilitation effects. The S himself reported after all testing had been completed that he had used no unusual strategies in making his response choices, and that he, like the other Ss, reported each stimulus as he heard it. As in the case of the other listeners, D.M. was able to identify correctly each of the adapting syllables and consistently heard all the adapting and test stimuli as speech. Both the atypical baseline function and the effects of facilitation thus seem to be valid perceptual phenomena for this S. Each of these two phenomena, as well as their possible relation, deserve to be studied further. Although facilitation effects have previously been reported for the sensory modalities of taste (cf. Mayer, 1927; Dallenbach & Dallenbach, 1943; Meiselman, 1968) and smell (cf. Engen & Bosack, 1969; Corbit & Engen, 1971), such effects have been found to be dependent upon certain pairings of the adapting and test stimuli, not dependent on the nature of the Ss' performance in the unadapted

state. The case presented here thus differs from the facilitation effects reported previously in the literature.

CONCLUSIONS

The results of the present experiment corroborate and extend the earlier finding that adaptation effects can be systematically produced along the consonant feature dimension *place of articulation*. The previously reported effects were accounted for by the fatiguing of an analyzing mechanism which decodes *place* information unidimensionally in terms of three major place analyzers, named the bilabial, alveolar, and velar analyzer modes.

The results of the present study are readily accommodated by the unidimensional model. The results also provide information about some additional properties of the analyzing system for *place*. First, the perceptual shift obtained after adaptation with the syllable [vae], containing a labio-dental consonant, indicates that the analyzer mode formerly termed "bilabial" actually extracts feature information that is more general in nature. To reflect the fact that [v] and [b] produced similar adaptation effects, we must change the term used to describe this analyzer mode from "bilabial" to "labial." The results for [vae] show that the adaptation effects do not depend on a strict correspondence between the articulatory values of the adapting stimulus and members of the test stimuli. Rather, the adaptation effects appear to depend on either the sharing of certain invariant acoustic patterns, in particular the sharing of rising and steeply sloping

Table 7
Individual Loci of Phonetic Boundaries
for the Two Baseline Tests

S	Without Adaptation	
	First Test	Second Test
Table 7a: b-d Phonetic Boundary		
D.M.	5.07	4.86
Table 7b: d-g Phonetic Boundary		
D.M.	8.61	8.13

Note—The locus of the phonetic boundary was determined in each case by first assigning to each stimulus an arbitrary number, ranging from 1 to 13, and then performing a least mean squares analysis.

Fig. 2. Percentages of identification responses ([b], [d], or [g]) obtained for the single listener D.M. in the unadapted state and after adaptation with [bæ], [p^hæ], [mæ], [væ], and [wæ].

second- and third-formant transition patterns, or on the sharing of more abstract phonetic information.

The acoustic pattern interpretation is certainly favored by the present data. Recall that relatively strong adaptation effects were obtained for the adapting stimuli [bæ], [mæ], and [væ]. The second- and third-formant transitions of these stimuli were of the same pattern as the transitions of the [b] members of the test series (cf. Tables 1 and 2); these adapting stimuli contained strong second- and third-formant transitions that were both

rising and steeply sloped. On the other hand, adaptation effects were small for the adapting stimuli [p^hæ] and [wæ]. Unlike the [b] members of the test series, [p^hæ] contained second- and third-formant transitions that were relatively weak in energy, while [wæ] contained transitions that had a gradual, rather than steep, slope.

The perceptual shifts obtained in this experiment indicate further that the feature analyzer sensitive to labial *place* values extracts this information from

consonants belonging to any of three different consonant classes; that is, the analyzer extracts information from consonants independent on their particular *manner* of articulation. Support for this conclusion is derived from the fact that perceptual shifts were obtained for the stop consonant test series after adaptation with [b], a stop consonant, [m], a nasal consonant, and [v], a fricative consonant.

A clue to the operating limit of the labial analyzer was provided by the failure to obtain consistent perceptual shifts after adaptation with the semiconsonant [w]. Further research must be conducted to determine whether this failure is complete. If [w] is indeed inadequate as an adapting stimulus for the stop consonant series, the defining limit of the labial analyzer would appear to be that it extracts *place* information only for the class of true consonants.

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NOTES

1. Blumstein, S. The role of distinctive features in speech perception. In preparation.
2. The phonetic segment [g] is described by Jakobson et al (1963) as being [+grave] and [+compact] and by Chomsky and Halle (1968) as being [-anterior] and [-coronal], in addition to [+high], [-low], and [+back]. In both feature systems, [g] shares more place feature values with [b] than with [d]. Thus, according to a model of the feature analysis mechanism based on either of these feature descriptions, adaptation with [g] should produce some decrease in response to [b] as well as to [d]. This prediction was not supported by the results of tests using response measures of either identification or discrimination. Rather, the responses to [b] remained relatively fixed, as predicted by the unidimensional model.
3. The assumption that recovery from adaptation would be complete after 20 h was substantiated by the results of the second baseline test, administered about 20 h after the fifth adaptation test (cf. Tables 4 and 7).
4. It may well be that baseline fluctuations account for the inability to obtain predicted shifts in the case of some Ss. Evidence in support of this view is derived from the fact that the three Ss showing minimal baseline variability, A.S., B.S., and W.N., showed the most clear-cut and consistent shifts in the predicted direction, whereas the performance of other Ss was less uniform across the various adaptation test conditions.

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