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Simple and contingent adaptation effects for place of articulation in stop consonants

JAMES R. SAWUSCH
State University of New York at Buffalo, Buffalo, New York 14226

and

DAVID B. PISONI
Indiana University, Bloomington, Indiana 47401

Experiments on selective adaptation have shown that the locus of the phonetic category boundary between two segments shifts after repetitive listening to an adapting stimulus. Theoretical interpretations of these results have proposed that adaptation occurs either entirely at an auditory level of processing or at both auditory and more abstract phonetic levels. The present experiment employed two alternating stimuli as adaptors in an attempt to distinguish between these two possible explanations. Two alternating stimuli were used as adaptors in order to test for the presence of contingent effects and to compare these results to simple adaptation using only a single adaptor. Two synthetic CV series with different vowels that varied the place of articulation of the consonant were employed. When two alternating adaptors were used, contingent adaptation effects were observed for the two stimulus series. The direction of the shifts in each series was governed by the vowel context of the adapting syllables. Using the single adaptor data, a comparison was made between the additive effects of the single adaptors and their combined effects when presented in alternating pairs. With voiced adaptors, only within-series adaptation effects were found, and these data were consistent with a one-level model of selective adaptation. However, for the voiceless adaptors, both within- and cross-series adaptation effects were found, suggesting the possible presence of two levels of adaptation to place of articulation. Further, the contingent adaptation effects with the voiceless adaptors seemed to be the result of the additive effects of the two alternating adaptors. This result indicates that previously reported contingent adaptation results may also reflect the net vowel specific adaptation effects after cancellation of other, nonvowel dependent effects and that caution is needed in interpreting such results.

In recent years, the selective adaptation paradigm has been extensively employed in research on speech perception. This paradigm has been used to investigate a number of phonetic features, including those of place, manner, and voicing in stop consonants. One particular issue that has been addressed repeatedly by these experimental investigations involves the locus or loci of occurrence of the adaptation effects found within the perceptual system. The original interpretation of Eimas and Corbit (1973) of their results on the feature of voicing was that the adaptation effects originated at a linguistic level of perceptual analysis where the phonetic feature of voicing was treated as an abstract unit. Since the original studies of Eimas and his colleagues (Eimas, Cooper, & Corbit, 1973; Eimas & Corbit, 1973), two other interpretations of the selective adaptation results have assumed dominant roles. Most of the accounts that have recently been proposed assume either a single, auditory level of processing or both auditory and phonetic levels to explain the selective adaptation results.

A number of investigators have proposed one-level, auditory accounts of selective adaptation (Ades, 1976; Bailey, 1975; Eimas & Miller, Note 1). Although these models differ in some details, they all assume that there is only one locus for the selective adaptation results. The arguments for a one-level model have been presented extensively elsewhere (Ades, 1976; Bailey, 1975) and will not be reviewed here. However, one particular set of results should be mentioned. Bailey (1975) employed two series of synthetic CV speech stimuli that varied along the phonetic feature of place of articulation. When the adapting syllable was a member of the test series (e.g., a [bi] adaptor and testing on a [bi]-[di] series or a [bu] adaptor and testing on a [bu]-[du] series), there was a significant adaptation effect. The

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category boundary of the test series shifted toward the adapting syllable. However, when the adapting syllable was not from the test series (e.g., [bu] adaptor and testing on the [bi]-[di] series), no adaptation effect was found.

This absence of cross-series adaptation results was interpreted by Bailey (1975) as evidence against the involvement of an additional phonetic level in selective adaptation. At a phonetic level, the "b" in [bi] and the "b" in [bu] should be represented identically, and hence, if adaptation was occurring at such a level, a [bu] adaptor should cause a shift in the category boundary for the [bi]-[di] test series. The synthetic stimuli in Bailey's (1975) experiment were constructed so that they did not share any spectral (frequency) components in common in their second and third formants. Thus, the initial consonants in these two series were spectrally distinct, despite their presumed phonetic identity. On the basis of these and other results, Bailey (1975) argued that spectral commonality or overlap was required for selective adaptation to occur. The selective adaptation results previously reported could then be attributed to a single level of processing, where the speech signal was represented as a "neural spectrogram," prior to phonetic categorization.

Although results such as those found by Bailey (1975) seem, at first glance, to favor a one-level account of selective adaptation, the results of recent experiments appear to fit better within a two-level framework. Results of experiments by Sawusch (1977) and Ganong (Note 2), in which the spectral overlap between adapting and test syllables was manipulated, have shown selective adaptation effects when the adaptor and test syllables do not share any frequency components in common. For example, Sawusch (1977) constructed two sets of synthetic [bae] and [dae] syllables. The formant frequencies for one set (termed the "high" series) were scaled upward logarithmically from the formant frequencies of the other ("low") series. The formants of the high series were separated by at least one critical bandwidth from the formants of the low series (see Scharf, 1970). Both high- and low-syllable adaptors were found to cause a shift in the low-series category boundary. Furthermore, the low adaptors caused about twice as much adaptation as their high-series counterparts. In the second experiment, Sawusch (1977) also found that the high adaptors yielded 100% interaural transfer of adaptation, indicating that this effect was occurring at a central stage of processing. In contrast, the adapting effect of the low syllables on the low test series seemed to contain both peripheral and central components. These results were interpreted by Sawusch as reflecting the involvement of two distinct stages of perceptual analysis in selective adaptation. These results, together with others, seem to provide support for a two-level interpretation of selective adaptation, at least for the place feature (Cooper, 1975; Sawusch, 1977; Tartter & Eimas, 1975).

A number of possible resolutions to the conflict between one- and two-level interpretations are possible (see Ades, 1976, and Sawusch, 1977, for a few possibilities). One of these is that there may indeed be two levels of adaptation as proposed in the two-level model. However, to account for the results of Bailey (1975), certain restrictions need to be placed on the properties of the second level. Processing at this level may still be partly frequency or vowel dependent. Under this assumption, a [bu] syllable would not have an adapting effect on a [bi]-[di] series which would agree with the results of Bailey (1975). However, as long as the vowels in the adapting stimulus and the test series are similar, selective adaptation effects would be expected. This explanation of Bailey's (1975) results would then be consistent with those of Sawusch (1977) and Ganong (Note 2).

The present experiment was designed to further explore the effects of vowel context upon selective adaptation to place of articulation in CV syllables. The CV syllables for the present experiment were constructed with [i] and [a] vowel contexts to investigate whether adaptation would transfer across CV stimuli with these two vowels. The procedure in the present experiment involved both single adaptors (e.g. [ba] or [di]) and alternating adaptor pairs ([ba]-[di]). This alternating adaptors procedure has previously been used by Cooper (1974) and Eimas et al. (1973) to study the feature of voicing and by Miller and Eimas (1976) to study the features of voicing and place in stop consonants. In this experimental procedure, two adapting syllables are presented to subjects in an alternating fashion. With this procedure, Cooper (1974) found that voicing information was extracted in a vowel-dependent fashion. Cooper's alternating adaptors were the syllables [da] and [ti]. Subjects listened to these alternating adaptors and were then tested on both a [bi]-[pi] series and a [ba]-[pa] series. The [bi]-[pi] series showed a reliable category boundary shift toward [pi] (both the [ti] adaptor and [pi] are voiceless), while the [ba]-[pa] series showed a shift in the opposite direction, toward [ba] (both [da] and [ba] are voiced). Thus, each subject showed two category boundary shifts, in opposite directions. Cooper (1974) interepreted these results as reflecting a level of analysis of the voicing feature which was vowel dependent. Miller and Eimas (1976) and Pisoni, Sawusch, and Adams (Note 3) have replicated Cooper's original results for the voicing feature, and Miller and Eimas (1976) found a similar pattern of results for the place feature using a [bae]-[dae] series and a [bi]-[di] series. However, the presence of a vowel-contingent adaptation effect is not, by itself, sufficient evidence to indicate that selective adaptation does not generalize across vowel environments. It is possible that the adapting effects at a later, nonvowel-dependent (phonetic) level may have cancelled each other out with alternating adaptors such as [bae] and [di]. This would leave only the vowel- or frequency-specific effect from an earlier auditory level of processing. In order to investigate this possibility of cancellation, the effects of alternating adaptors need to be compared to the summed effects of the two adaptors used separately. This comparison of the summed effects of two single adaptors with the net effect of an alternating pair of adaptors has previously been reported by Eimas et al. (1973) for the voicing feature and by Pisoni et al. (Note 3) for place of articulation. In both of these studies, however, only one vowel context was used. Consequently, these studies allow a check for additivity and cancellation of adaptation effects when the vowel environment is constant.

In the study of Eimas et al. on the voicing feature, no consistent support was found for additivity. However, in the data of Pisoni et al. on the place feature, the summed effects of the single [ba] and [da] adaptors closely matched the net effect of the [ba]-[da] alternating pair. Thus, the evidence indicates that adaptation effects do sum for the level or levels affected using a single vowel context on the place of articulation dimension. In the present experiment, a comparison was made between the summed effects of single adaptors with different vowels (e.g., [bi] and [da]) and the net effect of the same adaptors as an alternating pair ([bi]-[da]). If the net shift of the alternating adaptors can be predicted more accurately from the addition of the separate effects of the two adaptors than from the adaptation effect of the single adaptor whose vowel matches the test series, we will have evidence for cancellation and the involvement of two levels of processing in selective adaptation. If the converse holds true, the evidence would indicate that selective adaptation does not span the two vowel environments chosen, and hence only one level of processing would be implicated. Thus, this procedure permits a strong test of one particular two-level model in which alternating effects in opposite directions at the phonetic level should cancel each other out.

METHOD

Subjects

The subjects were 72 undergraduates at Indiana University who participated as part of a course requirement. All were right-handed, native speakers of English with no known history of either speech or hearing disorder. The subjects were divided into 12 groups of six subjects each.

Stimuli

Two sets of three-formant synthetic CV syllables were generated. One set ranged perceptually from [ba] to [da] and the other set varied from [bi] to [di]. These stimuli were synthesized on the parallel resonance synthesizer at Haskins Laboratories and recorded on magnetic tape. They were later digitized and stored on disk memory under the control of a PDP-11 computer in the Psychology Department at Indiana University. Each series contained nine stimuli which varied in the direction and extent of the second and third formant transitions. The starting frequencies of the second and third formant transitions for these two series are shown in Table 1. The [i] vowel series had steady-state formant center frequencies of 286, 2,307, and 3,026 Hz for F1 through F3, respectively. The [a] vowel series had formant center frequencies of 769, 1,232, and 2,525 Hz, respectively. All formant transitions were 50 msec in duration and were followed by a 250-msec steady-state vowel.

Four other syllables were also prepared to be used as adaptors. They were [pa], [ta], [pi], and [ti] and were identical to their voiced counterparts (the end points of the two series), except that they had a voice onset time (VOT) of +60 msec in place of the 0-msec VOT of their voiced counterparts.

Procedure

All experimental events were controlled by a PDP-11 computer. The digitized waveforms of the stimuli were reconverted to analog form and presented binaurally through Telephonics (TDH-39) matched and calibrated headphones to subjects. All stimuli were presented at a level of 80 dB SPL for a steady-state calibration vowel [a]. On each day, the subjects were first presented with the baseline identification tests for the [ba]-[da] and [bi]-[di] series separately. Each test contained 90 trials in which the nine stimuli from one of the two series were presented 10 times each in random order. The subjects recorded their identification of the stimulus by pushing the appropriate button on a response box in front of them.

Each of the 12 groups received a different adaptation sequence. Eight of the groups received single adapting syllables ([bi], [pi], [di], [ti], [ba], [pa], [da], and [ta]). The other four groups received alternating adaptor pairs ([ba]-[di], [bi]-[da], [pa]-[ti], and [pi]-[ta]). For the single adaptor groups, the adapting syllable was presented 100 times in succession, with a 300-msec interrepetition interval. For the double adaptor groups, each of the adaptors was presented three times in succession before changing over to the other syllable. A total of 96 adapting syllables was presented with a 300-msec interrepetition interval. An adaptation trial consisted of listening to the appropriate adaptor sequence and then identifying a different randomized sequence of nine stimuli selected from one of the test series. On half of the trials, the stimuli were drawn from the [ba]-[da] series, and on the other half, they were drawn from the [bi]-[di] series. Eighteen of these adaptation and test sequences

Table 1
Starting Frequencies in Hertz of the Second and Third Formant Transitions for the [ba]-[da] and [bi]-[di] Test Stimuli

	[ba]-[da]		[bi]-[di]	
Stimulus	F2	F3	F2	F3
1	1,075	2,348	1,465	2,180
2	1,155	2,525	1,541	2,348
3	1,232	2,694	1,620	2,525
4	1,312	2,868	1,695	2,694
5	1,386	3,026	1,772	2,862
6	1,465	3,195	1,845	3,026
7	1,541	3,363	1,920	3,195
8	1,620	3,530	1,996	3,363
9	1,695	3,698	2,078	3,530

were run each day. Thus, by the end of the experiment, each subject had provided 20 identification responses to each stimulus in the baseline conditions and 18 responses to each stimulus in an adaptation condition.

RESULTS AND DISCUSSION

The pre- and postadaptation identification functions for the eight single adaptor groups are shown in Figures 1 through 4. The [bi] adaptor group data are shown on the left side of Figure 1 and the [ba] adaptor group data appear on the right side of Figure 1. For both groups, the adaptor had a significant effect in moving the category boundary of the test series from which it was drawn [$t(5) = 5.09$, $p < .005$, for the [bi] within-series condition; $t(5) = 6.89$, $p < .001$ for the [ba] within-series condition].[1] However, neither voiced labial adaptor showed any significant cross-series adaptation. Much the same pattern was found for the [di] adaptor (Figure 2, left side) and the [da] adaptor (Figure 2, right side). Both voiced alveolar adaptors produced significant within-series adaptation effects [$t(5) = 7.65$, $p < .001$, for the [di] adaptor on the [bi]-[di] series; $t(5) = 8.93$, $p < .001$, for the [da] adaptor on the [ba]-[da] series], but no significant cross-series adaptation effects were found. Thus, voiced adaptors produced substantial adaptation effects on the test series from which they were drawn but showed no cross-series adaptation effects.

The pattern of results for the single voiceless adaptors was substantially different from that found for

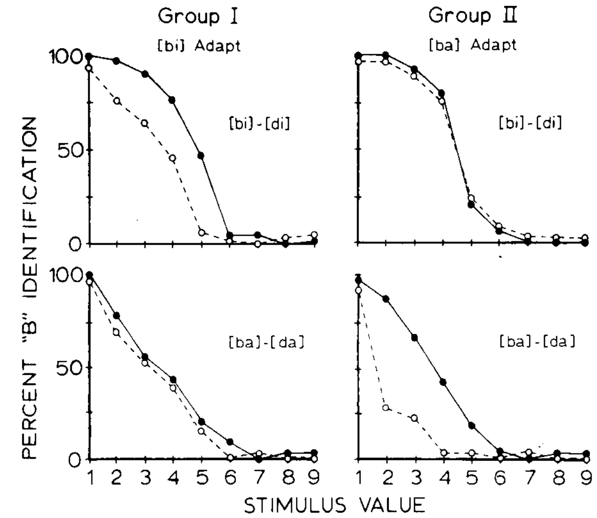

Figure 1. Baseline (solid circles) and adapted (open circles) identification functions for the single [bi] syllable adapted group (left panels) and [ba] syllable adapted group (right panels).

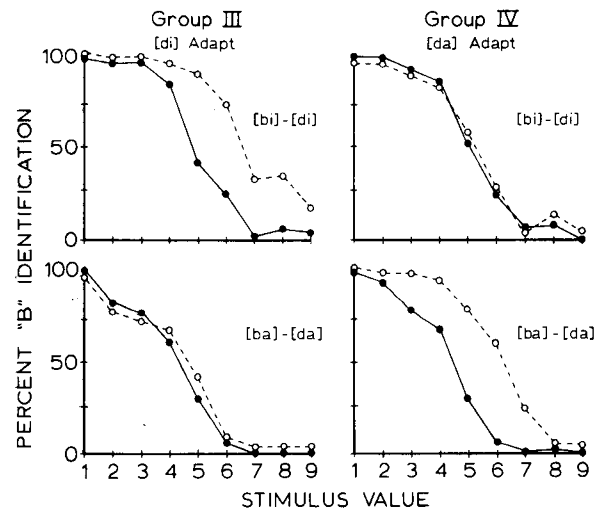

Figure 2. Baseline (solid circles) and adapted (open circles) identification functions for the single [di] syllable adapted group (left panels) and [da] syllable adapted group (right panels).

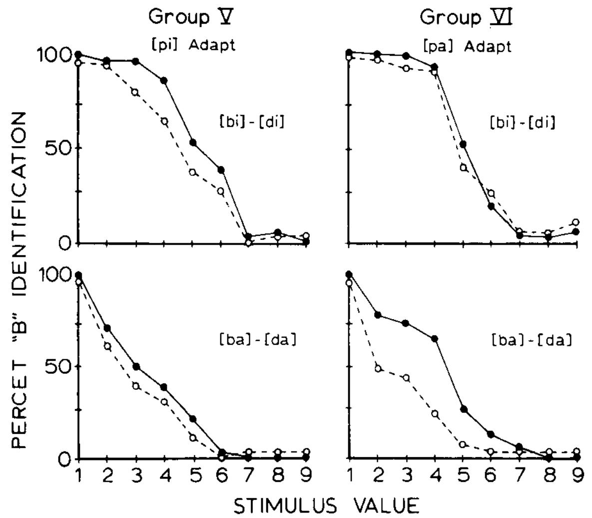

Figure 3. Baseline (solid circles) and adapted (open circles) identification functions for the single [pi] syllable adapted group (left panels) and [pa] syllable adapted group (right panels).

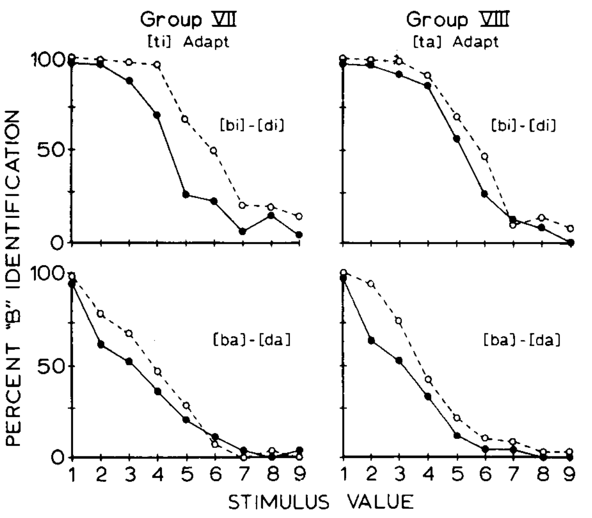

Figure 4. Baseline (solid circles) and adapted (open circles) identification functions for the single [ti] syllable adapted group (left panels) and [ta] syllable adapted group (right panels).

the voiced adaptors. In all cases except one ([pa] adaptor, [bi]-[di] test), the voiceless adaptors produced significant category boundary shifts in both test series. The data for the [pi] and [pa] adaptor groups are shown in Figure 3. All of the category boundary shifts, except the cross-series shift for the [pa] adaptor group, were significant [$t(5) = 3.62$, $p < .01$, for [pi] adapt, [bi]-[di] test; $t(5) = 2.23$, $p < .05$, for [pi] adapt, [ba]-[da] test; $t(5) = 3.31$, $p < .025$, for [pa] adapt, [ba]-[da] test; $t(5) = 1.81$, $.05 < p < .10$, for [pa] adapt, [bi]-[di] test]. A similar pattern was found with the [ti] and [ta] adapted groups, as shown in Figure 4. All four of the category boundary shifts were significant [$t(5) = 4.08$, $p < .005$, for [ti] adapt, [bi]-[di] test; $t(5) = 2.07$, $p < .05$, for [ti] adapt, [ba]-[da] test; $t(5) = 2.62$, $p < .025$, for [ta] adapt, [ba]-[da] test; and $t(5) = 2.12$, $p < .05$, for [ta] adapt, [bi]-[di] test]. Thus, two distinct patterns of results have emerged. For the voiced adaptors, only within-series adaptation effects were found. However, with the voiceless adaptors, both within- and cross-series effects were found.

The results for the four alternating adaptor groups are shown in Figures 5 and 6. The two groups that received voiced alternating adaptors (i.e., b and d) are shown in Figure 5. On the left are the data for the [bi]-[da] group and on the right are the data for the [ba]-[di] group. In all cases, the direction of the category boundary shift followed the vowel of the test series. For the [bi]-[da] adaptors on the [bi]-[di] test series, a significant shift in the category boundary toward [bi] was found [$t(5) = 3.24$, $p < .05$].[2] These same adaptors produced a shift in the opposite direction, toward [da], in the [ba]-[da] series [$t(5) = 8.77$, $p < .002$]. A complimentary pattern was found for the [ba]-[di] alternating adaptors

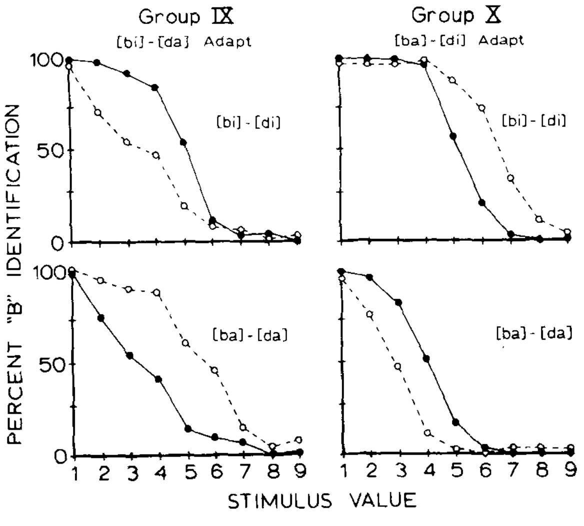

Figure 5. Baseline (solid circles) and adapted (open circles) identification functions for the double [bi]-[da] syllable adaptors group (left panel) and the [ba]-[di] syllable adaptors group (right panel).

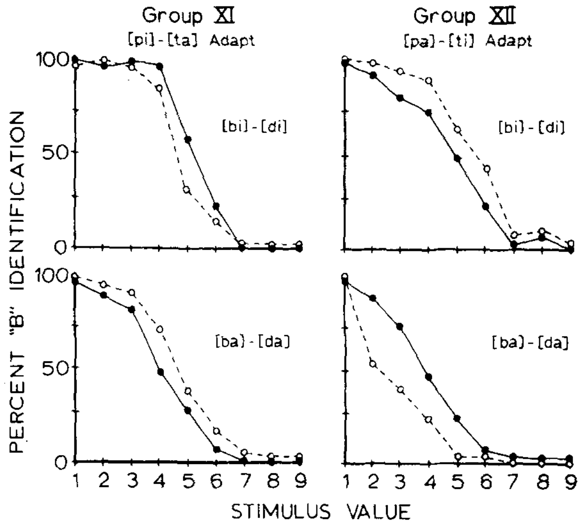

Figure 6. Baseline (solid circles) and adapted (open circles) identification functions for the double [pi]-[ta] syllable adaptors group (left panel) and the [pa]-[ti] syllable adaptors group (right panel).

[$t(5) = 11.87$, $p < .002$, for the shift toward [di] on the [bi]-[di] series and $t(5) = 12.28$, $p < .002$, for the shift toward [ba] in the [ba]-[da] series].

For the [pi]-[ta] and [pa]-[ti] adaptation conditions, the direction of the category boundary shifts also followed the vowel of the test series (see Figure 6). The shifts in the category boundaries were significant for three of these four conditions [$t(5) = 4.70$, $p < .01$, for [pi]-[ta] adapt, [bi]-[di] test; $t(5) = 1.93$, $p > .10$ for [pi]-[ta] adapt, [ba]-[da] test; $t(5) = 5.43$, $p < .01$, for [pa]-[ti] adapt, [bi]-[di] test; and $t(5) = 5.31$, $p < .01$, for [pa]-[ti] adapt, [ba]-[da] test]. These contingent results for place of articulation replicate and extend the findings of Miller and Eimas (1976) in that the effects of the alternating adaptors seem to be vowel specific.

To determine whether the contingent adaptation results show additivity or not, the data were broken down into two parts. The voiced and voiceless adaptor data were compared separately because of the differential pattern of results found with the simple adaptors. The comparison between the contingent adaptation results and the single adaptor results for the voiced adaptors is shown in Table 2. The additive shift column contains the summed shifts from the two single adaptor columns. Positive category boundary shifts indicate that the category boundary moved toward the end of the test series represented by the adaptor whose vowel matched the test series. In all cases, both the effects of the single adaptor (vowel same as test) and the additive sum of the single adaptors matched the direction of the contingent shifts. The fit of the additive model to the contingent data is, on the whole, no better than the fit of the same vowel single adaptor data to the contingent results. The difference between the two fits was

Table 2
A Comparison of the Contingent, Single, and Additive Adaptation Effects for the Voiced Adaptors

	Different Vowel		Same Vowel			
Test Series	Single Adaptor	Shift	Single Adaptor	Shift	Additive	Contingent
bi-di	da	-.04	bi	1.38	1.34	1.80
ba-da	bi	-.25	da	1.88	1.63	2.64
bi-di	ba	-.17	di	1.77	1.60	1.37
ba-da	di	-.13	ba	1.72	1.59	1.16

Note–Shifts are in stimulus units.

not significantly different from zero [$t(3) = -0.17$, $p > .8$, for a two-tailed, correlated t test). This result fits in well with the results found for the single voiced adaptors and suggests nonadditivity of the combined effects of the two adaptors. Thus, this evidence favors a single level of adaptation which does not generalize from the [i] vowel environment to the [a] vowel environment (or vice versa).

The comparison between contingent, single, and additive adaptation for the voiceless adaptors is shown in Table 3. As in Table 2, a positive shift indicates that the boundary moved toward the end of the test series represented by the place feature of the adaptor whose vowel matched the test series. In all four cases, the additive model provided a better fit to the contingent data than the fit from the same vowel adaptors. The difference between these two fits was significant [$t(3) = 9.29$, $p < .01$, using a two-tailed t test for correlated measures]. Consequently, the evidence from the voiceless adaptors favors a two-level model of adaptation in which adaptation from one vowel environment generalizes to the other vowel. However, this account conflicts with the previous findings obtained with the voiced adaptors, and a resolution of this conflict is needed.

One possible resolution is that there was a certain degree of spectral overlap between the adaptors and the test series even when they did not share the same vowel. From an inspection of Table 1, it appears that the third formant in the [a] vowel series was very similar to the third formant in the [i] vowel series. This would account for the cross-series effects of the single voiceless adaptors (e.g., the [pi] adaptor causing a shift in the [ba]-[da] series category boundary), and hence the better fit of the additive model to the voiceless contingent data. However, this explanation would also predict cross-series adaptation effects for the voiced adaptors, since the formant trajectories for both the voiced adaptors and their voiceless counterparts were identical. Consequently, it immediately becomes apparent that any explanation based solely on spectral overlap as the distinguishing factor must be abandoned because of the distinctly different patterns of results found between the single voiced and voiceless adaptors.

Table 3
A Comparison of the Contingent, Single, and Additive Adaptation Effects for the Voiceless Adaptors

	Different Vowel		Same Vowel			
Test Series	Single Adaptor	Shift	Single Adaptor	Shift	Additive	Contingent
bi-di	ta	-.53	pi	.79	.26	.41
ba-da	pi	-.35	ta	1.04	.69	.47
bi-di	pa	-.21	ti	1.33	1.12	.96
ba-da	ti	-.71	pa	1.53	.82	1.02

Note–Shifts are in stimulus units.

An alternative, as yet untested, explanation relies on the concept of source effects (see Ades, 1976; Darwin, 1976). Briefly, a source effect means that a listener is able to keep distinct sets of auditory stimuli selectively separate, as if by processing them through separate channels. The term source effect arises from a listener's ability to segregate information coming from different sources, as in listening to one particular conversation at a cocktail party. In the present experiment, the two test series, [bi]-[di] and [ba]-[da], are distinctly different because of their different vowels. If the listener is able to separate these two sets of stimuli into different channels at an early point in perceptual processing, then all adaptation effects might reasonably be expected to be channel specific. If the adapting and test stimuli were assigned to a channel according to their vowel, the adaptation results observed would be vowel specific. This would account for the present voiced adaptor results and their lack of a cross-series adaptation effect.

One additional assumption must be made to account for the voiceless adaptor results. In this case, the listener is faced with four potential "sources," because the adaptors differ on the voicing feature from the two sets of test stimuli. Under such circumstances, the listener may use only a single channel for processing all of the stimuli rather than attempting to maintain complete separation into four channels. In this case, adaptation with the voiceless adaptors would yield cross-series adaptation effects, either because of some spectral overlap between the third formants of the adaptor and the test series or because of adaptation at an abstract, nonvowel-specific level.

This source effect explanation is entirely post hoc and in need of a more direct experimental test. However, it does appear to fit the data from the present experiment. Any interpretation of selective adaptation of place of articulation that either relied solely on a single level of adaptation or did not include the potential for source effects would have trouble accounting for the differential results of the voiced and voiceless adaptors from the present experiment. It should also be noted that caution is necessary in interpreting the contingent adaptation effects found here and previously by Cooper (1974) and Miller and

Eimas (1976). These results have usually been interpreted as reflecting the operation of vowel-specific analyzers. However, from the results of the voiceless adaptors in the present experiment, it is also possible that the observed contingent effects may reflect the net vowel-specific processing after cancellation of adaptation at another, possibly different nonvowel-specific level. Thus, while contingent adaptation effects may reveal the extent of adaptation at an early, vowel (spectral) specific level of processing, they may also obscure any further adaptation effects at other levels of perceptual analysis. From the present results, selective adaptation on the place feature does seem to generalize from the [i] vowel environment to the [a] vowel, and vice versa, under certain conditions. These results alone do not, however, allow a decision as to whether there are two levels of perceptual analysis involved in selective adaptation to place of articulation in these results or only one level. Further experimentation dealing directly with the possibility of source effects in adaptation is needed before any final decision can be made on these possibilities.

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NOTES

1. All t tests for the single adaptor conditions were one-tailed due to the predicted direction of the observed category boundary shifts.

2. For the double adaptor conditions, two-tailed t tests were used, since there was a potential for category boundary shifts to occur in either direction.

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