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Adaptation of place perception for stops: Effects of spectral match between adaptor and test series

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Recent experiments have provided evidence for an auditory locus of selective adaptation effects. The present experiment further tests this theory. A [pa]-[ka] series was constructed. The burst frication from the [ka] syllable was added to the vowels [u] and [i]. Subjects identified these syllables as [tu] and [pi]. These three syllables contained physically identical bursts but were identified by subjects as stops with three different places of articulation. The [pa], [ka], [tu], and [pi] syllables were used as adaptors on the [pa]-[ka] test series. The [ka], [tu], and [pi] syllables, which contained identical bursts, produced similar boundary shifts. The spectrally different [pa], although sharing its initial phoneme with [pi], produced an opposite shift. These results support an auditory locus for adaptation with little or no phonetic or linguistic influence. In a paired-comparison procedure, [pa], [ka], [pi], and [tu] were used as exemplars. Both the [pa] and [pi] syllables produced fewer [p] responses to an ambiguous test item, whereas [ka] had the opposite effect of producing more [p] responses. The phonetic quality of the exemplar appears to have been the primary determinant of its effects in the paired-comparison procedure. Together, these results support a two-stage model of speech perception, in which neither of these stages are vowel contingent.

A recurring issue in speech perception research is the question of which aspects of perceptual processing reflect general auditory coding and which reflect specialized, speech-specific coding. A variety of experimental procedures have been employed in an attempt to factor out the auditory and phonetic coding contributions to speech perception. One procedure that has been used extensively over the past 15 years is selective adaptation. In the selective adaptation procedure, a subject's categorization of a test series is assessed before and after the repetition of an adaptor, usually one of the endpoints from the test series. Adaptation results in a shift in the category boundary toward the adaptor end of the test series. This shift in the category boundary constitutes the basic phenomenon of selective adaptation and has been found repeatedly for many phonetic distinctions (see Ades, 1976, W. E. Cooper, 1979, and Eimas & Miller, 1978, for reviews).

The effects of selective adaptation with speech have raised two central questions. The first is whether selective adaptation affects speech-specific phonetic coding processes or more general auditory coding processes. The second question concerns the nature of how selective adaptation produces its effects within any particular coding process. Eimas and Corbit (1973) were among the first researchers to utilize the selective adaptation paradigm with speech stimuli. They argued that the adaptation effect was a result of feature detector fatigue. These feature detectors were presumed to be sensitive to the linguistic qualities of the stimulus. Other research, however, has emphasized the auditory coding of the stimulus. Specifically, the degree of spectral match between the adaptor and the test series seems to dictate the degree of adaptation. A "better" match results in a greater boundary shift in the direction of that match (Ades, 1976; Bailey, 1975). However, a general problem exists with most experiments that have tried to address these questions. The spectral structure (and hence auditory coding) and the phonetic identity of the speech stimuli that have been used have been highly correlated. Consequently, it has been difficult to separate the potential contributions of auditory and phonetic coding processes in selective adaptation.

In an attempt to separate the spectral structure of a stimulus from its phonetic percept, Roberts and Summerfield (1981) utilized the McGurk effect. The auditory presentation of a [bɛ] syllable was synchronized with the video presentation of a [gɛ] syllable. In this situation, subjects reported a [dɛ] phonetic percept (see McGurk & MacDonald, 1976). However, as an adapting syllable, the audio-visual [dɛ] had the same effects as the audio-only [bɛ] on a [bɛ]-[dɛ] series. Subjects' phonetic identification of the audio-visual adaptor as [dɛ] did not influence the adaptation effects that were found. Thus, the spectral

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match of the adaptor and test series seems to be the sole determinant of the selective adaptation effects with speech.

Sawusch and Jusczyk (1981) approached this problem in a slightly different fashion. They constructed a fricative-stop-vowel syllable consisting of [s] frication followed by 75 msec of silence and then a 10-msec voice-onset-time (VOT) [ba]. This resulted in a syllable whose spectral structure matched the [ba] end of a [ba]-[$\mathrm{p^ha}$] series, yet was identified by subjects as [spa]. This stimulus (referred to as [spa] hereafter) was used as an adaptor with a [ba]-[$\mathrm{p^ha}$] voicing continuum. If adaptation affected phonetic processing, the [spa] should have produced effects similar to those of [$\mathrm{p^ha}$], since they share phonetic labels. However, the [spa] produced adaptation effects virtually identical to those of the [ba], following its spectral structure (and auditory coding) rather than its phonetic percept.

In a second experiment, Sawusch and Jusczyk used a paired-comparison procedure. Diehl, Elman, and McCusker (1978) and Diehl, Lang, and Parker (1980) had previously shown that this procedure produced contrast effects. That is, when a good exemplar of a phonetic category was paired with an ambiguous stimulus, subjects identified the ambiguous stimulus as belonging to the phonetic category opposite to that of the good exemplar. Using this same procedure, Sawusch and Jusczyk paired an ambiguous VOT syllable (30-msec VOT) with [ba], [$\mathrm{p^ha}$], and [spa]. The effects of [$\mathrm{p^ha}$] and [spa] were identical and opposite those of the [ba] exemplar. Sawusch and Jusczyk concluded that the contrast effects produced in the paired-comparison procedure occur at a phonetic level of coding, whereas adaptation affects an auditory level of coding that is based on the spectral overlap of the adaptor and the test series. These results have since been replicated and extended by Sawusch and Mullennix (1985).

Sawusch and Nusbaum (1983) also tested the effects of an adaptor that spectrally matched one end of a series but was identified by subjects to match the opposite end. They constructed a [da]-[ga] series and added frication appropriate for [s] to one of the [da] syllables. The resulting syllable was identified by subjects as [ska], sharing the place of articulation feature with the [ga] end of the test series. The same effects were found as in Sawusch and Jusczyk: the adaptation followed the spectral overlap between adaptor and test series. The [ska] and [da] adaptors produced identical effects, opposite those produced by [ga]. The [ska], [da], and [ga] syllables were also used as exemplars in a paired-comparison procedure. The results found were similar to those found by Sawusch and Jusczyk (1981). The contrast effects of the paired-comparison procedure followed the phonetic quality of the exemplars and not their spectral structure.

Diehl, Kluender, and Parker (1985) have recently put forward an alternative interpretation of the adaptation results. They proposed that the stimuli used as adaptors in the above experiments were highly likely to produce streaming. Streaming is the perceptual segregation of a sequence of rapidly repeated sounds into two or more streams. For example, the rapid alternation of a high-pitched tone and a buzz produces the impression of two separate sound sequences. One consists of a repeating tone and the other, of a repeating buzz (see Bregman, 1978b, 1981, for reviews). The formation of streams is dependent on the stimulus structure. Components similar in structure (e.g., pitch) will group together and form a single stream.

If streaming occurred during the adapting sequence in the Sawusch and Jusczyk (1981) experiment, the frication ([s]) would perceptually separate from the rest of the syllable. The [spa] would separate into [s] and [ba], destroying the phonetic percept of [p] in the adapting syllable. Since the frication [s] consisted of high frequencies while the rest of the syllable contained predominantly low frequencies, Diehl et al. (1985) claimed that this difference in frequency would facilitate the splitting of the [s] from the [ba]. Diehl et al. also proposed that the short interadaptor interval with multiple repetitions of the adaptor used by Sawusch and Jusczyk would further increase the probability of streaming. Bregman (1978a) found that the optimal conditions to promote stream segregation were a rapid presentation rate with multiple repetitions. Given the structure of the adaptor and the presentation rate used in the Sawusch and Jusczyk study, Diehl et al. claimed that streaming of the adapting sequence would be highly likely. If the adapting sequence did segregate into streams of [s] and [ba], the phonetic percept of the adaptor would then match its spectral structure. With this change of percept, it would be difficult to conclude that no phonetic processes were involved in selective adaptation, or that selective adaptation and paired-comparison procedures produced opposite effects.

If the rapid presentation of many repetitions of a sound sequence facilitates stream segregation, then relatively few repetitions and/or a slow presentation rate should inhibit stream segregation. With this in mind, Sawusch and Nusbaum (1983) and Sawusch and Mullennix (1985) took measures to avoid streaming in their adaptation sequences. The interadaptor interval was increased to 800 msec, and the number of repetitions of the adaptor was reduced. Sawusch and Nusbaum used 30 repetitions; Sawusch and Mullennix used 50 (as compared with the 75 repetitions with a 300-msec interval used by Sawusch and Jusczyk, 1981). One should note that Bregman reported that with an indefinite number of repetitions of tones, the longest interval to produce streaming was a 275-msec onset-to-onset time. The 800-msec interval used by these two studies was more than twice that. This long interval, with the reduced number of repetitions, would seem to have substantially reduced the likelihood of streaming.

In addition, none of the subjects run by either Sawusch and Mullennix or Sawusch and Nusbaum reported any experience of the adaptor sequence's splitting into two streams, even when stream segregation was explicitly described to them. It seems unlikely that streaming could have occurred in either of these studies (but see Diehl et al., 1985, for an alternative view). The evidence from these studies seems to favor an interpretation of selective adaptation in terms of auditory coding processes.

If selective adaptation affects the auditory coding of speech, the results of adaptation experiments can be used to address the second major question: What type of coding operations are involved in the auditory processing of speech? Some empirical findings related to this question come from cross-series adaptation experiments. Previous experiments have found vowel-contingent adaptation. Sawusch and Pisoni (1978) constructed two consonant-vowel series that varied along place of articulation: [ba-da] and [bi-di]. They then tested the effects of two alternating adaptors (i.e., [bi] and [da] or [ba] and [di]) on each series. Contingent effects were found for both series; [bi] did not adapt the [ba-da] series and [da] did not adapt the [bi-di] series. Similar results were found for the [ba]-[di] adaptor pair. Cooper (1974) constructed two series that varied in VOT—[ba]-[p^{h}a] and [bi]-[p^{h}i]—and used a [da]-[t^{h}i] adapting sequence. These alternating adaptors produced opposite effects for both series. The boundary of the [ba]-[p^{h}a] series shifted toward [ba], and the [bi]-[p^{h}i] series shifted toward [p^{h}i]. Cooper claimed that these opposing shifts indicated that adaptation was dependent upon the vowel environment: strong adaptation occurred only when adaptor and test series shared the same vowel.

The lack of cross-series adaptation poses a problem for a phonetic interpretation of the adaptation effects. The [b]s in [ba] and [bi] should have similar representations in a linguistic system and therefore should produce similar adaptation effects on a linguistic feature detector. The absence of cross-series adaptation effects makes the existence of linguistic feature detectors for place of articulation and voicing seem highly doubtful. However, the lack of adaptation does not discount an auditory locus for selective adaptation. As Bailey (1975) has noted, the stimuli used in cross-series adaptation experiments seem to show little or no spectral overlap.

In general, when the vowel is changed in a stop consonant-vowel series, the detailed spectral-temporal structure of the syllable changes substantially. For example, Bailey (1975) constructed two-formant stop-vowel series that were identified by subjects as [bi]-[di] and [ba]-[da]. In the [ba]-[da] series, the [ba] end was cued by a moderately rising second formant (F2) transition whereas the [da] end was cued by a moderately falling F2 transition. However, for the [bi]-[di] series, the [bi] end was cued by a rather substantially rising F2 transition whereas the [di] end contained an essentially flat F2. Bailey found no cross-series adaptation between these two series. The question now becomes: Which aspect of these various differences between the [ba]-[da] and the [bi]-[di] series was responsible for the lack of a cross-series adaptation effect? Was it, as suggested by Bailey (1975; also Ades, 1976), the lack of spectral overlap between the two series, regardless of the vowel? Alternatively, was the lack of a cross-series effect due to the presence of two different vowels that produced two different contexts, as proposed by W. E. Cooper (1974)? The adaptors that have shown some overlap with the test series generally produced some degree of adaptation. The spectral match between adaptor and the test series seems to be the important factor for adaptation, yet few of these experiments have carefully controlled the spectral overlap/separation between the adaptor and test series.

To describe the auditory coding processes that underlie speech perception, it is critical to distinguish between these two alternative explanations for the lack of cross-series adaptation effects. If selective adaptation effects are, indeed, vowel contingent regardless of the spectral overlap between adaptor and test series (as suggested by W. E. Cooper, 1974), then we run the risk of a proliferation of "contingent coding mechanisms." In essence, we would need "smart devices" which would determine the vowel in a syllable before deciding whether or not to respond to the prior auditory information which serves to cue the identity of the stop-consonant. Furthermore, every time a new contingent adaptation effect was found, the list of smart mechanisms and what they are sensitive to would grow, potentially beyond all reasonable bounds. On the other hand, if adaptation effects were found to depend on the spectral commonality of the acoustic cues to stops regardless of the vowel environment, then mechanisms such as auditory feature detector fatigue (Ades, 1976; Bailey, 1975; Sawusch, 1977) or the retuning of an auditory coding network (Sawusch, 1977; Simon & Studdert-Kennedy, 1978) would seem to be reasonable explanations for the effects of selective adaptation to speech.

EXPERIMENT 1

To distinguish between these two alternatives and simultaneously determine whether any adaptation effects that are observed occur at an auditory or a phonetic level of coding, the speech stimuli must meet two requirements. First, stimuli are needed where the spectral commonality of the adaptor and test series is preserved while at the same time the adapting and test syllables contain different vowels. Second, the adapting syllables should share their spectral structure with one end of the test series while maintaining a phonetic identity that is identical to that of the opposite end of the test series (or neutral with regard to the test series). Such a set of stimuli would allow us to test both the effects of vowel environment on spectrally identical stops and the perceptual locus of adaptation. Previous work by F. S. Cooper, Delattre, Liberman, Borst, and Gerstman (1952) provides the basis for an appropriate set of stimuli. They created synthetic stop-vowel syllables in which bursts at 12 frequency positions were paired with seven steady-state vowels. A burst of around 1400 Hz was found to produce two different percepts when placed in different vowel environments: [p] in front of [i] or [u], and [k] when placed in front of [a]. Thus, when placed in different vowel environments, a physically (spectrally) identical burst was identified by subjects as two phonetically different stops with different places of articulation.

In the present experiment, similar stimuli were generated. In pilot testing, these syllables were identified by subjects as [pi], [ka], and [tu]. In addition, a [pa]-[ka] series of stimuli was generated by varying the spectral structure of the burst. The syllables [pi], [ka], and [tu], which share the same burst, and [pa], which is spectrally dissimilar from the three, were used as adaptors. With this series and these adaptors, spectral separation of the information underlying the identity of the consonants across vowel environments is controlled.

With this set of stimuli, the locus of adaptation (phonetic or auditory) can be pinpointed. The spectral structures of [pi] and [tu] at syllable onset matched one end of the test series ([ka]), the phonetic identity of [pi] matched the other end of the test series ([pa]), and the [tu] was neutral in its phonetic match with the test series. A phonetic explanation would expect adaptation to follow the phonetic labels: [pi] should produce the same direction of boundary shift as [pa]. An auditory theory, based on spectral overlap, would predict that [pi], [ka], and [tu] would produce similar shifts toward the [ka] end of the series, whereas [pa] would produce an opposite shift. Finally, if vowel environment plays a role in adaptation, there should be little or no effect on the [pa]-[ka] series when [pi] and [tu] are used as adaptors, since these syllables contain different vowels.

Method

Subjects. The subjects were 40 undergraduates who participated in partial fulfillment of a course requirement. All were native speakers of English with no reported histories of speech or hearing disorders.

Stimuli. A seven-stimulus [pa]-[ka] series was generated using the cascade/parallel software synthesizer described by Klatt (1980) and implemented by Kewley-Port (1978). All stimuli were 250 msec in duration. The initial 20 msec consisted of burst frication, which was followed by 40 msec of silence. Voicing began at 60 msec after onset of the burst. The formant frequencies for the [a] vowel were constant at 700 Hz (for the first formant, F1), 1220 Hz (F2), 2450 Hz (F3), 3300 Hz (F4), and 3850 Hz (F5). The fundamental frequency was linearly interpolated from 126 to 102 Hz over the duration of the vowel. Voicing amplitude (AV) was held constant and then linearly ramped off over the final 50 msec of the syllable.

The only difference between the stimuli in the series was in the burst frication. For the [pa] endpoint stimulus, the amplitudes of F1, F3, F4, and F5 were set to zero for the duration of the burst. Only F2 was excited with its center frequency at 1060 Hz, its amplitude (A2) set at 60 dB, and its bandwidth (B2) at 160 Hz. Frication amplitude (AF) was set to 42 dB for 15 msec, dropped to 21 dB for the next 5 msec, and then to 0 dB for the remainder of the syllable. The Klatt synthesizer parameters for the initial 65 msec of the [pa] endpoint are shown in Table 1.

To generate the seven-element [pa]-[ka] series, F2 frequency during the burst was increased in 90-Hz steps, B2 was decreased in 10-Hz steps, and the AF was increased in 2-dB steps to the [ka] endpoint values shown in Table 2. These changes were made in six steps to form the seven stimuli in the [pa]-[ka] continuum.

Table 1
Klatt Synthesizer Parameters for the [pa] Endpoint Syllable Onset

Time	AV	AF	F1	A1	B1	F2	A2	B2	F3	A3	B3
0	0	42	400	0	300	1060	60	220	2450	0	300
5	0	42	400	0	300	1060	60	220	2450	0	300
10	0	42	400	0	300	1060	60	220	2450	0	300
15	0	21	400	0	300	1060	60	220	2450	0	300
20	0	0	400	0	300	1060	60	220	2450	0	300
25	0	0	400	0	300	1060	60	220	2450	0	300
30	0	0	400	0	300	1060	60	220	2450	0	300
35	0	0	400	0	300	1060	60	220	2450	0	300
40	0	0	400	0	300	1060	0	220	2450	0	300
45	0	0	400	0	300	1060	0	220	2450	0	300
50	0	0	400	0	300	1113	0	177	2450	0	300
55	0	0	550	0	210	1167	0	137	2450	0	235
60	54	0	700	0	120	1220	0	90	2450	0	170
65	60	0	700	0	120	1220	0	90	2450	0	170

The values for the [ka] burst (Table 2) were added to values appropriate for [i] and [u] vowels to generate the [pi] and [tu] syllables. Onset frequencies for the [u] vowel were 330 Hz (F1), 1000 Hz (F2), 2250 Hz (F3), 3300 Hz (F4), and 3850 Hz (F5). F1, F3, F4, and F5 remained steady while F2 was linearly interpolated to 870 Hz at 140 msec and then remained constant at 870 Hz for the rest of the syllable. Onset frequencies for the [i] vowel were 310 Hz (F1), 2020 Hz (F2), 2800 Hz (F3), 3500 Hz (F4), and 4000 Hz (F5). F3, F4, and F5 remained steady while F1 was linearly interpolated to 295 Hz at 250 msec and F2 was interpolated to 2070 Hz at 250 msec.

Procedure. The stimuli were stored on computer disk in digital form and presented to subjects under the real-time control of a Digital Equipment Corporation PDP-11/34 computer. They were converted to analog form via a 12-bit digital-to-analog converter running at a 10-kHz sampling rate. The stimuli were lowpass filtered at 4.8 kHz, and presented to subjects binaurally through TDH-39 matched and calibrated headphones at an intensity level of 72 dB SPL for a steady-state [a] vowel. The subjects responded by pushing the appropriately labeled button on a computer-controlled response box. All responses were recorded by computer. In all the conditions, sessions were run with groups of 1 to 5 subjects.

All subjects were first given a baseline identification test. For the first block, the subjects were given five repetitions of each of the [pa]-[ka] series stimuli, in random order, as a practice set. The subjects responded using a 6-point rating scale, 1 being a "good" [p], 3 and 4 being guesses of [p] and [k], respectively, and 6 being a "good" [k]. For the practice set, the subjects were given feedback for the Stimulus 1 and Stimulus 7 endpoints in the form of a light over Button 1 or Button 6 indicating whether a [p] or a [k]

Table 2
Klatt Synthesizer Parameters for the [ka] Endpoint Syllable Onset

Time	AV	AF	F1	A1	B1	F2	A2	B2	F3	A3	B3
0	0	54	400	0	300	1600	60	160	2450	0	300
5	0	54	400	0	300	1600	60	160	2450	0	300
10	0	54	400	0	300	1600	60	160	2450	0	300
15	0	27	400	0	300	1600	60	160	2450	0	300
20	0	0	400	0	300	1600	60	160	2450	0	300
25	0	0	400	0	300	1600	60	160	2450	0	300
30	0	0	400	0	300	1600	60	160	2450	0	300
35	0	0	400	0	300	1600	60	160	2450	0	300
40	0	0	400	0	300	1600	0	160	2450	0	300
45	0	0	400	0	300	1600	0	160	2450	0	300
50	0	0	400	0	300	1473	0	137	2450	0	300
55	0	0	550	0	210	1347	0	113	2450	0	235
60	54	0	700	0	120	1220	0	90	2450	0	170
65	60	0	700	0	120	1220	0	90	2450	0	170

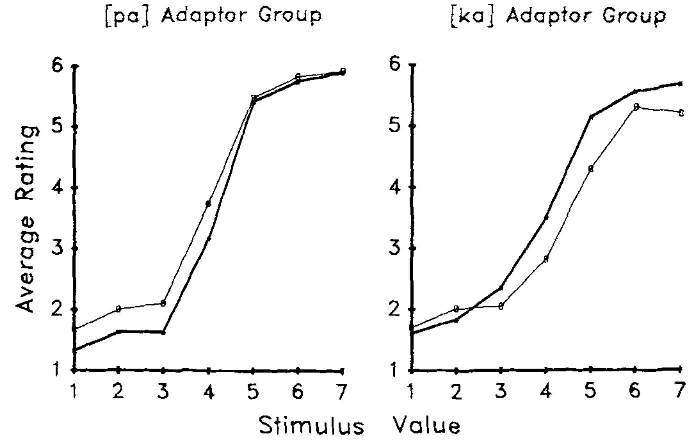

Figure 1. Baseline (heavy line and *) and adapted (light line and ○) rating functions for the [pa] adaptor group (left) and the [ka] adaptor group (right).

had been presented. No feedback was provided for the remaining trials. The subjects then listened to two blocks of identification trials. Each block contained 10 repetitions of each of the [pa]-[ka] stimuli in random order. This was followed by another block of identification trials, which consisted of the test series endpoints ([pa] and [ka]), [pi], and [tu]. For this block, the subjects used just three labels: [p], [t], or [k]. The subjects received one block of 20 repetitions of each of these four stimuli in random order.

The subjects were divided into four groups of 10 for the adaptation trials. Each group listened to a different adapting syllable: [pa], [ka], [pi], or [tu]. Adaptation testing consisted of two blocks of 10 adaptation trials each, for a total of 20 adapted presentations of each of the [pa]-[ka] test stimuli. Each adaptation trial started with 30 repetitions of the adaptor with an interadaptor interval of 500 msec. This was followed by the seven test syllables in random order. The subjects used the 6-point rating scale to respond to the test syllables, as in the identification set.

Results

An average (mean) rating was computed for each stimulus in both the baseline and adaptation conditions for each of the subjects. The baseline and adapted rating functions for each of the four adaptor groups are shown in Figures 1 and 2. The [pa]-[ka] category boundary for each subject was then determined by linear interpolation between the two stimuli on either side of the boundary. The mean differences between the baseline and adapted category boundaries for each of the four adaptor groups are shown in Table 3. A positive value indicates movement of the category boundary toward the [pa] end of the series; a negative value indicates movement toward the [ka] end of the series.

The [pa] and [ka] adaptors produced the expected effects; the category boundary shifted toward the adaptor end of the series, relative to the baseline. The [ka] produced a significant shift [$t(9) = -2.86$, $p < .02$].[1] The [pa] adaptor did not produce a significant shift in the category boundary, although it did produce a shift in the proper direction [$t(9) = 1.72$, $p > .1$]. The [pi] and [tu] adaptors also produced significant shifts [$t(9) = -3.61$, $p < .01$, and $t(9) = -2.28$, $p < .05$]. In both cases, the shift in the category boundary was toward the [ka] end of the series (see Table 3).

As a further check on these adaptation results, the per-

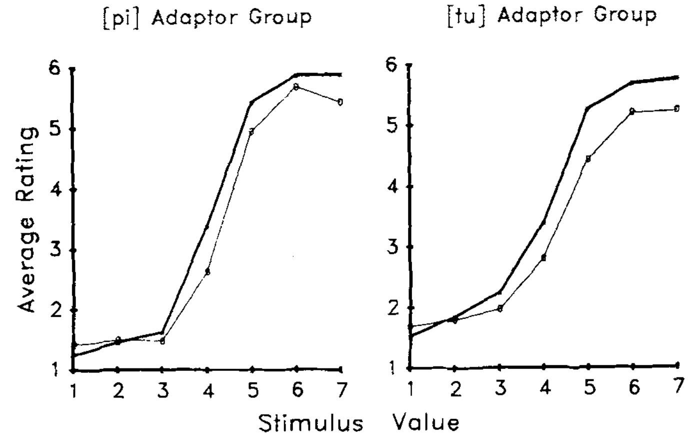

Figure 2. Baseline (heavy line and *) and adapted (light line and ○) rating functions for the [pi] adaptor group (left) and the [tu] adaptor group (right).

Table 3
Mean Shift in the Category Boundary and Change in the Percentage of [p] Responses for the Test Series for Each of the Adaptation Groups

	Adaptor			
	[pa]	[ka]	[pi]	[tu]
Category Boundary Shift	.23	−.38	−.32	−.26
(standard deviation)	.36	.35	.26	.28
Percent [p] Response Change	4.3	−6.6	−6.8	−4.8
(standard deviation)	3.9	6.8	4.5	6.5

centage of [p] responses to the test series as a whole was determined for both the baseline and the adapted conditions for each subject. Ratings of 1, 2, or 3 were considered to represent [p] identification responses, and 4, 5, and 6 represented [k]. Table 3 shows the difference in the percentage of [p] responses to the test series between baseline and adapted conditions for each of the four adaptor groups. As before, a positive value indicates a change toward the [pa] end of the series. Both [pa] and [ka] produced significant changes in the overall percentage of [p] responses, with [pa] producing a significant decrease [$t(9) = 3.23, p < .02$] and [ka] producing the opposite effect, a significant increase in [p] responses [$t(9) = -2.89, p < .02$]. Both [pi] and [tu] produced changes similar to that of [ka] (an increase in the overall percentage of [p] responses), with the significant effect of [tu] [$t(9) = -4.51, p < .002$] and the marginal effect of [pi] [$t(9) = -2.19, .05 < p < .1$].

The adaptation effects produced by [pi], [tu], and [ka] were all significantly different from the effect of [pa] [$t(18) = 4.03, p < .002$; $t(18) = 3.42, p < .01$; $t(18) = 3.32, p < .01$, respectively]. Furthermore, the effects of [pi], [tu], and [ka] were all virtually identical. Comparison of the category boundary shifts of [pi] and [tu], [ka] and [pi], and [ka] and [tu] all produced nonsignificant differences [$t(18) = .80, p > .2$; $t(18) = -.32, p > .5$; and $t(18) = .37, p > .5$].[2]

In addition, the subjects were asked to identify the four adapting syllables as containing [p], [t], or [k]. These data are shown in Table 4 as the percentage of [p], [t], and [k] responses for each group for their adapting syllable. Thus, the data for each syllable in Table 4 represent a different group of 10 subjects. The [pa] and [ka] endpoints were identified, as expected, as [p] and [k], respectively. Subjects consistently identified the [pi] syllable as [p] and the [tu] syllable as containing a [t]. The single burst placed in front of the the vowels [i], [a], and [u] produced phonetic percepts of [p], [k], and [t], respectively. In spite of the three different percepts, the effects of these three syllables as adaptors were virtually identical. Thus, there appears to be no significant relationship between the phonetic percept for a syllable and its effect as an adaptor in the selective adaptation paradigm.

Table 4
Percentages of [p], [t], and [k] Responses to Each of the Four Adapting Syllables

	Adapting Syllables			
	[pa]	[ka]	[pi]	[tu]
Percent [p] Responses	88	8	91	15
Percent [t] Responses	7	9	9	78
Percent [k] Responses	5	83	0	7

Discussion

These results support previous findings that adaptation is dependent upon the spectral match between adaptor and test series, regardless of phonetic identity. The single burst produced three phonetic percepts—[pi], [ka], and [tu]—yet resulted in nearly identical boundary shifts (all toward [ka]). The syllable [pi], even though it shared the phoneme [p] with [pa], produced an opposite shift, one in the direction of its spectral mate, [ka]. Any phonetic involvement would have dictated that [pa] and [pi] should produce similar effects. At the least, [pi], sharing its phonetic identity with one end of the series and sharing its physical identity with the opposite end, should have shown a lesser shift due to this conflict. Since no such effect was found, it seems safe to conclude that little or no phonetic processing is involved in adaptation. The lack of any phonetic involvement found for voicing (Sawusch & Jusczyk, 1981; Sawusch & Mullennix, 1985) and for place of articulation (Roberts & Summerfield, 1981; Sawusch & Nusbaum, 1983; and this experiment) leaves little doubt that the locus of adaptation is in early auditory processes. No effect of the phonetic coding of the adaptors has been found in any of these experiments.

Also tested for were the effects of vowel environment on adaptation. Previous experiments had found vowel-contingent effects: a change in the vowel environment resulted in lesser adaptation effects (W. E. Cooper, 1974; Sawusch & Pisoni, 1978). With these studies, however, alternating adaptors were used and the degree of spectral match between adaptor and test series was not precisely controlled for. The present experiment controlled for spectral match and used a single adaptor. Vowel-contingent effects were not found. Rather, stimuli with identical bursts produced shifts in the same direction and of the same magnitude. The vowel did not affect adaptation of the stop portion of the syllable. Vowel-contingent adaptation would have been seen as a greater shift for the adaptor that shared the same vowel with the test series ([ka]) relative to the other stimuli ([pi] and [tu]). No such greater shift was found, since [ka], [pi], and [tu] all produced similar effects. Thus, it appears that the auditory coding processes that are being tapped by the selective adaptation procedure are coding the bursts in [pi], [ka], and [tu] identically. This indicates that the temporal window over which the auditory coding process is operating is relatively brief, since it does not appear to include vowel information in its analysis of the burst.

EXPERIMENT 2

An alternative to our interpretation of the adaptation results of Experiment 1 is that during adaptation, the burst and the vowel segregated and formed separate streams of sound (see Diehl et al., 1985). This would have destroyed the different phonetic percepts of [pi], [ka], and [tu] and would make the interpretation of the adaptation results problematic. Our own experience in listening to the adaptors repeat with a 500-msec interadaptor interval (IAI) was that the stimuli did not stream. However, Diehl et al. have reported (on the basis of their experience of listening to an adaptor sequence) that some syllables appeared to stream at IAIs as long as 1,000 msec. Given the conflict between the account of selective adaptation proposed here and that proposed by Diehl et al., a direct test of the streaming hypothesis seemed to be warranted.

The only alternative to this seemed to be to lengthen the IAI to a few seconds, as proposed by Diehl et al. This alternative carries with it two problems. One is that some previous research has found that as the IAI is lengthened to a few seconds, adaptation effects are reduced or eliminated (Simon, 1977). The second potential problem is that, as proposed by Sawusch and Mullennix (1985), the contrast effects produced by long IAIs (on the order of several seconds) may not reflect the same perceptual processing operations as those produced by short IAIs. Although this proposal requires further experimental investigation, it mitigates against the use of long IAIs in adaptation experiments.

Given this set of constraints, Experiment 2 was conducted to determine both the threshold for stream segregation and the psychometric function (relating repetition interval, or ISI, to streaming judgments) for each of the four adapting syllables used in Experiment 1. If the longest ISI at which any of the four adaptors stream (for any subject) is shorter than the 500-msec IAI used in Experiment 1, then we will have evidence that streaming *cannot* be used as a counterargument to our interpretation of Experiment 1. Alternatively, if some or all of these four syllables do show some evidence of breaking up into two streams of sound with a 500-msec ISI, then stream segregation, as described by Diehl et al. (1985), would constitute a viable alternative explanation for the results of Experiment 1.

Method

Subjects. The subjects were 8 undergraduate and graduate students at SUNY/Buffalo who were paid $4 an hour for their participation. They reported no histories of either speech or hearing disorders and were native speakers of English.

Stimuli. The stimuli used were the four adaptors ([pi], [ka], [tu], and [pa]) from Experiment 1.

Procedure. Each subject was tested individually. The format for all subjects was the same. The stimuli were presented to subjects in real time by the PDP-11/34 computer in the Speech Perception Laboratory at SUNY/Buffalo. The stimuli were converted to analog form via a 12-bit digital-to-analog converter at a 10-kHz sampling rate, lowpass filtered at 4.8 kHz, and presented to subjects binaurally over TDH-39 headphones. All stimuli were presented at an intensity of 72 dB SPL. Each subject participated in three conditions. The first consisted of identification trials. The four stimuli used as adaptors ([pi], [ka], [pa], and [tu]) were presented to the subjects, one at a time, for identification. Two blocks of identification trials were run. In the first (practice) block, each stimulus occurred five times in random order. In the second block, each stimulus occurred 20 times in random order. On each trial, the subjects were asked to indicate, by pressing the appropriate button on a computer-controlled response box in front of them, whether the stimulus presented contained a [p], [t], or [k].

In the second condition, an adaptive testing procedure (PEST, Taylor & Creelman, 1967) was used to determine the approximate interval at which each stimulus would stream or break up into two separate components on half of the trials. Four blocks of adaptive trials were run, one for each of the four stimuli. In each block, an adaptive trial consisted of 30 repetitions of a stimulus at a particular ISI. After the repetitions, the subjects indicated whether or not the sequence streamed. Streaming was described to the subjects as the impression that the presentation consisted of two distinct sequences of sound. Nonstreaming was described as the impression that a single sound was being repeated. For each subject, a starting ISI of 1,000 msec was used. The stopping criterion was 20 reversals of the judgment of streaming. This adaptive procedure was used here to provide an estimate of the 50% threshold for subjects and to familiarize them with the streaming phenomenon.

In the third condition, an up-down transform procedure with a fixed step size (fixed change in the ISI) was used (see Penner, 1978). The starting value for the ISI for each subject for these trials was just above the 50% threshold from the previous PEST run for that syllable. The ISI step size was fixed at 20% (one fifth) of the initial interval. On each trial, the subject listened to 30 presentations of one stimulus with one ISI. The subjects then made a forced choice between streaming and nonstreaming (as described above). Following each streaming response, the size of the ISI was increased (by one step) for the next trial. Following each nonstreaming response, the ISI was decreased (by one step) on the next trial. This rule for increasing or decreasing the ISI was designed to track the 50% point on a psychometric function for streaming judgments. Trials were run for each of the four stimuli until 24 reversals from streaming to nonstreaming (or vice versa) had occurred. By using a constant step size for each subject and a starting ISI near the 50% threshold, we were able to obtain data that could be used to determine a psychometric function relating the subjective experience of stream segregation to ISI for each of the four stimuli for each subject.

Results

For each subject, the percentage of streaming and nonstreaming responses was computed for each syllable at each ISI. The resulting psychometric functions are shown for each subject in Figures 3, 4, 5, and 6 for the syllables [pa], [ka], [pi], and [tu], respectively. As these functions show, the subjects were able to make consistent streaming and nonstreaming judgments. As the ISI increased, the percentage of nonstreaming responses increased, in most cases monotonically. Finally, with respect to these data, it should be noted that the longest ISI at which any of the four syllables received any streaming responses was 420 msec (for Subject h with the [ka] syllable; see Figure 4). At ISIs of 480 msec and longer, none of the four syllables received any streaming responses from any of the 8 subjects.

Discussion

The results from this experiment are entirely unambiguous in that subjects showed no evidence of hearing the syllables break up or stream at ISIs of 500 msec or more. Thus, it seems highly implausible that the adaptation se-

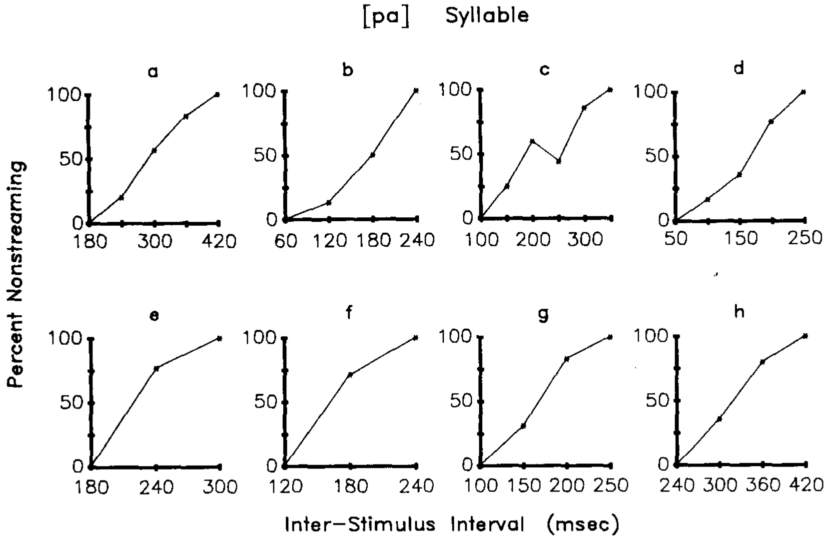

Figure 3. Percentage of nonstreaming responses at each ISI for the [pa] syllable for each subject.

quences used in Experiment 1 would have broken up and created the experience of two separate sound sequences. In both the adaptation trials and the streaming trials, the same number of syllable repetitions were used. Since these syllables broke up into two separate streams only at intervals shorter than the 500-msec interadaptor interval used in Experiment 1, streaming does not appear to have been a factor in our adaptation results. Consequently, this objection to our interpretation of the results of Experiment 1 can be safely dismissed.

EXPERIMENT 3

Our final concern in this series of experiments was to further explore the degree to which the contrast effects found in studies using the paired-comparison procedure reflect the phonetic quality of the exemplars, as proposed by Sawusch and Jusczyk (1981). A paired-comparison procedure similar to that used by Diehl et al. (1978; Diehl et al., 1980) and Sawusch and Jusczyk (1981) was employed. If the contrast effects produced by the paired-comparison procedure reflect the phonetic similarity between the exemplars and the test item, then, to the extent that our [pa] and [pi] syllables are labeled by subjects as containing the phoneme [p], both of these syllables should produce identical effects on an ambiguous test item. If this type of result is not found, then something other than the phonetic similarity of the items in a pair must be mediating the contrast effects produced by this procedure. In particular, if the contrast effects of both the paired-

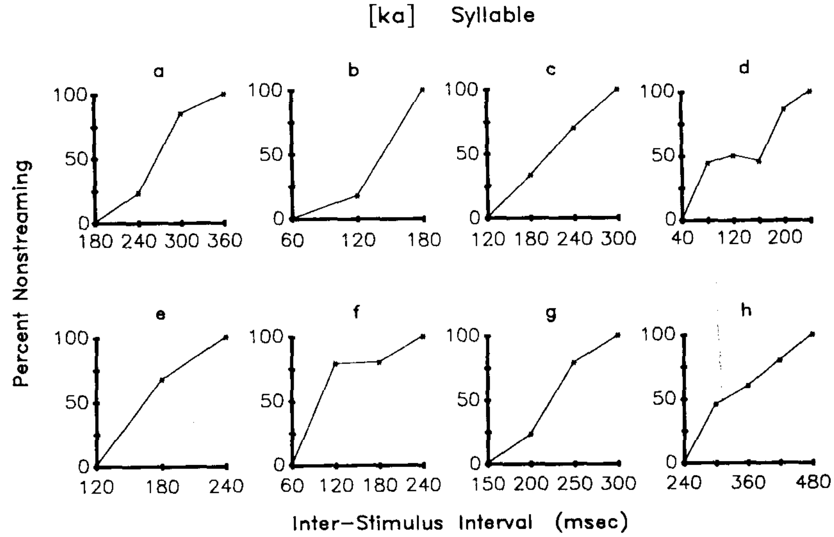

Figure 4. Percentage of nonstreaming responses at each ISI for the [ka] syllable for each subject.

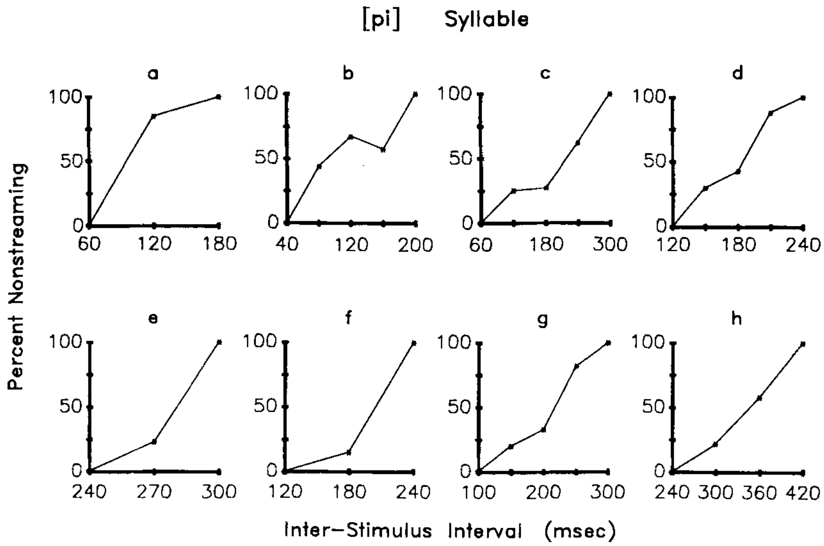

Figure 5. Percentage of nonstreaming responses at each ISI for the [pi] syllable for each subject.

comparison and adaptation procedures result from a common perceptual process (as proposed by Diehl et al., 1978), the [pa] and [pi] exemplars should produce different effects. On the basis of Diehl et al.'s proposals, we would expect to find substantially similar contrast effects for [ka], [pi], and [tu].

Method

Subjects. The subjects were 23 undergraduates who participated in partial fulfillment of a course requirement. All were native speakers of English with no reported histories of speech or hearing disorders.

Stimuli. The stimuli used were the four adapting syllables from Experiment 1 and an ambiguous syllable from the [pa]-[ka] series. Stimulus 4 was chosen for use as the test item in the paired-comparison procedure. This stimulus was closest to the category boundary for the [pa]-[ka] series baseline identification results (see Figures 1 and 2 from Experiment 1).

Procedure. The subjects were run in small groups of 2 to 6 at a time. All stimulus presentation was controlled by computer, as described for the two previous experiments. Each subject participated in two conditions. The first consisted of identification trials. The four adaptors ([pa], [ka], [pi], and [tu]) and Stimulus 4 from the [pa]-[ka] series were presented to the subjects, one at a time, for identification. Two blocks of identification trials were run. In the first, practice, block, each of the five stimuli was presented five times in random order. In the second block, each stimulus was presented 20 times in random order. For both blocks of trials, the subjects were asked to identify each syllable as containing [p], [t], or [k] and to enter their responses by pushing the appropriate button on a computer-controlled response box.

In the second condition, the subjects received two blocks of 72 trials each in a paired-comparison procedure. Each trial consisted

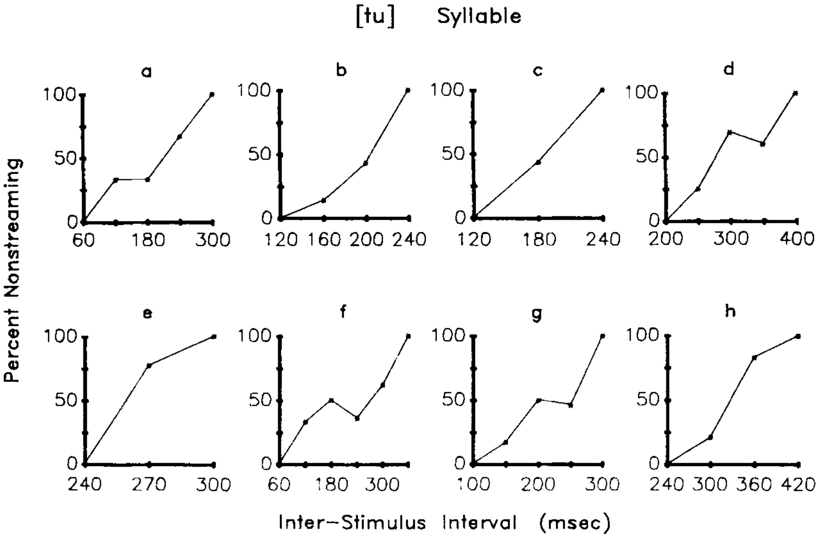

Figure 6. Percentage of nonstreaming responses at each ISI for the [tu] syllable for each subject.

of the presentation of two stimuli with an ISI of 400 msec and a response interval of 5,000 msec. Each block contained 48 stimulus pairs consisting of an ambiguous test syllable (Stimulus 4 from the [pa]-[ka] series) and a good exemplar (one of the four adaptors) in random order. The subjects were asked to identify the two stimuli, in order, as [p] or [k] by pressing the appropriately labeled button. The other 24 trials in each block were filler pairs that consisted of the [pa] and [ka] exemplars, presented in random order. Subjects responded to these pairs in the same fashion as they had to the exemplar-test pairs described previously. Thus, each subject provided 24 responses to the ambiguous test item when paired with each of the four exemplars.

Results

The results for the paired-comparison procedure are shown in Table 5. The percentage of [p] responses to the ambiguous test item is shown for each of the four exemplars that it was paired with. These data represent the means across all 23 subjects.

The [pa] and [ka] exemplars produced significantly different effects, with the [ka] exemplar inducing 15% more [p] responses to the test item than the [pa] exemplar [$t(22) = 2.93, p < .012$]. Similarly, the influences of the [pi] and [ka] exemplars were also significantly different [$t(22) = 2.58, p < .02$, for the mean difference of 11%]. Again, the [ka] exemplar produced more [p] responses. The effects of the [pa] and [pi] exemplars were *not* significantly different [$t(22) = 0.98, p > .2$, for the mean difference of 4%]. Thus, in the paired-comparison procedure, the [pa] and [pi] syllables produced similar effects. The effects of the [tu] exemplar were intermediate and not significantly different from either those of [pa] [$t(22) = 1.42, p > .1$] or [ka] [$t(22) = 2.03, p > .05$].

As in the adaptation conditions, the paired-comparison subjects were also presented with the four exemplar syllables, individually, and asked to identify each as containing [p], [t], or [k]. As was found for the adaptation subjects, the syllables [pa], [ka], [pi], and [tu] were identified as containing [p], [k], [p], and [t], respectively. The means for the percentages of [p], [t], and [k] responses across all 23 subjects are shown in Table 6.

Using these results as an index of the phonetic quality of the exemplars, we see that the two syllables identified by subjects as containing [p] ([pa] and [pi]) produced substantially similar results. Both of these syllables produced results opposite to those of the [ka]. Finally, the [tu] was identified by subjects as containing a [t]. This means that the [tu] syllable was perceived by subjects as being phonetically distinct (and dissimilar) from both the [pa] and [ka] exemplars. The [tu] syllable also produced results that were intermediate to those of both [pa] and [ka] in the paired-comparison procedure.

Table 5
Percentage of [p] Responses to the Ambiguous Test Item When Paired with Each of the Four Exemplars

	Exemplar			
	[pa]	[ka]	[pi]	[tu]
Percent [p] Responses	30	45	34	37

Table 6
Percentages of [p], [t], and [k] Responses to Each of the Four Exemplar Syllables

	Exemplar			
	[pa]	[ka]	[pi]	[tu]
Percent [p] Responses	82	1	79	24
Percent [t] Responses	5	13	17	70
Percent [k] Responses	13	86	4	6

Discussion

Our paired-comparison results are also similar to those previously reported by Sawusch and Jusczyk (1981) and Sawusch and Nusbaum (1983). In addition, the present results extend these previous findings and those of Diehl et al. (1978; Diehl et al., 1980) in important ways. First, subjects identified the [pa] and [pi] syllables as being similar in that both contain the stop [p]. When used as exemplars in the paired-comparison procedure, [pa] and [pi] produced similar effects. Thus, the contrast effects produced by paired comparison seem to be independent of the vowels in the syllables. The phonetic percept that is produced by the exemplar seems to be the major (and possibly only) determinant of its effects on the ambiguous test item.

The [tu] exemplar was identified by subjects as containing the stop [t]. In some sense, then, this exemplar can be seen as being equally similar (or dissimilar) to both [pa] and [ka], since its perceived phonetic quality ([t]) matches neither of these. As an exemplar, the [tu] produced results intermediate between [pa] and [ka]. This intermediate result is to be expected if the effects of the paired-comparison procedure are based on the perceived phonetic similarity between the exemplar and the test item.

Finally, the results of the [tu] exemplar have some bearing on the question of whether the effects of the paired-comparison procedure originate at a phonetic level of coding or at some later, response stage. In the three-alternative categorization task, the [tu] syllable was identified by subjects as containing the stop [t]. However, in the paired-comparison procedure, subjects were requested to label all stimuli, including the [tu], as either [p] or [k]. In response to the [tu], 10 of the 23 subjects used the [k] response on a majority of the trials, 12 used the [p] response on a majority of the trials, and 1 subject used [p] and [k] equally often. For both the 10 subjects who chose to label the [tu] as [k] and the 12 who used the label [p], the effects of the [tu] exemplar were intermediate between those of the [pa] and [ka] exemplars. Consequently, the response label provided by the subject when forced to choose between [p] and [k] does not appear to have influenced the effect of the [tu] exemplar in any way. This effectively rules out any overt response bias account (such as range-frequency theory; Parducci, 1975) of the effects produced by the paired-comparison procedure. (See Diehl, 1981, for a review of additional data counter to a response bias explanation.) Rather, the phonetic similarity between the exemplar and the test item, irrespective of the rest of the syllable, appears to determine the direction and extent of the contrast effects found with this procedure.

GENERAL DISCUSSION

The data support the notion that selective adaptation effects are dependent upon the spectral commonality of stop cues between adaptor and test series, regardless of vowel environment. From these data, the locus of adaptation is in early auditory processes, since spectral match is the major determinant of the effects found. No effect of shared phonetic identity was found. Thus, it seems evident that no phonetic processes are involved in selective adaptation.

The lack of any vowel contingency in our adaptation results has two major implications. First, this result is consistent with the operation of passive feature detectors or the retuning of an auditory coding network. Our results demonstrate that when spectral overlap is maintained, no vowel contingency effects in adaptation are found. Thus, one need not propose "smart" mechanisms that take surrounding context (e.g., vowel) into account before deciding whether to respond to a particular segment of the speech waveform in order to account for selective adaptation results. The previous vowel-contingent adaptation results appear to be the result of changes in the spectral overlap between adaptor and test series. Secondly, the lack of any influence of vowel environment indicates that the perceptual processes or representation affected by selective adaptation is sensitive to relatively short stretches of the stimulus. Since the duration of the burst plus the following silence before the vowel in our four adaptors was 60 msec, this would appear to represent the upper limit for the temporal window of stimulus information that produces adaptation.

It is tempting to speculate about the neural locus in the human auditory system at which adaptation effects occur. For example, the work of Delgutte and Kiang (1984) shows evidence of adaptation in the pattern of neural discharge in the peripheral auditory system (following basic frequency analysis) for consonant-vowel syllables. Since these neural units are frequency specific, they would be expected to produce adaptation that is spectrally specific, such as that found in the present experiment. Although this account might be sufficient to explain our data from Experiment 1, it is not sufficient as a general account of selective adaptation with speech (see also Summerfield, Haggard, Foster, & Gray, 1984). Ades (1974), Eimas, Cooper, and Corbit (1973), Jamieson and Cheesman (1986), and Sawusch (1977) have all reported evidence of centrally located adaptation effects. In some of these experiments, adapting in one ear and testing in the other ear resulted in an 80% to 100% interaural transfer of adaptation (see Jamieson & Cheesman, 1986). That is, the magnitudes of cross-ear adaptation and same-ear (monaural) adaptation effects were substantially similar. This indicates that at least part of the effects of selective adaptation are central, after the peripheral, frequency-specific coding described by Delgutte and Kiang (1984). Other results reported by Bryant (1978) and Sawusch (1977) seem to require the involvement of an abstract (not frequency-specific) representation to account for selective adaptation (see Sawusch, 1986, for a review). Thus, although a peripheral, frequency-specific neural coding of the waveform may be affected by adaptation, further auditory processing operations (or, alternatively, a more abstract auditory representation) also seem to be affected by selective adaptation.

The paired-comparison procedure seems to have produced its effects at a phonetic level of processing. That this level is relatively abstract is confirmed by the substantially similar effects of [pi] and [pa] exemplars. Neither the difference in spectral overlap between the [pa] and [pi] exemplars and the test item nor the variation in vowel seems to have influenced the results. Rather, the perceived phonetic quality of the stop seems to be the sole determinant of the effects that we obtained. Thus, the paired-comparison procedure seems to tap an abstract, phonetic representation of speech. Recent results reported by Samuel (1986) add further support to this dissociation between selective adaptation and paired-comparison results. Samuel found that contrast effects were obtained only when the exemplar and the test item were both presented to the right ear. No left ear monaural effect was found, and no interaural transfer was found. Since adaptation does produce interaural transfer and monaural effects for both ears, Samuel concluded that adaptation and paired-comparison procedures affected different representations of the speech signal. His finding that paired-comparison effects are right-ear specific, and thus possibly left-hemisphere specific, is consistent with our findings that paired-comparison contrast effects follow the phonetic (language-specific) coding of the stimuli.

In summary, our data support a multistage model of the auditory to phonetic coding of speech. Furthermore, they indicate that the early, auditory coding of speech may be mediated by passive, spectrally specific processes. The auditory coding of speech is followed by an abstract, phonetic coding process. Our data are counter to the unified, adaptation level account of contrast effects in speech perception previously offered by Diehl (1981). Rather, contrast effects produced by different experimental procedures seem to arise at distinct stages or representations in perceptual processing. The behavioral similarity of the contrast effects is an illusion, caused by the usual near-perfect correlation between the acoustic stimulus, its auditory coding, and its phonetic percept. As our results and those of Samuel (1986) demonstrate, the different experimental procedures of selective adaptation and paired comparison can be employed to probe the nature of different perceptual representations (or processing operations) in the perception of speech.

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NOTES

1. All statistical tests, unless otherwise noted, are correlated t tests. All p levels are two-tailed.
2. Independent t tests were used.

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