Stimulus order effects in vowel discrimination

Bruno H. Repp
Haskins Laboratories, 270 Crown Street, New Haven, Connecticut 06511-6695

Robert G. Crowder
Department of Psychology, Yale University, New Haven, Connecticut 06520

(Received 9 August 1989; accepted for publication 2 August 1990)

In same–different discrimination tasks employing isolated vowel sounds, subjects often give significantly more "different" responses to one order of two stimuli than to the other order. Cowan and Morse [J. Acoust. Soc. Am. 79, 500–507 (1986)] proposed a *neutralization hypothesis* to account for such effects: The first vowel in a pair is assumed to change its quality in memory in the direction of the neutral vowel, schwa. Three experiments were conducted using a variety of vowels and some initial support for the hypothesis was obtained, using a large stimulus set, but conflicting evidence with smaller stimulus sets. Rather than becoming more similar to schwa, the first vowel in a pair seems to drift toward the interior of the stimulus range employed in a given test. Several possible explanations are discussed for this tendency and its relation to presentation order effects obtained in other psychophysical paradigms is noted.

PACS numbers: 43.71.Pc, 43.71.Es, 43.71.An, 43.66.Jh

INTRODUCTION

The perception of vowels has long been of central interest to speech researchers (see Nearey, 1989, for a recent review). Isolated vowels, being the simplest instantiation of speech, provide a common testing ground for theories of auditory psychophysics and of speech perception. For the former, they offer the challenge of complexity; for the latter, the advantage of simplicity. Even though these sounds are far removed from the connected speech that speech perception theories ultimately need to be concerned with, they are not entirely unnatural: Some isolated vowels occur as exclamations, fillers, or even as real words; all are readily elicited as pronunciation "prototypes" from native speakers; and their presentation in a perceptual test usually engages the listeners' mechanisms of phonetic categorization unless stimulus uncertainty is minimized (see Macmillan *et al.*, 1988).

To study the identification and discrimination of isolated vowels, many researchers have used stimuli drawn from an acoustic continuum spanning two or three phonetic categories. Although the perception of isolated vowels is not strongly categorical (i.e., discrimination performance within phonetic categories is well above chance), there is usually a contribution of phonetic categorization to discrimination performance (i.e., discrimination is most accurate in the category boundary regions). This was demonstrated, for example, by Pisoni (1973, 1975) in several discrimination paradigms, including a "same–different" task. This simple task has been employed in a number of later studies concerned with the role of auditory memory in vowel discrimination.

In one of these studies, we (Repp *et al.*, 1979) presented subjects with pairs of stimuli from a 13-member synthetic /i/–/ɪ/–/ɛ/ continuum, obtained by stepwise linear interpolation between the formant frequencies of /i/ and /ɛ/. Our most important finding was that a substantial part of the discrimination performance could be accounted for by contrast effects between the members of stimulus pairs, as revealed in a labeling task, though it remained unclear whether these contrast effects were the cause or the consequence of heightened discriminability (see also Healy and Repp, 1982). We also observed, in agreement with earlier results of Shigeno and Fujisaki (1980), that retroactive contrast (the effect of the second vowel in a pair on the labeling of the first) was larger than proactive contrast (the converse) when both vowels in a pair had to be classified, presumably because the first vowel in a pair had to be held longer in memory and thus was less stable when the second vowel arrived. In addition to these contrast effects, however, the subjects' responses revealed an unexpected effect of stimulus order: For pairs of nonidentical stimuli from the /i/–/ɪ/ region of the continuum, a higher percentage of correct "different" responses was obtained when the more /i/-like stimulus came second in a pair than when it came first.[1] At the /ɛ/ end of the continuum, however, this order effect was absent or even reversed.

Earlier authors employing the same–different paradigm had not paid any attention to such order effects and had simply combined the responses for the two orders of each pair. The order effects attracted our attention because they were quite large in some stimulus pairs and, apparently, different in nature from the contrast effects, whose occurrence among vowel stimuli has been known for a long time (e.g., Eimas, 1963; Thompson and Hollien, 1970). Whereas contrast effects extended across the whole vowel continuum, order effects were most pronounced at the /i/-end. More importantly, contrast effects virtually disappeared when the interstimulus interval was lengthened and filled with an intervening irrelevant vowel, but stimulus order effects survived such interference. Thus they seemed to be caused by a different mechanism. At the time, we did not pursue the explanation of this secondary finding any further.

An article by Cowan and Morse (1986) drew renewed attention to these order effects and suggested that they reveal a hitherto unnoticed property of memory for vowels. These authors used stimuli ranging from /i/ to /ɪ/, corresponding to one-half of our earlier continuum. Again, discrimination accuracy was higher when the more /i/-like stimulus came second in a pair. However, the effect also interacted with interstimulus interval: It grew *larger* as the (empty) interval was increased from 250 to 2000 ms, due to a more rapid decrease in discriminability for those stimulus pairs in which the more /i/-like stimulus came first. On the basis of these results, Cowan and Morse proposed that the perceived quality of the first vowel in a pair changes gradually while it is held in memory.[2] Specifically, they suggested that it changes toward a more neutral quality—that its internal representation drifts toward the center of the acoustic–phonetic vowel space (henceforth, the *neutralization hypothesis*). They further speculated that this drift may be strongest for vowels such as /i/, which are near the periphery of the vowel space.

Thus, according to this hypothesis, an /i/-like vowel held in memory becomes more like /ə/ and hence more similar to /ɪ/ (/ɪ/ being more central than /i/ in the vowel space; see Fig. 1 below), whereas an /ɪ/-like vowel held in memory becomes even more central, and hence more dissimilar from /i/. Therefore, an /i/-like vowel is difficult to discriminate from a following, more /ɪ/-like vowel, while the reverse order is easy to discriminate. The neutralization hypothesis also predicts a reduction of the order effect at the /ɛ/-end of an /i/–/ɪ/–/ɛ/ continuum, though not a reversal (as mistakenly claimed by Cowan and Morse), since /ɛ/ is somewhat more central than /ɪ/ (Fig. 1).

The neutralization hypothesis is interesting because it suggests a speech-specific memory mechanism. However, at this point its supporting evidence rests entirely on high front vowels. Cowan and Morse stressed the need for studies of order effects in other regions of the vowel space. The purpose of the present experiments was to fill this gap, and thereby to assess the validity of the neutralization hypothesis.

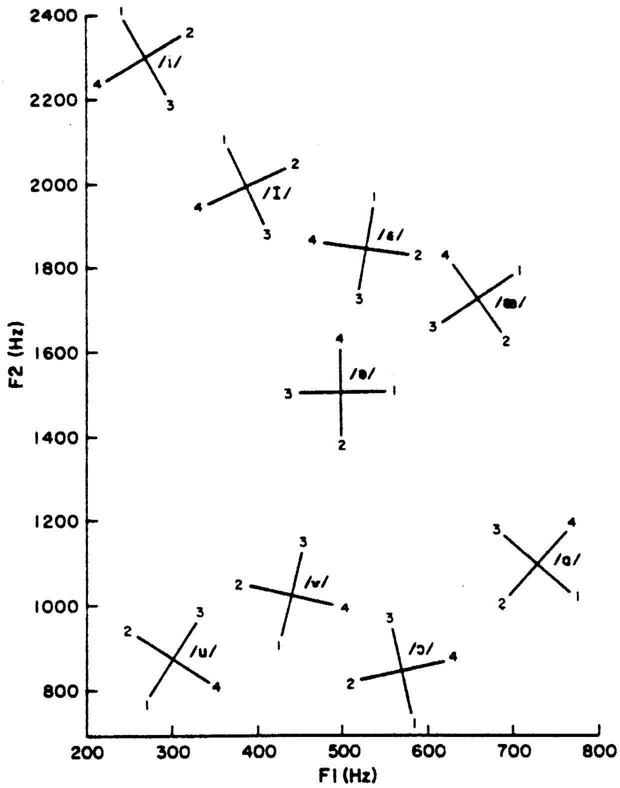

FIG. 1. Positions of the stimuli of experiment 1 in $F1$–$F2$ space.

I. EXPERIMENT 1

In this experiment we employed nine groups of stimuli from all over the vowel space, arranged in a way that enabled us to make clear predictions about the direction and magnitude of order effects.

A. Methods

1. Stimuli

Figure 1 represents the stimuli schematically as points in the two-dimensional acoustic space defined by the frequencies of the lowest two formants ($F1$ and $F2$). Eight monophthongal vowels, /i,ɪ,ɛ,æ,ɑ,ɔ,ʊ,u/, were selected from the Peterson and Barney (1952) norms for adult male speakers of American English.[3] In addition, the neutral vowel /ə/, which was not included in the study of Peterson and Barney and is less well defined phonetically, was assumed to have $F1$ and $F2$ frequencies of 500 and 1500 Hz, respectively (i.e., the resonance frequencies of a uniform tube having the length of the average male vocal tract; see Chiba and Kajiyama, 1941). These nine *prototype* vowels are located at the centers of the crosses in Fig. 1.

For each of the prototype vowels, four *neighbors* in vowel space were chosen as indicated by the endpoints of the cross arms in Fig. 1. Each cross was oriented so that one of its arms pointed directly to the neutral /ə/ vowel. The four neighbors of each prototype were numbered in a clockwise fashion starting with the vowel farthest from /ə/ (cf. Fig. 1). The neighbors of the /ə/ prototype were arbitrarily determined by a cross whose arms were parallel to the $F1$–$F2$ coordinates, and they were numbered arbitrarily. The fixed arm length of all crosses was chosen on the basis of pilot observations, so as to make the neighbors fairly difficult to discriminate from the prototypes in a high-uncertainty task.

The formant frequencies of all the vowels are listed in Table I. The third formant of all stimuli was fixed at 2440 Hz, except for /i/ and its neighbors, which had an $F3$ of 3010 Hz. The stimuli were synthesized on the Haskins Laboratories serial resonance software synthesizer with a duration of 250 ms and a linearly falling fundamental frequency contour (100–80 Hz). An experimental tape was recorded containing four blocks (replications) of 117 randomly ordered stimulus pairs each. The 117 pairs resulted from each of the nine prototypes being paired with each of its four neighbors in both temporal orders (72 pairs), and each vowel being paired with itself (45 pairs). The ratio of "different" to "same" pairs thus was 8:5. The interstimulus intervals were 500 ms within pairs, 2 s between pairs, and 5 s after each group of 13 pairs.

TABLE I. Formant frequencies (in Hz) of the stimuli used in experiment 1. (P prototype, N neighbor.)

Stimulus		$F1$	$F2$
/i/	P	270	2290
	N1	245	2380
	N2	315	2340
	N3	295	2200
	N4	225	2240
/ɪ/	P	390	1990
	N1	370	2080
	N2	435	2030
	N3	410	1900
	N4	345	1950
/ε/	P	530	1840
	N1	538	1940
	N2	580	1825
	N3	522	1740
	N4	480	1855
/æ/	P	660	1720
	N1	700	1780
	N2	690	1640
	N3	620	1660
	N4	630	1800
/ɑ/	P	730	1090
	N1	767	1020
	N2	695	1010
	N3	693	1160
	N4	765	1170
/ɔ/	P	570	840
	N1	580	740
	N2	520	820
	N3	560	940
	N4	620	860
/ʊ/	P	440	1020
	N1	425	920
	N2	390	1045
	N3	455	1120
	N4	490	995
/u/	P	300	870
	N1	272	785
	N2	258	925
	N3	328	955
	N4	342	815
/ə/	P	500	1500
	N1	500	1600
	N2	550	1500
	N3	500	1400
	N4	450	1500

2. Subjects and procedure

Twenty-four undergraduate subjects participated in this study for course credit. Each subject listened to the tape once, and then to the first three blocks again, so that seven blocks were presented in all. The first block was considered practice and was not scored. Presentation was over loudspeakers in a quiet room. The task was to respond "same" or "different" to each pair by circling the appropriate response on an answer sheet.

B. Results and discussion

The predictions of the neutralization hypothesis were as follows: Pairings of prototype (P) vowels with neighbors N1 and N3, which lie on the axis pointing toward /ə/, should yield large order effects of opposite sign. N1 pairs should show a positive order effect (defined as more correct "different" responses when P comes first than when it comes second), whereas N3 pairs should show a negative order effect, perhaps of smaller absolute size because of their more central location in vowel space. N2 and N4 pairs, on the other hand, should not show any significant order effects. For pairs involving the /ə/ prototype there were no clear predictions, except that order effects should be small. Any large order effects obtained in this region would suggest that the true /ə/ prototype is located elsewhere.

The results are shown in Table II. It is evident, first, that discrimination accuracy was not very high but obviously above chance: Hit rates ("different" responses to nonidentical pairs) were uniformly higher than false-alarm rates ("different" responses to identical pairs). This performance level was optimal for observing large order effects. Pairs involving /i/ received markedly fewer "different" responses than the rest; otherwise, performance did not vary substantially across the vowel space.

The results of interest, the order effects, are shown at the bottom of the table. These effects were computed by subtracting the percentage of "different" responses for pairs in which P came second from that for pairs in which P came first. It can be seen that a number of stimulus pairs showed large ($> \pm 10\%$) order effects, but that pairs involving /ə/ showed only small effects, as predicted. In the following statistical analyses, these latter pairs were excluded because they did not follow the general stimulus design.

Two separate ANOVAs were conducted, one on Nl and N3 pairs, and the other on N2 and N4 pairs. Each had the factors Vowel (8), Neighbor (2), and Order (2). For the first analysis, the neutralization hypothesis predicted a significant Neighbor by Order interaction, due to positive order effects in pairs involving Nl and negative order effects in pairs involving N3. This interaction was indeed highly significant, $F(1,23) = 34.48$, $p < 0.0001$, although there was also a significant triple interaction involving Vowel, $F(7,161) = 4.19$, $p = 0.0003$. Two-way follow-up analyses were therefore conducted on N1 and N3 pairs separately.[4]

For Nl pairs, there was a highly significant positive Order effect, $F(1,23) = 54.78$, $p < 0.0001$, but also a significant Vowel by Order interaction, $F(7,161) = 4.75$, $p = 0.0001$. As can be seen in Table II, seven of the eight vowels showed large positive order effects, though their magnitude varied considerably; one vowel (/ʊ/), however, showed a small negative effect. For N3 pairs, there was the predicted negative Order effect, $F(1,23) = 8.62$, $p = 0.0074$, as well as a weak Vowel by Order interaction, $F(7,161) = 2.73$, $p = 0.0106$. Actually, only three vowels showed large negative effects; all other effects were of negligible size. Although the neutralization hypothesis predicted smaller absolute order effects in N3 than in N1 pairs (which held for seven of the eight vowels), this large variability was unexpected.

For the analysis of the N2 and N4 pairs, the neutraliza-

TABLE II. Average percentages of "different" responses for all stimulus pairs in experiment 1, and order effects (prototype first minus prototype second).

Pair	Prototype vowel (P) /i/	/ɪ/	/ɛ/	/æ/	/ɑ/	/ɔ/	/ʊ/	/u/	/ə/
Identical pairs									
P–P	6.9	17.4	16.0	15.3	11.8	13.9	22.2	26.4	4.2
N1–N1	11.1	19.4	13.2	9.7	11.1	13.2	18.8	12.5	16.0
N2–N2	12.5	13.9	15.3	15.3	10.4	18.8	21.5	22.9	6.3
N3–N3	9.0	16.7	18.8	19.4	13.2	18.1	19.4	19.4	6.3
N4–N4	8.3	16.7	16.0	18.1	9.7	16.0	16.7	18.1	10.4
Nonidentical pairs: prototype first									
P–N1	22.2	39.6	70.1	63.2	64.6	72.2	54.9	59.7	43.8
P–N2	37.5	63.9	52.8	38.2	46.5	56.3	71.5	66.0	35.4
P–N3	15.3	34.0	54.9	61.8	50.7	56.9	48.6	35.4	35.4
P–N4	43.1	74.3	49.3	49.3	54.9	60.4	64.6	40.3	34.0
Nonidentical pairs: prototype second									
N1–P	10.4	27.8	46.5	35.4	43.8	53.5	61.8	27.1	36.8
N2–P	41.0	70.1	49.3	39.6	54.9	48.6	46.5	32.6	36.8
N3–P	20.1	53.5	69.4	65.3	54.9	54.9	49.3	56.3	28.5
N4–P	23.6	68.1	54.9	52.8	38.2	55.6	66.7	62.5	31.9
Nonidentical pairs: order effects (difference scores)									
N1	11.8	11.8	23.6	27.8	20.8	18.7	− 7.1	32.6	7.0
N2	− 3.5	− 6.2	3.5	− 1.4	− 8.4	7.7	25.0	33.4	− 1.4
N3	− 4.8	− 19.5	− 14.5	− 3.5	− 4.2	2.0	− 0.7	− 20.9	6.9
N4	19.5	6.2	− 5.6	− 3.5	16.7	4.8	− 2.1	− 22.2	2.1

tion hypothesis predicted an absence of order effects. There was, however, a significant (positive) main effect of Order, $F(1,23) = 8.46$, $p = 0.0079$, and although the Neighbor by Order interaction was not significant, there was a highly significant triple interaction, $F(7,161) = 7.28$, $p < 0.0001$. A separate follow-up analysis of N2 pairs again revealed a main effect of Order, $F(1,23) = 8.60$, $p = 0.0075$, and a strong Vowel by Order interaction, $F(7,161) = 5.38$, $p < 0.0001$. As can be seen in Table II, two vowels (/ʊ/ and /u/) unexpectedly showed large positive order effects; all other vowels showed small effects, as predicted. A separate analysis of N4 pairs did not yield a significant main effect of Order but again a significant Vowel by Order interaction, $F(7,161) = 4.53$, $p = 0.0001$. Table II shows that two vowels (/i/, /ɑ/) yielded sizable positive order effects, and one (/u/) a negative effect, with the rest being negligible.

On the whole, these results confirm the main predictions of the neutralization hypothesis: positive order effects for Nl pairs, negative effects for N3 pairs, and mostly negligible effects for N2 and N4 pairs. There are a number of local deviations from the predictions, however, which are too large to be ignored. Some of these deviant results could be explained by the *ad hoc* assumption that back vowels changed in memory not toward /ə/ but toward a quality close to the N3 of /ɔ/ (see Fig. 1). This would predict positive order effects for pairings of /u/ with its N1 and N2, of /ʊ/ with its N2, of /ɔ/ with its N1, and of /ɑ/ with its N1 and N4, all of which were, in fact, obtained; also, negative order effects for pairings of /u/ with its N3 and N4, of /ʊ/ with its N4, of /ɔ/ with its N3, and of /ɑ/ with its N2 and N3, which were clearly realized only in the case of /u/ but were not strongly contradicted elsewhere; and no order effects for pairings of /ʊ/ with its N1 and N3, and for /ɔ/ with its N2 and N4, which was confirmed (cf. Table II). Front vowels and /ə/, on the other hand, must still be assumed to decay toward a quality near /ə/; otherwise, order effects would have to be predicted for /ə/ paired with its N2 and N4, and for /æ/ paired with its N4, none of which were obtained. Thus, if different neutral points are assumed for front and back vowels, only one large order effect remains unaccounted for (/i/ paired with its N4).

Unfortunately, we have no independent justification for assuming different neutral points for front and back vowels. It was also surprising that pairs including /i/ and its N3, which are similar to stimulus pairs that had yielded large negative order effects in the studies of Repp *et al.* (1979) and Cowan and Morse (1986), showed only a negligible order effect here. This suggested to us the possibility that the pattern of order effects is not fixed but depends on the stimulus ensemble used in an experiment. Experiment 2 was conducted to address this question.

II. EXPERIMENT 2

In this study we reused four of the vowel sets of experiment 1, those grouped around the /ɪ/, /ɛ/, /æ/, and /ə/ prototypes. These are precisely the stimulus sets that yielded results supporting the neutralization hypothesis. The critical set was /ɛ/, which was adjacent to each of the other three in vowel space (see Fig. 1). The stimulus pairs from that set were presented in three separate tests, each time intermixed with the stimulus pairs from one of the other three sets. If order effects were sensitive to stimulus context, they should follow significantly different patterns for the same /ɛ/ stimuli in the three different tests. The pattern of order effects for the context stimuli should also be changed in comparison to experiment 1. Specifically, we suspected that the hypothetical neutral point might be in different locations in different contexts, perhaps closer to the centroid of the stimulus ensemble used in a particular test.

As an additional manipulation, we included two different ISIs in our design. Cowan and Morse (1986) found that order effects in the /i/–/ɪ/ region increased with ISI, due to a more rapid decline in discrimination performance for pairs in which the more /i/-like stimulus came first. They pointed out that this provides important support for the neutralization hypothesis, whose main assumption is that the memory representations of vowels change over time. In the present study we intended to replicate their finding by using two ISIs (200 ms and 1 s) that straddled the ISI of 500 ms used in experiment 1.

A. Methods

1. Stimuli

The stimuli were the /ɪ/, /ɛ/, /æ/, and /ə/ sets of experiment 1. Three separate test tapes were recorded, the first containing /ɛ/ and /ɪ/ stimuli, the second /ɛ/ and /æ/ stimuli, and the third /ɛ/ and /ə/ stimuli. Each tape contained six randomized sequences of 52 stimulus pairs. These consisted of 10 pairs of identical stimuli (each of the two prototypes and each of the eight neighbors paired with itself once) and 16 pairs of nonidentical stimuli (each of the two prototypes paired with each of its four neighbors, in both orders), each presented with two ISIs: 200 ms and 1 s.

2. Subjects and procedure

Eighteen subjects from the same general pool participated. Each subject listened to each stimulus tape, in a balanced order. The procedure was identical to that of experiment 1.

B. Results and discussion

The results are presented in Table III, with the order effects at the bottom. Consider first the results for the /ɛ/ stimuli, shown in the last three columns. A four-way ANOVA was conducted on these data, with the factors Context (/ɪ/, /æ/, /ə/), Order (P first, second), ISI (short, long), and Neighbor (1, 2, 3, 4). Several significant effects did not involve Order: The main effect of ISI, $F(1,17) = 8.15$, $p = 0.0109$, reflected better discrimination performance at the shorter ISI, which is not surprising; the main effect of Neighbor, $F(3,51) = 11.18$, $p = 0.0001$, was due to much better performance for N3 pairs than for the other pairs, a surprising finding; and the Context by Neighbor interaction, $F(6,102) = 3.07$, $p = 0.0084$, reflected a tendency toward reduced discrimination performance for pairs involving the neighbor stimulus most dissimilar to the context (N2 in the /ɪ/ context, N4 in the /æ/ context, Nl in the /ə/ context), which suggests a contrastive influence of the context on the perceptual structure of the /ɛ/ category.

Effects involving Order were of primary interest: There was a highly significant main effect of Order, $F(1,17) = 25.54$, $p = 0.0001$, which indicated a positive stimulus order effect overall. The interaction of Order and Neighbor fell short of significance. Several other interactions were significant, however. One was between Order, ISI, and Neighbor, $F(3,51) = 8.08$, $p = 0.0002$, indicating that an Order by Neighbor interaction emerged at the longer ISl. Another significant interaction involved Context, Order, and Neighbor, $F(6,102) = 4.05$, $p = 0.0011$, indicating that the pattern of order effects did change with test context. This was particularly true at the longer ISI; the quadruple interaction was just significant, $F(6,102) = 2.24$, $p = 0.0449$.

Since /ɛ/ stimuli showed no really large order effects at the shorter ISI, the results at the longer ISI are of primary interest. Table III reveals that N1 pairs showed a positive order effect, as predicted by the neutralization hypothesis, though the effects were smaller here than in experiment 1, especially in the /æ/ test context, despite the longer ISI. N3 pairs, on the other hand, showed results highly discrepant from those of experiment 1. Instead of the negative effect obtained there and predicted by the neutralization hypothesis, these pairs exhibited positive order effects, with the effect in the /ɪ/ context condition being more than twice as large as the effects in the other two context conditions. Furthermore, N2 and N4 pairs, which had not shown any order effects in experiment 1 (as predicted by the neutralization hypothesis), showed some large effects here that depended on context: N2 pairs showed a large negative effect in the /æ/ context, but a positive effect in the /ə/ context. N4 pairs showed a large positive effect in the /æ/ context.

We turn now to the results for the contextual stimuli, which are shown in the first three columns of Table III. We dispense with statistical analyses here, which presumably would show many complex interactions, and instead discuss the pattern of substantial order effects in relation to experiment 1. Even more consistently than with the /ɛ/ stimuli, order effects increased in absolute magnitude at the longer ISI, but there were also a number of large order effects at the short ISI here. The results for the /ɪ/ stimuli were not unlike those in experiment 1, though the effects differed in size and, overall, were less compatible with the neutralization hypothesis: a large positive effect for N1 pairs, but only a negligible negative effect for N3 pairs; a moderate negative effect for N2 pairs, and a large positive effect for N4 pairs. The results for /æ/ stimuli at the shorter ISI were quite similar to the experiment 1 results, showing only a positive effect for N1 pairs. At the longer ISI, however, positive effects emerged for N2 and N4 pairs as well. The most discrepant results were obtained for /ə/ stimuli, which in experiment 1 had not exhibited any large order effects at all. In this experiment, all pairs showed order effects. Those for N1 and N4 pairs were extremely large and positive, those for N2 and N3 pairs smaller and negative.

These data provide strong indications that changes in the test environment affected the pattern of order effects. Overall, the results are much less favorable to the neutralization hypothesis than the results of experiment 1. The reason for this may be that the "neutral point" that vowels in memory drift toward is specific to each stimulus ensemble. If such

TABLE III. Average percentages of "different" responses for all stimulus pairs in experiment 2, and order effects (prototype first minus prototype second).

Pair	ISI	Prototype vowel (P) /ɪ/	/æ/	/ɔ/	$/ε/_{ɪ}$	$/ε/_{æ}$	$/ε/_{ɔ}$
Identical pairs							
P–P	200	13.9	5.6	15.7	7.4	9.3	15.7
	1000	5.6	9.3	9.3	11.1	13.0	13.9
N1–N1	200	13.0	3.7	7.4	7.4	5.6	9.3
	1000	13.0	5.6	16.7	7.4	10.2	5.6
N2–N2	200	7.4	3.7	9.3	5.6	7.4	13.9
	1000	11.1	9.3	11.1	6.5	7.4	8.3
N3–N3	200	4.6	7.4	6.5	4.6	6.5	7.4
	1000	8.3	5.6	9.3	5.6	8.3	9.3
N4–N4	200	3.7	10.2	18.5	7.4	4.6	13.9
	1000	9.3	5.6	13.0	12.0	6.5	13.0
Nonidentical pairs: prototype first							
P–N1	200	62.0	71.3	74.1	63.9	63.0	63.9
	1000	55.6	67.6	73.1	53.7	51.9	52.8
P–N2	200	60.2	52.8	48.1	51.9	51.9	61.1
	1000	57.4	45.4	31.5	40.7	38.0	62.0
P–N3	200	46.3	72.2	68.5	72.2	75.0	74.1
	1000	32.4	68.5	55.6	80.6	78.7	71.3
P–N4	200	75.9	66.7	74.1	59.3	62.0	71.3
	1000	75.0	64.8	65.7	58.3	57.4	63.9
Nonidentical pairs: prototype second							
N1–P	200	35.2	54.6	33.3	53.7	53.7	56.5
	1000	27.8	39.8	19.4	38.9	44.4	32.4
N2–P	200	72.2	49.1	60.2	46.3	59.3	55.6
	1000	74.1	24.1	46.3	48.1	66.7	47.2
N3–P	200	49.1	71.3	75.0	71.3	75.9	76.9
	1000	38.9	62.0	72.2	42.6	61.1	58.3
N4–P	200	63.0	63.0	46.3	59.3	53.7	60.2
	1000	41.7	45.4	33.3	50.9	33.3	56.5
Nonidentical pairs: order effects (difference scores)							
N1	200	26.9	16.7	40.7	10.2	9.3	7.4
	1000	27.8	27.8	53.7	14.8	7.4	20.4
N2	200	− 12.0	3.7	− 12.0	5.6	− 7.4	5.6
	1000	− 16.7	21.3	− 14.8	− 7.4	− 28.7	14.8
N3	200	− 2.8	0.9	− 6.5	0.9	− 0.9	− 2.8
	1000	− 6.5	6.5	− 16.7	38.0	17.6	13.0
N4	200	13.0	3.7	27.8	0.0	8.3	11.1
	1000	33.3	19.4	32.4	7.4	24.1	7.4

a point exists, it should be possible to infer its location from the patterns of order effects for the two stimulus sets in a given context condition: Arms of a stimulus cross that are associated with negative order effects point outward, toward the "neutral point," whereas arms associated with positive effects point inward. If the results for each of the two stimulus crosses are internally consistent in that they point in a particular direction, then the neutral point is located at the intersection of these two directions.

In the test containing /ɪ/ and /ε/ stimuli, the pattern of order effects for the /ɪ/ stimuli (N2 and N3 negative, N1 and N4 positive) points toward /ε/; the pattern for the /ε/ stimuli in that context is not internally consistent (both N1 and N3 positive) but is most compatible with a neutral point at the /ε/ prototype. Thus these data suggest a neutral point in the vicinity of the /ε/ prototype, which incidentally is consistent with the data of Repp *et al.* (1979) and of Cowan and Morse (1986).

In the test containing /æ/ and /ε/ stimuli, the results for the /æ/ stimuli (all positive) point inward toward the /æ/ prototype, whereas the results for /ε/ stimuli (N2 negative, N3 and N4 positive) point "north of" /æ/. Thus the neutral point here may have been located near the /æ/ prototype.

Finally, in the test containing /ɔ/ and /ε/, the results for the /ɔ/ stimuli (N2 and N3 negative, Nl and N4 positive) point quite clearly to the "southwest" (i.e., away from /ε/), whereas the /ε/ order effects are all positive and therefore indicate a "neutral" point at the /ε/ prototype. Thus the data from this test are contradictory and do not suggest a unique neutral point.

Although these results do not provide very clear support for stimulus range specific "neutral points," they are even less supportive of the range-independent neutralization hypothesis of Cowan and Morse (1986). They replicate only their finding that order effects, regardless of their direction, increase with interstimulus interval. It is noteworthy, however, that the results for *individual* vowel sets (i.e., for each cross in Fig. 1) are nearly always internally consistent and thus "point" in a particular direction. Opposite neighbors *never* yielded large negative order effects. Thus we need to consider the possibility that each vowel set has its own individual neutral point, as it were. This seems unparsimonious, but there is, in fact, a plausible rationale. Each vowel category has a best exemplar or prototype (see, e.g., Grieser and Kuhl, 1989), which may or may not coincide with the prototype suggested by the data of Peterson and Barney (1952). Moreover, the location of a vowel prototype is likely to be sensitive to stimulus context. The pattern of order effects may tell us something about the actual locations of vowel prototypes and their shifts with changes in context. Rather than becoming more neutral in memory, vowels may become more prototypical.

Although this seems a very reasonable hypothesis, there is a serious problem with it: It makes just the opposite predictions of the neutralization hypothesis. The data of experiments 1 and 2 are not at all compatible with the idea that vowels in memory become assimilated to prototypes, because they would imply that these prototypes are often located centrally in vowel space, which does not make sense. It is still possible that prototypes play a role, but that this role is not assimilative but contrastive in nature. Before discussing this idea further, we report the results of a third experiment, in which we employed the methodology of our original study (Repp *et al.*, 1979)—viz., stimulus continua spanning two vowel categories—to partially replicate experiment 2 and to conduct another specific test of the predictions of the neutralization hypothesis. Replication of experiment 2 results seemed desirable because of their striking inconsistencies with experiment 1 (see footnote 5).

III. EXPERIMENT 3

In experiment 3 we employed two vowel continua, one ranging from /ɛ/ to /æ/, and the other from /ɛ/ to /ə/. The first stimulus series continued where the /i/–/ɪ/–/ɛ/ continuum used by Repp *et al.* (1979) ended. Since the two endpoint vowels, /ɛ/ and /æ/, are about equally peripheral in the vowel space (see Fig. 1), the neutralization hypothesis of Cowan and Morse (1986) predicts no pronounced order effects along this continuum. Indeed, in experiment 1 pairings of /ɛ/ with its N2 and of /æ/ with its N4, which lie approximately on this continuum (see Fig. 1), yielded no order effects. In experiment 2, however, large order effects (negative and positive, respectively) emerged for these very same pairs at the longer ISI. Since experiment 3 used the same long ISI and an even more restricted stimulus context, it was expected to replicate the results of experiment 2.

The second continuum ranged from /ɛ/ to /ə/. According to the neutralization hypothesis, strong negative order effects should be obtained at the /ɛ/ end of this continuum, but none at the /ə/ end. These predictions were upheld in experiment 1 for pairings of /ɛ/ with its N3 and of /ə/ with its N4, which lie almost exactly on the /ɛ/–/ə/ continuum (see Fig. 1). Again, the results of experiment 2 were contradictory: The very same pairs yielded a small and a large positive order effect, respectively. We wondered whether experiment 3 would replicate this curious pattern.

A. Methods

1. Stimuli

The formant frequencies for the /ɛ/, /æ/, and /ə/ prototypes, which served here as continuum endpoints, were the same as in experiments 1 and 2 (see Table I). Five additional vowels were interpolated linearly between /ɛ/ and /æ/, and between /ɛ/ and /ə/, to obtain two 7-member vowel continua. Other stimulus characteristics were the same as previously.

The stimuli of each continuum were recorded in pairs on separate experimental tapes. The interstimulus interval was 1 s within pairs and 2.4 s between pairs. The pairs varied in the degree of stimulus separation (measured in steps on the continuum). For each continuum, there were 37 pairs: 7 identical pairs, 12 one-step pairs (6 stimulus combinations, 2 orders), 10 two-step pairs, and 8 three-step pairs. Ten blocks of these 37 pairs were recorded for each continuum, with different random orders in each block.

2. Subjects and procedure

Twenty-four undergraduate students served as subjects. Each participated in two sessions, in each of which the same stimulus tapes were presented. In one session, they were asked to give same–different responses; in the other, they identified the second vowel in each pair. The identification data will not be reported here in detail.[6] The order of these two conditions, and of the two stimulus sets within sessions, was counterbalanced across subjects. The tapes were played back monaurally in a quiet room using a tape recorder and earphones of good quality. Half the subjects listened to the stimuli in their right ear, and the other half in their left ear; no significant ear differences were observed.

B. Results and discussion

1. /ɛ/–/æ/ continuum

Figure 2, left panel, shows the results for nonidentical pairs from the /ɛ/–/æ/ continuum as a function of location on the continuum, step size, and stimulus order. Predictably, the percentage of "different" responses increased as the step size increased. Scores also tended to be highest in the middle of the continuum, which is in agreement with the previously demonstrated tendency for isolated vowels to be perceived in a semicategorical fashion (Repp *et al.*, 1979). Effects of stimulus order are represented by the difference between the closed and open symbols. There were large order effects for one-step and especially two-step pairs; for three-step pairs, a ceiling effect probably prevented order effects from emerging. At the /ɛ/ end of the continuum discrimination performance was much better when the more /ɛ/-like stimulus occurred second than when it occurred first; this difference is particularly large for stimulus pair 1-3. In the middle of the continuum there were no pronounced order effects, but at the /æ/ end a reversal occurred: Correct responses were

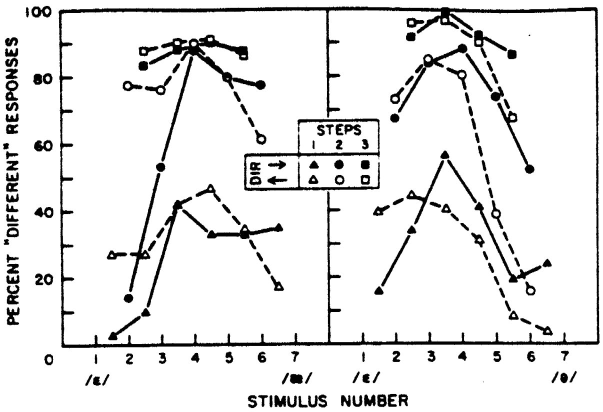

FIG. 2. Results of experiment 3: Percentages of "different" responses to pairs of nonidentical stimuli from /ɛ/–/æ/ (left panel) and /ɛ/–/ə/ (right panel) continua. Parameters are stimulus order (ascending versus descending direction) and separation (one, two, or three steps).

more frequent when the /æ/ endpoint stimulus occurred second.

Analyses of variance were conducted on one-step and two-step pairs separately, with the factors Stimulus Pair and Order. The Stimulus Pair by Order interaction, which reflects the change in magnitude and direction of the order effect across the continuum, was highly significant for one-step pairs, $F(5,110) = 6.79$, $p < 0.0001$, and for two-step pairs, $F(4,88) = 39.09$, $p < 0.0001$. In addition, there was a main effect of Stimulus Pair for one-step pairs, $F(5,110) = 13.17$, $p < 0.0001$, and for two-step pairs, $F(4,88) = 27.20$, $p < 0.0001$, which reflects the aforementioned performance peak in the middle of the continuum, as well as the fact that discrimination was better at the /æ/ end than at the /ɛ/ end. For two-step pairs, there was also a main effect of Order, $F(1,22) = 22.03$, $p = 0.0001$, due to the exceptionally large order effect for the 1-3 stimulus pair.

In the terminology of the earlier experiments, these results show negative order effects at both continuum endpoints, which is inconsistent with the neutralization hypothesis and with the results of experiment 1. The results are more similar to those of experiment 2, where a large negative effect was obtained on the /ɛ/ side, but a small positive effect on the /æ/ side. There, a "neutral point" near the /æ/ prototype was suggested. Here, a neutral point is defined by the point on the continuum where no order effect is obtained (i.e., the point at which the functions for the two stimulus orders in Fig. 2 cross each other). That is somewhere between stimuli 4 and 5, which is closer to /æ/ than to /ɛ/. It is worth noting that the labeling data obtained from the same subjects showed the /ɛ/–/æ/ category boundary to be in the same location. These data, then, are reasonably consistent with experiment 2; the differences may be attributed to the changes in stimulus range and frequency (the prototype stimuli occurred more often than other stimuli in the earlier experiments, but not in experiment 3) (see footnote 7).

2. /ɛ/–/ə/ continuum

The results for this continuum are displayed in Fig. 2, right panel. Again, there were stimulus order effects that reversed direction along the continuum. At the /ɛ/ end, order effects emerged only for one-step pairs and favored pairs in which the more /ɛ/-like stimulus came second. Effects at the /ə/ end were larger and in the opposite direction. The crossover point was closer to /ɛ/ than to /ə/.

The statistical analyses showed the pattern of results to be very reliable. The Stimulus Pair by Order interaction was highly significant for one-step pairs, $F(5,110) = 9.71$, $p < 0.0001$, two-step pairs, $F(4,88) = 12.71, p < 0.0001$, and even for three-step pairs, $F(3,66) = 12.91, p < 0.0001$. In addition, there was a significant main effect of Stimulus Pair for one-step pairs, $F(5,110) = 14.36$, $p < 0.0001$, two-step pairs, $F(4,88) = 32.91$, $p < 0.0001$, and three-step pairs, $F(3,66) = 11.96$, $p > 0.0001$, due to better discrimination performance in the center of the continuum, plus higher scores at the /ɛ/ end than at the /ə/ end. A main effect of Order was obtained for two-step pairs, $F(1,22) = 29.96$, $p < 0.0001$, and for three-step pairs, $F(1,22) = 7.96$, $p = < 0.0099$, due to the large order effects at the /ə/ end of the continuum.

The /ɛ/–/ə/ continuum thus yielded negative order effects at both endpoints, with the larger effects at the /ə/ end. The negative order effect at the /ɛ/-end is consistent with the neutralization hypothesis and with the data of experiment 1. However, the large negative order effect at the /ə/-end is in strong contradiction to both. Unfortunately, it also contradicts the findings of experiment 2 which showed a large positive effect for /ə/ as well as a small positive effect for /ɛ/. These data, it will be recalled, were inconsistent in that they did not suggest a single neutral point; they remain mysterious. The present data suggest a neutral point somewhere between stimuli 3 and 4 on the continuum (i.e., closer to /ɛ/ than to /ə/). Again, we note that the category boundary obtained in the labeling task fell there also.

IV. GENERAL DISCUSSION

The purpose of the present series of experiments was to test the generality of the neutralization hypothesis proposed by Cowan and Morse (1986). We found many deviations from the predictions of this hypothesis, such as the large stimulus order effects in the vicinity of /ə/ obtained in experiments 2 and 3. Only experiment 1 yielded data that, on the whole, seemed to support the hypothesis. Although that experiment may seem to have been the strongest test because it included the largest variety of stimuli, it may actually have been the weakest: If stimulus order effects depend on the distribution of the stimuli in vowel space, then the most representative distribution has the neutral vowel at its center and therefore may yield data that seem to support the neutralization hypothesis. Only by using more limited stimulus distributions can the range-specific nature of the order effects be revealed.

The discrepancies among the results of experiments 1–3 provide ample evidence of such range-specific changes, though it must be admitted that the pattern of effects obtained cannot always be rationalized. On the whole, however, our data suggest that vowels change in memory not necessarily toward the neutral vowel /ə/, but toward a quality that lies within the stimulus range of a given experiment. What could be the reason for this?

It is well known, and the data from our experiment 3 confirm, that the perception of isolated vowels is weakly categorical: Discrimination tends to be best around the category boundaries. These discrimination peaks suggest that covert categorization plays a role in the "same–different" task. Almost certainly, the first vowel in a stimulus pair is remembered in a dual code, one categorical and the other continuous (Fujisaki and Kawashima, 1970; Pisoni, 1973, 1975). While, at a short ISI, subjects can utilize the auditory stimulus trace for comparisons, at longer ISIs they must rely increasingly on the category label assigned to the first vowel in a pair. Since the size of order effects increases with ISI, it seems likely that these effects are a phenomenon related to the covert categorization of the vowel stimuli.[8]

We already noted, however, that simple phonetic classification does not predict the order effects that were in fact obtained. Phonetic categorization amounts to an assimilation to the prototype, so that *positive* order effects would be predicted at the ends of stimulus continua. The negative order effects obtained suggest that vowels held in memory were assimilated toward some standard(s) located *between* prototypes. The only "special" point in that ambiguous region is the category boundary—the point of maximum uncertainty. Indeed, we found in experiment 3 that the "neutral point" suggested by the order effects coincided with the category boundary. It seems, therefore, that the category boundary somehow "attracts" vowels in memory; at the same time, however, such a process cannot be reconciled with the idea of covert phonetic categorization. Also, it is far from clear why the perceptually most stable vowels (the prototypes, and others near them) should exhibit the largest changes in memory.

There is a way, however, of accounting for these data on the basis of phonetic categorization. The apparent changes in the remembered quality of the first stimulus of a vowel pair may not occur autonomously during the silent interstimulus interval, but rather may be caused by the arrival of the second stimulus, which interacts with the memory trace of the first. This suggestion is supported by three solid findings from earlier research. First, it is well known that successively presented vowels engage in contrastive interactions (Thompson and Hollien, 1970; Repp *et al.*, 1979), provided the interstimulus interval is not too short (Shigeno and Fujisaki, 1980) and they can be perceived as belonging to different phonetic categories (Shigeno, 1986). Contrast, of course, facilitates discrimination. Second, vowels that are unambiguous representatives of a phonological category exert larger contrast effects than do more ambiguous vowels; it is the latter that are pushed around in the context of less ambiguous neighbors (Crowder, 1982). Third, it has also been shown that, when pairs of vowels are to be judged, retroactive contrast is larger than proactive contrast (Repp *et al.*, 1979; Shigeno and Fujisaki, 1980), presumably because a memory trace is less stable than a newly arrived stimulus. These three observations together predict stimulus order effects of the kind found in experiment 3 and earlier: At either endpoint of a vowel continuum, discrimination should be easier *when the more ambiguous vowel comes first and the less ambiguous vowel comes second in a pair*, because the retroactive contrast effect in such a pair will be larger than any proactive contrast effect obtained in the opposite arrangement. An increase in the order effect with temporal separation between the stimuli is also consistent with this explanation: As the memory trace of an initially stable vowel becomes weaker over time, its proactive contrast effect on a following unstable vowel will decrease, as shown by Crowder (1982). In fact, the labeling data in experiment 3 revealed no significant proactive contrast effects at all (footnote 6). On the other hand, when an unstable vowel is followed by a stable vowel, the retroactive contrast effect exerted by the latter on the former will stay the same or even increase with temporal separation. Thus, according to this interpretation, order effects occur not because prototypical vowels become less stable in memory, but because unstable vowels shift away from following stable vowels.

Attractive as this explanation seems, there is a problem with it. Repp *et al.* (1979) found that an interfering vowel sound eliminated retroactive contrast effects but left stimulus order effects intact. Similarly, reanalysis of data from an unpublished vowel discrimination experiment by one of us (RGC), in which interfering sounds were used together with a long ISI, revealed large stimulus order effects. These findings suggest that contrast and order effects are unrelated. The present experiments provide no additional information on that point. Since no interfering sound was present, it is possible that retroactive contrast was operating. However, since retroactive effects are only slightly larger than proactive effects (Repp *et al.*, 1979), the total absence of proactive contrast effects in experiment 3 suggests that retroactive contrast, if present at all, was not very strong. Thus it seems that the retroactive contrast explanation may not be correct, after all.

A possible solution to this dilemma is suggested by the psychophysical theory of Durlach and Braida (1969; Braida *et al.*, 1984), which has been applied to vowel resolution by Macmillan *et al.* (1988). These authors distinguish between a sensory trace and a more stable "context code." The context code is not limited to the phonetic labels listeners can apply; rather, it reflects their maximum labeling capacity. The context code thus is a subphonetic, quasicategorical representation. It is also unstable and, as its name indicates, subject to influences of stimulus context. Although listeners may assign a phonetic category to the first stimulus in a pair when it arrives, they may use its richer context code to compare it to a following stimulus. This context code may be subject to retroactive contrast, even when the phonetic category assigned to the first stimulus in a pair remains unaffected (i.e., is not revised by the listener).[9]

This interpretation receives independent support from other psychophysical studies involving nonspeech, even nonauditory, stimuli. Effects of presentation order in the method of constant stimuli have been noted since the earliest days of psychophysics (see Needham, 1934; Hellström, 1985). A recent demonstration was provided by Masin and Fanton (1989) who used vertical lines in a visual length discrimination task. They concluded that subjects used a quasicategorical code (i.e., a context code) to compare successive stimuli, and that "the categorical comparison is accompanied by an additional inferential decision process that uses only the category relative to the second stimulus because more weight is given to that category, or because the category relative to the first stimulus is momentarily forgotten" (p. 485). They do not assume a change in the memory code of the preceding stimulus through retroactive contrast, but the same net effect is achieved by a hypothetical weighting process favoring the more recent stimulus, which is really just another metaphor for memory degradation of the earlier stimulus. The argument is easily transferred to stimuli such as vowels, as long as it is assumed that their context code is always in terms of abstract labels that reflect the relative location of stimuli in the range of all stimuli employed. Within the context code, continuum endpoints do not function as anchors (Macmillan *et al.*, 1988) and therefore can plausibly degrade in memory.

It seems, therefore, that stimulus order effects in vowel discrimination represent an instance of more general presentation order effects in psychophysical judgment, not a phenomenon specific to the memory coding of speech sounds. The fact that there remain a number of unexplained irregularities in our results may be attributed to the acoustic complexity of vowels, compared to the simple unidimensional stimuli used in most psychophysical studies of "time order errors." In most general terms, such time order errors are due to a contraction of the effective range for remembered stimuli, a consequence of gradually substituting generic information for specific information that is lost (Hellström, 1985). The generic information reflects the recent stimulus history (Helson's, 1964, "adaptation level"). The neutralization hypothesis of Cowan and Morse (1986) may be seen as a specific application of these general principles to certain sets of vowels whose adaptation level happens to be in the neutral region.

ACKNOWLEDGMENTS

This research was supported by NICHD Grant HD01994 to Haskins Laboratories and by NSF Grant GB86 08344 to Robert G. Crowder. We are grateful to William Flack for assistance in running experiments and tabulating data, and to Nelson Cowan for helpful comments.

[1] We note, with some embarrassment, that the effect is incorrectly described in experiment 2 of Repp *et al.* (1979, p. 138). We are confident that this is a mistake in the text, and that the data conformed to the description given here and in experiment 1 of Repp *et al.* (1979, p. 134).

[2] They generously credit us (Repp *et al.*, 1979) with this idea, though we did not state it explicitly.

[3] We follow common practice in referring to the Peterson–Barney data for the synthesis of isolated vowels, even though these data derive from vowels produced in a /h_d/ context.

[4] We are aware of the dangers of conducting multiple analyses on the same data without adjusting the *p* levels. However, these follow-up analyses serve the sole purpose of clarifying complex interactions, and the significance levels are generally so high as to make adjustments superfluous.

[5] We are taking the liberty of describing experiment 3 in these terms for expository reasons. Actually, experiment 3 was conducted before experiments 1 and 2.

[6] The purpose of this condition was to assess proactive contrast effects. Somewhat surprisingly (see, e.g., Crowder, 1982), no significant effects were found. Note that the occurrence of retroactive contrast effects is not precluded by these findings (see Sec. IV).

[7] Additional evidence that order effects change with stimulus range is obtained from a comparison with the old data of Repp *et al.* (1979). They showed a small negative order effect at the /ɛ/ end of the /i/–/ɪ/–/ɛ/ continuum. In those pairs, however, the stimulus paired with the /ɛ/ prototype was more /ɪ/-like, while in the present pairs it was more /æ/-like; hence, the present negative order effect at the /ɛ/ end is contrary to the effect obtained previously.

[8] Accordingly, stimulus order effects should be smaller in tasks that force subjects to rely more on the stimulus trace. Kewley-Port and Atal (1989) conducted experiments with four sets of vowel stimuli (/i/–/ɪ/, /ɛ/–/æ/, /u/–/ʊ/, and /æ/–/ɑ/–/ɔ/) arranged in prototype–neighbor configurations, but the task required numerical dissimilarity judgments for the two vowels in a pair. We reanalyzed their raw data (kindly provided by Diane Kewley-Port) and found stimulus order effects to be small and following a consistent pattern in only one of the sets, /u/–/ʊ/. That pattern agreed with that obtained in our experiment 1, suggesting that /u/-like vowels drifted toward /ʊ/.

[9] Macmillan *et al.* (1988) also noted that points of perceptual stability serve as "anchors" for the context code. Although anchors are often located at the ends of stimulus continua, Macmillan *et al.* deduced from their vowel discrimination data that *boundary stimuli* served as anchors on their /i/–/ɪ/–/ɛ/ continuum. This surprising (and somewhat tentative) conclusion is in agreement with the order effects obtained in our experiments, though it leads back to the neutralization metaphor and should perhaps be regarded with caution.

Braida, L. D., Durlach, N. I., Lim, J. S., Berliner, J. E., Rabinowitz, W. M., and Purks, S. R. (1984). "Intensity perception. XIII. Perceptual anchor model of context coding," J. Acoust. Soc. Am. 76, 722–731.

Chiba, T., and Kajiyama, M. (1941). *The Vowel, Its Nature and Structure* (Kaiseikan, Tokyo).

Cowan, N., and Morse, P. A. (1986). "The use of auditory and phonetic memory in vowel discrimination," J. Acoust. Soc. Am. 79, 500–507.

Crowder, R. G. (1982). "Decay of auditory information in vowel discrimination," J. Exp. Psychol.: Hum. Learn. Mem. 8, 153–162.

Durlach, N. I., and Braida, L. D. (1969). "Intensity perception. I. Preliminary theory of intensity resolution," J. Acoust. Soc. Am. 46, 372–383.

Eimas, P. D. (1963). "The relation between identification and discrimination along speech and non-speech continua," Lang. Speech 6, 206–217.

Fujisaki, H., and Kawashima, T. (1970). "Some experiments on speech perception and a model for the perceptual mechanism," *Annual Report of the Engineering Research Institute*, University of Tokyo 29, 207–214.

Grieser, D., and Kuhl, P. K. (1989). "Categorization of speech by infants: Support for speech-sound prototypes," Dev. Psychol. 25, 577–588.

Healy, A. F., and Repp, B. H. (1982). "Context independence and phonetic mediation in categorical perception," J. Exp. Psychol.: Hum. Percept. Perf. 8, 68–80.

Helson, H. (1964). *Adaptation-Level Theory: An Experimental and Systematic Approach to Behavior* (Harper & Row, New York).

Hellström, A. (1985). "The time-order error and its relatives: mirrors of cognitive processes in comparing," Psychol. Bull. 97, 35–61.

Kewley-Port, D., and Atal, B. S. (1989). "Perceptual differences between vowels located in a limited phonetic space," J. Acoust. Soc. Am. 85, 1726–1740.

Macmillan, N. A., Goldberg, R. F., and Braida, L. D. (1988). "Resolution for speech sounds: Basic sensitivity and context memory on vowel and consonant continua," J. Acoust. Soc. Am. 84, 1262–1280.

Masin, S. C., and Fanton, V. (1989). "An explanation for the presentation-order effect in the method of constant stimuli," Percept. Psychophys. 46, 483–486.

Nearey, T. M. (1989). "Static, dynamic, and relational properties in vowel perception," J. Acoust. Soc. Am. 85, 2088–2113.

Needham, J. G. (1934). "The time error in comparison judgments," Psychol. Bull. 31, 229–243.

Peterson, G. E., and Barney, H. L. (1952). "Control methods used in a study of the vowels," J. Acoust. Soc. Am. 24, 175–184.

Pisoni, D. B. (1973). "Auditory and phonetic memory codes in the discrimination of consonants and vowels," Percept. Psychophys. 13, 253–260.

Pisoni, D. B. (1975). "Auditory short-term memory and vowel perception," Mem. Cognit. 3, 7–18.

Repp, B. H., Healy, B. H., and Crowder, R. G. (1979). "Categories and context in the perception of isolated steady-state vowels," J. Exp. Psychol.: Hum. Percept. Perf. 5, 129–145.

Shigeno, S. (1986). "The auditory Tau and Kappa effects for speech and nonspeech stimuli," Percept. Psychophys. 40, 9–19.

Shigeno, S., and Fujisaki, H. (1980). "Context effects in phonetic and non-phonetic vowel judgments," Ann. Bull. RILP (Tokyo) 14, 217–224.

Thompson, C. L., and Hollien, H. (1970). "Some contextual effects on the perception of synthetic vowels," Lang. Speech 13, 1–13.