Linguistic and acoustic correlates of the perceptual structure found in an individual differences scaling study of vowels

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Subjects judged the similarities among a set of American English vowels (/i,ɪ,ɛ,æ,ʌ,ɑ,ɔ,o,ʊ,u/) presented in isolation or in a /dVd/ consonantal frame. Individual differences scaling was employed to analyze these similarities data for each of the conditions separately and for the two conditions combined. In all cases, perceptual dimensions corresponding to the advancement, height, and tenseness vowel features were recovered. Given the determinacy of individual differences scaling, this finding is taken to provide strong evidence for the perceptual significance of those features. The perceptual dimensions are considered in relation to various acoustic parameters of the stimuli employed in this study. They are also considered in relation to perceptual dimensions that have been observed in other vowel scaling studies.

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INTRODUCTION

Multidimensional scaling provides a means of modeling the psychological structure that is reflected in perceptual judgments. Scaling is particularly useful because judgments regarding a large number of stimuli can very often be modeled with a structure of relatively few dimensions, and because those dimensions can then be interpreted in terms of properties familiar to an investigator (Carroll and Wish, 1974; Kruskal and Wish, 1978). In the domain of vowel perception, investigators have frequently found that the dimensions revealed by scaling can be related to various phonological features, a fact which is taken to imply that those features play a significant perceptual role (e.g., Singh and Woods, 1970; Shepard, 1972; Fox, 1983).

The strength of that implication is, however, contingent on the type of scaling method that is used in a study. One class of scaling techniques yields solutions for which no single interpretation is possible. This owes to the fact that the models of psychological structure, which are spatial in character, lack a fixed orientation for their axes. One must therefore rotate these structures in search of an orientation that permits interpretation of the dimensions. There are an infinite number of possible rotations and the search must be constrained by an investigator's *a priori* notions regarding interpretation. Any conclusions drawn are correspondingly vulnerable to the challenge that some alternative interpretation would have been equally supported by the data had some other rotation been carried out.

A second class of scaling techniques cannot be challenged on these grounds because they specify a fixed orientation of dimension axes for their models of psychological structure. This class, the *individual differences* scaling techniques, achieve their added determinacy by modeling multiple sets of data simultaneously, each set reflecting the performance of a different subject.[1] An important underlying assumption of individual differences scaling is that when judging a common set of stimuli subjects can differ from one another in terms of the relative weights they attach to a set of shared perceptual dimensions, but not in terms of the identity of the dimensions themselves (Carroll and Chang, 1970). Except in unusual cases, there is one and only one orientation in which the shared dimensions can be weighted so as to optimally account for the variance in those subjects' data. That is the orientation recovered by individual differences scaling. It has been conjectured that with a well-defined perceptual task the dimensions revealed by individual differences scaling will correspond to fundamental sensory or judgmental processes (Carroll and Chang, 1970). There are a number of instances in which that conjecture has been supported (Wish and Carroll, 1974).

In this paper, we report on an individual differences scaling study of vowel perception. It was conducted to address questions about the potential influences that consonantal context can exert on vowel perception, and elsewhere (Rakerd, 1984) we have considered the results in that regard. We did so by comparing the weights that subjects attached to a set of shared perceptual dimensions, depending on whether they heard vowels in or out of a consonantal frame. Our concern here is not with the weights, however, but with the shared dimensions themselves. Those dimensions can be usefully compared with linguistic features that have been found to be related to perceptual structure in other scaling studies (e.g., Terbeek, 1977; Fox, 1982, 1983), particularly those conducted with less determinate scaling techniques (Hanson, 1967; Pols *et al.*, 1969; Singh and Woods, 1970; Shepard, 1972). That is the first purpose of this paper. We examine subjects who judged vowels in consonantal context and subjects who judged isolated vowels, analyzing their data both separately and in combination.

The second purpose of this paper is to report on correlations between the perceptual structure revealed by individ-

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ual differences scaling and various acoustic parameters of our vowel stimuli. Though based on a limited number of stimulus tokens, those correlations are suggestive in that they speak to hypotheses which previous investigators have put forth regarding relationships between vowel features and the acoustic signal.

I. METHODS

A. Subjects

Twenty-three subjects participated in this experiment. All of them were native speakers of English with normal hearing according to self-report. Twelve of the subjects were randomly assigned to make perceptual judgments regarding vowels in consonantal context. The remaining 11 subjects judged vowels in isolation.

B. Stimuli

The stimuli for the experiment were ten different American English vowels (/i,ɪ,ɛ,æ,ʌ,ɑ,ɔ,o,ʊ,u/) spoken by a male talker with a general American dialect. For the consonantal context condition, he produced those vowels in the trisyllabic frame /hədVdə/, with stress placed on the second syllable (/dVd/). For the isolated condition, he produced them with no surrounding phonetic context (/#V#/). Two tokens of each vowel were produced in each condition. Recordings of those tokens were digitized at a sampling rate of 10 kHz and stored in separate computer files.

C. Procedure

Subjects were tested individually. Their task was to judge the similarity relations that they perceived among the ten different vowels. They were instructed to base those judgments on properties of the vowel sounds that seemed to them to distinguish words in English (Carlson and Granström, 1979; Klatt, 1979). The similarity judgments were made with a triadic comparisons method that has been employed in previous vowel perception studies (Pols *et al.*, 1969; Terbeek and Harshman, 1971; Terbeek, 1977). According to this procedure, three of the ten vowels were rated on each experimental trial. Subjects listened to these vowels in any order that they chose and as often as they chose.[2] They then reported which two of the three vowels sounded *most* alike to them and which two *least* alike. Over trials, all possible triads were judged. The judgments were then summed across trials, with a score of + 1 assigned to all most-alike pairs and − 1 to all least-alike pairs. This yielded a single (symmetrical) matrix of similarity judgments for each subject.

D. Data analysis

The matrices for all 23 subjects who participated in the experiment were submitted to nonmetric individual differences scaling, using the ALSCAL procedure developed by Takane *et al.* (1977). It was determined that a three-dimensional scaling solution was most appropriate for the data. That decision was based on several factors. First, modeling in three dimensions accounted for a substantially greater percentage of variance (an average of 70% for each subject) than modeling in two dimensions (60%), and only marginally less than modeling in four dimensions (72%). Second, the three dimensions were readily interpretable from a linguistic standpoint. And finally, those dimensions were quite stable, in that they were also found in separate analyses of the two experimental conditions (see Sec. II) and, with certain modeling constraints, in the scaling solution for a memory study (Rakerd, 1984) which complemented this perceptual study.

For additional details concerning the data analysis, as well as other aspects of the experimental method, see Rakerd (1984).

II. THE SCALING SOLUTIONS

We first consider the perceptual dimensions that emerged from an analysis of data matrices for all 23 subjects. Although these dimensions have been described elsewhere by Rakerd (1984), they are examined here in greater detail, with particular attention paid to comparisons with phonological features of linguistic description for vowels, and with dimensions that have been reported in previous scaling studies of vowels. In the second part of Sec. II, we describe the perceptual dimensions that resulted from *separate* analyses of the consonantal-context and isolated conditions of the study.

A. The two conditions combined

1. Dimensions 1 and 2

Dimension 2 (D2) of the scaling solution for all subjects is plotted against dimension 1 (D1) in the top half of Fig. 1. The distribution of vowels in this plane is clearly related to the traditional "vowel quadrilateral" (Ladefoged, 1975; Lindau, 1978), with D1 corresponding to the *advancement* feature of vowels,[3] and D2 to the *height* feature. There is considerable precedent for observing correlates of these two phonological features in vowel scaling studies (Hanson, 1967; Pols *et al.*, 1969; Singh and Woods, 1970; Shepard, 1972; Fox, 1982, 1983). Those findings, together with the results of the present study, strongly support the view that the advancement and height features play a significant role in the perception of vowels in English. The findings are also consistent with the larger view that advancement and height enjoy a special status in all languages (Lindau, 1978).

2. Dimension 3

The third dimension of the combined group space (D3) is plotted against D1 in the bottom half of Fig. 1. The vowels are ordered along it such that /ɪ,æ,ɛ,ʌ,ʊ/ have negative values and /i,ɑ,ɔ,o,u/ have positive values. The former are lax vowels, the latter tense. Hence, D3 can be interpreted as corresponding to the *tenseness* feature. Unlike advancement and height, a tenseness dimension has very rarely been recovered in vowel scaling studies. To our knowledge, only Anglin (1971; cited in Singh, 1976), who scaled similarity judgments for vowels in /hVd/ context, has recovered a dimension similar to D3. In that analysis, the scaling method did not yield a single, interpretable orientation for the model of psychological structure. The present, more determinate scaling result might therefore be taken to provide the strongest available evidence for perceptual significance of the tenseness feature.

B. Separate analyses of the conditions

When perceptual judgments for the isolated and consonantal-context conditions were scaled separately, in three dimensions, the amount of variance that could be accounted for in the data (VAF) improved marginally over its corresponding value in the combined analysis. (VAF for analysis of the isolated condition was 74%, that for the consonantal-context condition was 72%. This compares with 70% in the combined analysis.) This marginal improvement resulted from some local shifts in the positioning of vowels in the separate scaling solutions. As will be seen, the global structure nevertheless remained quite similar to that of the combined analysis.

1. The isolated condition

The perceptual dimensions for the isolated condition are shown in Fig. 2. Only D2 is notably different from the corresponding dimensions of the combined analysis (see Fig. 1). Along this dimension, the vowels /ɛ/ and /o/ have assumed values that are somewhat more positive than they had been previously. The movement of /ɛ/ principally reflects the fact that /ɛ/ and /ɪ/ were judged to be highly similar, indeed, the most similar of all vowel pairs in the isolated condition. Likewise, the movement of /o/ is largely dictated by a single vowel pairing; /o/ and /u/ were judged to be extremely similar in isolation, perhaps reflecting the fact that they were the only two diphthongized vowels in the isolated set.

Despite repositioning of these two vowels, the dimensions of the isolated solution maintain a strong correspondence with the advancement, height, and tenseness features, respectively.

This analysis can be usefully compared with one by Singh and Woods (1970) in which it was found that tenseness had no perceptual significance for listeners who rated the relative similarity of isolated vowels. Those investigators attributed their finding to listeners' knowledge that isolated lax vowels are phonologically impermissible in English. The outcome of the present study indicates that there may have been other factors at work as well. For several of our isolated-vowels subjects the tenseness dimension (D3) did, indeed, have little or no perceptual salience, but for others it was the most heavily weighted dimension (Rakerd, 1984). Perhaps talkers produced their isolated vowels differently in the Singh and Woods study, or perhaps, by averaging their data over subjects prior to scaling, Singh and Woods lost any statistical evidence of the significance of tenseness. Whatever the case, it is apparent that under certain conditions

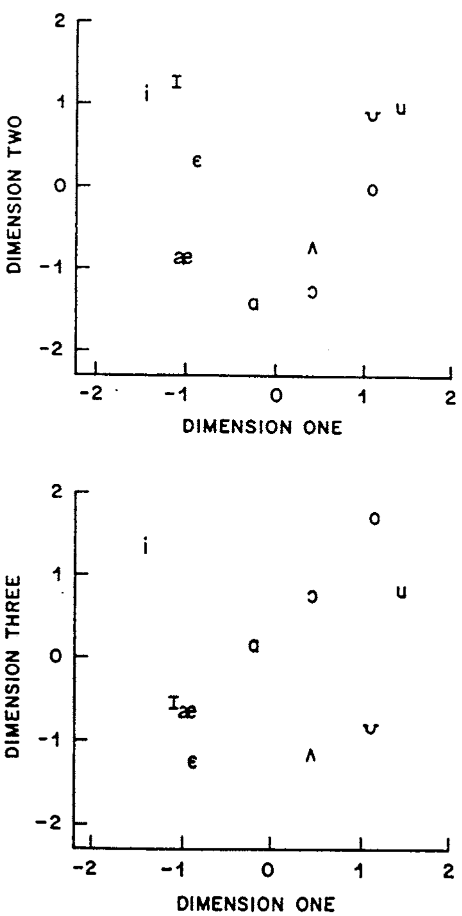

FIG. 1. Perceptual structure for subjects from the two experimental conditions combined. This figure is reproduced from Rakerd (1984) by permission of The Psychonomic Society.

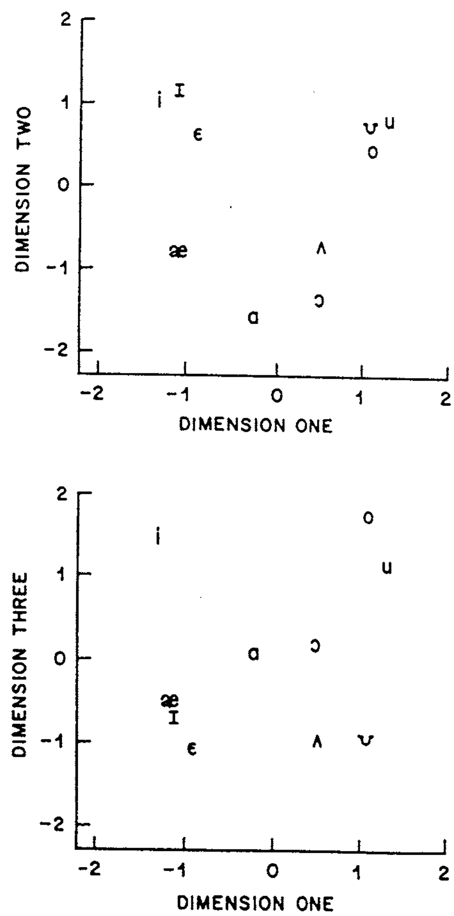

FIG. 2. Perceptual structure for subjects from the isolated condition.

listeners can attend to the tenseness dimension of isolated vowels, despite the phonological restriction.

2. The consonantal-context condition

Perceptual dimensions for the separate analysis of the consonantal-context condition are shown in Fig. 3. D1 and D2 are quite similar to their counterparts in the combined analysis (Fig. 1), again reflecting sensitivity to advancement and vowel height, respectively. Along the third dimension, there is some divergence from the combined solution, with the vowel /ɪ/ moving in a more positive direction. This movement resulted from the fact that the /i-ɪ/ vowel pair was judged highly similar in consonantal context. Nevertheless, D3 retains a correspondence with tenseness.

3. Stability of the scaling solutions

The agreement among these separate scaling solutions and the combined solution is evidence of the stability of this modeling outcome. Perceptual dimensions closely related to advancement, height, and tenseness were recovered in all cases, which makes it extremely unlikely that their emergence in any individual case was a coincidental consequence of the scaling analysis itself.

III. ACOUSTIC CORRELATES OF THE PERCEPTUAL DIMENSIONS

We computed correlations to assess the strength of relationships between the perceptual dimensions revealed by our combined scaling analysis and various acoustic parameters of the vowel stimuli. The acoustic measurements were made from wideband spectrograms. In the case of isolated vowels, center frequencies of the first three formants ($F1$, $F2$, and $F3$) were measured at a point approximately halfway through each token. Duration of voicing was also measured for the isolated vowels.

The acoustic structure of the /dVd/ syllables comprised an onglide (or period of syllable-initial formant transition) and an offglide (syllable-final transition), with little or no region in which the formants could be described as maintaining a steady-state frequency. Therefore, we adopted the convention of measuring $F1$, $F2$, and $F3$ at the end of the onglide (a point also representing the beginning of the offglide). Duration was measured from the first evidence of voicing following initial-/d/ release to the last prior to final-/d/ closure. Last, we computed the proportion of total syllable duration which was taken up by the offglide.

Recall that there were two tokens of each vowel in each context. The mean parameter values for those two tokens are listed in Table I. Isolated-vowel parameters appear in the top half of the table, /dVd/ parameters in the bottom half. An examination of Table I shows that the stimuli were acoustically "normal" in the sense that their parameters were roughly comparable to those that other investigators have reported for much larger data bases (Peterson and Barney, 1952; Peterson and Lehiste, 1960; Klatt, 1975; Umeda, 1975). The data also provide evidence of vowel reduction (Joos, 1948; Lindblom, 1963) in consonantal context. Formant frequency differences among the vowels were smaller in the /dVd/ condition than in isolation.

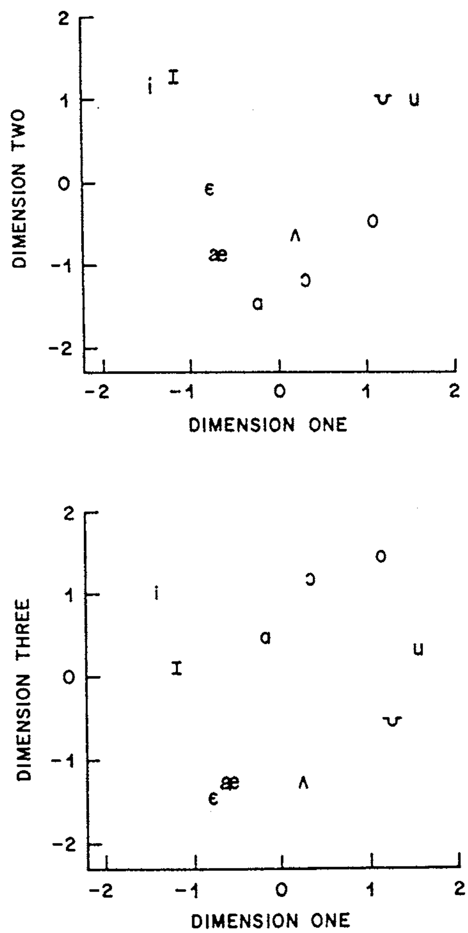

FIG. 3. Perceptual structure for subjects from the consonantal-context condition.

TABLE I. Acoustic parameters of the stimuli.

Condition	Vowel	Formant frequencies $F1$	$F2$	$F3$	Duration	Offglide proportion
Isolated vowels	i	225	2210	2835	235	...
	ɪ	465	1920	2600	165	...
	ε	555	1620	2135	180	...
	æ	665	1200	2225	180	...
	ʌ	640	1640	2170	155	...
	ɑ	780	1180	2090	235	...
	ɔ	680	1000	2175	195	...
	o	515	950	2110	225	...
	ʊ	565	1125	2020	135	...
	u	395	875	2085	220	...
Consonantal context	i	330	2060	2595	120	0.50
	ɪ	455	1795	2435	90	0.61
	ε	545	1640	2515	125	0.61
	æ	620	1595	2280	165	0.67
	ʌ	575	1375	2000	125	0.60
	ɑ	730	1300	2200	175	0.42
	ɔ	655	1005	2125	175	0.45
	o	530	1160	2045	160	0.37
	ʊ	460	1460	2380	95	0.60
	u	420	1355	2110	130	0.38

TABLE II. Rank-order correlations between acoustic parameters of the stimuli and perceptual dimensions of the combined analysis.

Condition	Acoustic parameter	Perceptual dimensions D1	D2	D3
Isolated vowels	$F1$	0.12	-0.92^{b}	-0.37
	$F2$	-0.95^{b}	0.30	-0.31
	$F3$	-0.84^{b}	0.19	0.09
	Duration	-0.13	-0.17	0.76^{b}
Consonantal context	$F1$	0.04	-0.95^{b}	-0.31
	$F2$	-0.72^{a}	0.67^{a}	-0.32
	$F3$	-0.66^{a}	0.47	-0.18
	Duration	0.23	-0.87^{b}	0.27
	Offglide prop.	-0.61^{a}	0.15	-0.73^{a}

$^{a}p<0.05$.
$^{b}p<0.01$.

Rank-order correlations (Spearman's *rho*) were computed between the acoustic data reported in Table I and coordinates for the perceptual dimensions of the combined analysis. The results are reported in Table II. First consider correlations for the isolated vowels, which appear in the top half of the table. The following correlations (and no others) proved significant: D1 (which we have interpreted as advancement) with $F2$ and $F3$, D2 (height) with $F1$, and D3 (tenseness) with duration. The findings regarding D1 and D2 are anticipated by a number of previous scaling studies (Pols *et al.*, 1969; Shepard, 1972; Fox, 1982, 1983). The finding for D3 is consistent with the report that vowel tenseness is related to duration (Peterson and Lehiste, 1960).

The bottom half of Table II shows correlations for vowels in /dVd/ context. Note that relative to the isolated vowels there is a substantial reduction in the strength of the correlation between D1 and $F2$ (0.72, down from 0.95) and between D1 and $F3$ (0.66, down from 0.84). These statistical changes reflect the fact that the high-back vowels /o,ʊ,u/ were radically reduced in /dVd/ context, as might be expected given the alveolar place of articulation of the consonants. Though not unusual, this circumstance merits comment in that it calls into question strong statements to the effect that the relationship between the advancement feature and the formant structure of vowels is a simple one (see, e.g., Singh, 1976; Lindau, 1978). Our finding is one of the sort which shows that this relationship is affected by the phonetic context in which a vowel occurs.

It can also be seen in Table II that, in the consonantal-context condition, duration was not significantly correlated with D3 (tenseness), as it had been with isolated vowels. It appears that judgments regarding D3 could not have been made on the basis of vowel duration in this condition. Apparently, subjects' perceptions of tenseness were cued by some other acoustic property in the /dVd/ context. A likely candidate is offglide proportion, which was significantly correlated with D3. Indeed, it is possible to perfectly account for at least the macrostructure of D3 ordering on the basis of offglide proportion alone. Table I shows that the tense vowels, which all had positive D3 coordinates, also had offglide proportions of 50% or less, and that the lax vowels, which all had negative D3 coordinates, also had offglide proportions of 60% or more. This finding is reminiscent of an observation made by Lehiste and Peterson (1961), although our measurement procedures were somewhat different from theirs. In both instances, tense vowels were found to be marked by a relatively brief period of offglide into a following consonant, and lax vowels by an offglide which was more substantial in duration.

A number of investigators have reported that vowels in consonantal context are identified with greater accuracy than isolated vowels (Strange *et al.*, 1976, 1979; Gottfried and Strange, 1980; Rakerd *et al.*, 1984). It has been suggested that one reason for this perceptual advantage may be that the dynamic acoustic structure of syllables is a unique source of vowel information (Strange *et al.*, 1976, 1983). Our observation of an association between offglide proportion and the tenseness feature is certainly consistent with this view.

IV. SUMMARY AND CONCLUSIONS

A stable, interpretable individual differences scaling solution was found for subjects' similarity judgments regarding a set of American English vowels. This solution had three dimensions, which corresponded, respectively, to the linguistic features of advancement, height, and tenseness. Those correspondences provide particularly strong evidence for the perceptual significance of the features due to the determinacy of individual differences scaling.

While the results regarding the advancement and height features confirm expectations based on a number of previous scaling studies, recovery of a tenseness dimension is more surprising. One reason for its recovery in the present instance may have to do with the individual differences scaling method itself. Across subjects, there was wide variability in the perceptual salience of tenseness, particularly among those who rated isolated vowels (Rakerd, 1984). With individual differences scaling, this variability was manifest in the different weighting that each subject attached to D3. However, had the data been averaged over subjects prior to analysis, as required by many scaling methods, it is likely that the variability would have made it impossible to recover a tenseness dimension. It may also be relevant that we instructed subjects to attend to those aspects of the vowel sounds that seemed to them to distinguish words in English. Previous investigators (Carlson and Granström, 1979; Klatt, 1979) have reported that an instruction of this type can strengthen the linguistic character of subjects' perceptual judgments.

There were two noteworthy findings regarding correlations between the scaling results and acoustic parameters of the vowel stimuli. The first was that vowel duration was not significantly correlated with the tenseness dimension in /dVd/ context. Hence, the emergence of this dimension, particularly in the separate analysis of the consonantal-context condition, cannot be attributed to subjects having attended to durational differences among the vowels.

The second observation was that in /dVd/ context tenseness was significantly correlated with offglide proportion. Tense vowels had an internal syllable structure in which the offglide constituted 50% or less of the vocalic region. For lax vowels, the offglide made up 60% or more of the vocalic region. This finding is similar to one reported by

Lehiste and Peterson (1961). The two findings together support the view that the dynamic acoustic structure of syllables can be a unique source of vowel information for a perceiver (Strange *et al.*, 1976, 1983).

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[1]Although this is most commonly the case, and was the case in the present study, each of the several data matrices submitted to an individual differences scaling analysis need not represent the performance of a single subject. As alternatives, there could, for example, be one matrix for each of the several conditions of an experiment, or one for each of the several experiments in a study. From a computational standpoint, it is only required that there be multiple matrices.

[2]The subjects had complete control over the ordering and pacing of stimulus presentation. They directed presentation of the triad of stimuli for each trial by pressing three different buttons on a computer terminal.

[3]The term advancement is used to be consistent with the earlier work of Singh and Woods (1970), and with Rakerd (1984). An alternative, and perhaps more common term for this feature would be backness (Ladefoged, 1975).

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