A multidimensional scaling analysis of 16 complex sounds

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The INDSCAL multidimensional scaling model was used to investigate the distinctive features involved in the perception of 16 complex nonspeech sounds. The signals differed along four physical dimensions: fundamental frequency, waveform, formant frequency, and number of formants. Scaling results indicated that subjects' similarity ratings could be accounted for by three psychological or perceptual dimensions. A statistically reliable correspondence was observed between these perceptual dimensions and the physical characteristics of fundamental frequency, waveform, and a combination of the two formant parameters. These results were further explored with Johnson's (1967) hierarchical clustering analysis. Large differences in featural saliency occurred in the group data with fundamental accounting for more variability than the remaining dimensions. Further analysis of individual subject data revealed large individual differences in featural saliency. These differences were related to past musical experience of the subject and to earlier findings using similar signals. It was concluded that (1) the INDSCAL model provides a useful method for the analysis of auditory perception in the nonspeech mode, and (2) featural saliency in such sounds is likely to be determined by an unspecified attentional mechanism.

The human ability to perceive complex sounds is of central importance as demonstrated by our continual reliance on speech as a medium of communication. Although the perception of speech sounds is clearly important, we readily perceive a variety of other complex sounds as well (e.g., the sounds of aircraft, birds, and musical instruments). While much research effort has been expended in an attempt to understand the perception of speech (e.g., Kavanagh & Mattingly, 1972; Liberman, 1970), relatively little research has focused on the perception of other complex sounds (e.g., Massaro, 1972; Webster, Woodhead, & Carpenter, 1973). This paper investigates the multidimensional structure underlying the perception of a specific set of 16 complex nonspeech sounds.

Auditory perception, as any cognitive process, will be constrained by both the information available to the subject (i.e., in the signal) and the processes applied to the information by the subject (Garner, 1974; Norman & Bobrow, 1975). While both of these performance-limiting factors influence perception, the second, or process, factor is of primary psychological importance. What are the processes that underlie the perception of complex sounds? In general, research has indicated that auditory perception depends crucially on the ability of the subject to extract information about the presence of

certain distinctive features in the acoustic signal (e.g., Mattingly, Liberman, Syrdal, & Halwes, 1971; Webster et al., 1973). Consequently, an understanding of this "feature extraction" process is central to the understanding of auditory perception.

Since the assumed feature extraction process is not directly observable, the features involved in perception can only be inferred from performance data. For example, subjects could be asked to classify synthetically generated signals of varying physical specification (e.g., Mattingly et al., 1971). Here, the relation between the subject's response and the physical characteristics of the signals would be examined. A high correlation between the pattern of responding and the value of a particular physical characteristic would indicate that the physical dimension is important psychologically. Alternatively, the features underlying perception could be determined by subjecting the end result of the perceptual process—some prescribed perceptual response—to a multidimensional scaling analysis (e.g., Carroll & Wish, 1974a; Shepard, Nerlove, & Romney, 1972). The outcome of this analysis is a decomposition of the perceptual data into a set of n orthogonal dimensions or features. Each stimulus can be represented as a point in the space defined by the n features. For example, Shepard (1972) and Wish (Note 1) have scaled Miller and Nicely's (1955) perceptual confusion data for 16 consonant phonemes with impressive success. Similarly, Carterette & Barnebey (Note 2) have undertaken an analysis of the features underlying human voice recognition with promising results.

Several studies have used the first of the above methods to examine the features involved in the

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perception of complex nonspeech sounds. In a recent study, Webster et al. (1973) required subjects to learn labels for a set of 16 complex sounds. The sounds varied along four physical dimensions: fundamental frequency, waveform, number of formants, and formant frequency. Their results indicated that subjects were more likely to confuse sounds differing in formant characteristics (i.e., formant frequency and number of formants) than they were to confuse sounds differing in source characteristics (i.e., fundamental frequency and waveform). They concluded that, while all four physical parameters were important psychologically, the relative importance or saliency of these features differed considerably, with fundamental frequency and waveform being more salient than formant frequency and number of formants.

The present study employs the INDSCAL multidimensional scaling procedure to analyze the distinctive features involved in the perception of complex sounds similar to those studied by Webster et al. (1973). In the study, subjects are asked to provide similarity ratings for all possible pairs of a set of 16 complex sounds. The INDSCAL model assumes that an individual subject's judgment of stimulus similarity is a decreasing linear function of the interstimulus distance (assuming a modified Euclidean metric) in a hypothetical underlying perceptual space (Carroll & Chang, 1970). Subject proximity judgments are converted to estimated distances using Torgerson's (1958) additive constant estimation method (Carroll & Wish, 1974b). It differs from most other metric scaling procedures in that information regarding individual subjects is preserved (cf. Shepard et al., 1972). The net outcome of an INDSCAL analysis is an overall group perceptual space reflecting the perceptual structure of the stimulus set, as well as a dimensional weight vector for each subject indicating the relative saliency of each dimension for that subject. Each of the 16 stimuli are represented as points in the perceptual space defined by the distinctive features, and the saliency weights for each subject reflect the degree to which that subject used each dimension in making his similarity judgments.

The present method offers at least two advantages over that used by Webster et al. (1973). First, the INDSCAL analysis provides precise quantitative estimates of featural saliency. Second, the INDSCAL method will permit individual subject differences to be considered.

METHOD

Subjects

Subjects were 34 undergraduate student volunteers at The Catholic University who were paid \$3 for their participation in a 1-h session. A random selection of 17 subjects was screened for hearing abnormalities by the Catholic University Speech and Hearing Clinic.

Figure 1. Spectral analysis of filter output with two formants (600 and 1,550 Hz) while white noise (20 Hz to 20 kHz) was applied at the input.

Apparatus

Four infinite-gain, state-variable, second-order filters were constructed (Graeme, 1971) and tuned to preselected formant frequencies of 600, 940, 1,550, and 2,440 Hz. The roll-off, formant Q values and formant frequencies were calibrated to approximate those values reported by Webster et al. (1973). The output of each filter and combinations of various filters were summed by a variable gain amplifier. Individual filters or summed combinations were excited by 90- or 140-Hz fundamental, square, or triangular wave signals. The response of each filter was investigated by analyzing its spectral composition with a Federal Scientific Analyzer, Model UA-10. The response of a filter with two summed formants at 600- and 1,550-Hz center frequencies is shown in Figure 1 (filter excited with broadband white noise, 20-20K Hz). A schematic representation of the spectra of each of the 16 sounds is presented in Figure 2.

Each of the 16 possible signals (2 driving frequencies $\times$ 2 waveforms $\times$ high or low frequency $\times$ 1 or 2 formants) was recorded onto magnetic tape with a Sony Model TC-270 tape recorder. Signal intensity was equated for RMS amplitude (Hewlett-Packard 400H True RMS Meter). Signal pairs were made by splicing 3-sec segments of these signals between 1-sec segments of blank tape. Individual stimulus pairs were separated by a 4-sec silent response period. A total of 120 randomized pairs of the 16 signals were generated, with each signal occurring with every other signal exactly

Figure 2. Schematic power spectra for each of the 16 sounds (adapted from Webster et al., 1973).

Figure 3. Total proportion of variance accounted for as a function of solution dimensionality.

once. The presentation order of stimuli within each pair was randomly determined to avoid any systematic time-order errors. A single stimulus tape was used for all subjects.

Procedure

Stimuli were presented on a Sony Model TC-270 tape recorder over a loudspeaker placed approximately 1.5 m in front of the subject. Amplifier gain was set to a comfortable listening level (approximately 65 dB re: .0002 dynes/cm²). The use of a loudspeaker enabled more than one subject to be tested at a time, although no more than three subjects were tested during any one session. The subjects sat in a carpeted, sound-attenuated room and were provided with an answer sheet for manually recording their responses. Subjects were read instructions that described the nature of their task, and a 5-point rating scale for judging stimulus similarity (1 = very dissimilar, 5 = very similar) was explained to them. Examples of each of the 16 sounds were presented during a 5-min practice session to permit subjects to become accustomed to use of the scale. Following the practice session, subjects were asked to rate the degree of similarity of each of the 120 signal pairs by marking the appropriate box on their answer sheets. At the conclusion of the session, subjects were asked to complete a biographical information sheet and questionnaire. The data were analyzed on the Catholic University DECSys 10 computer.

RESULTS

Scaling Analysis

An off-diagonal 16 by 16 matrix of similarity judgments was obtained for each of the subjects in the experiment. These data were subjected to a three-way scaling analysis using the INDSCAL procedure. Preliminary solutions were obtained in spaces of from one to seven dimensions. The total proportion of variance accounted for by each solution is presented in Figure 3. Although the total variance accounted for ranged from 43% with one dimension to 68% with

seven dimensions, it is clear from Figure 2 that little additional variance is accounted for by increasing the dimensionality of the solution beyond three dimensions. Since three dimensions are also relatively easy to conceptualize and interpret, the three-dimensional solution was selected for further analysis.¹ The resulting normalized three-dimensional solution is represented graphically in Figure 4 and the coordinates for each of the 16 sounds are presented in Table 1. Visual inspection of these data suggests a correspondence between the psychological features ψ_1 and ψ_2 obtained in the solution and the physical

Figure 4. Normalized three-dimensional INDSCAL solution.

Table 1
Stimulus Coordinates for Each of the 16 Auditory Signals

Signal	Physical Characteristics				Psychological Dimensions		
	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ψ_1	ψ_2	ψ_3
1	90	Sq	1	Lo	-.208	-.002	.377
2	90	Sq	2	Lo	-.261	.382	.139
3	90	Sq	1	Hi	-.256	.329	.114
4	90	Sq	2	Hi	-.238	.328	-.486
5	90	Tr	1	Lo	-.278	-.265	.143
6	90	Tr	2	Lo	-.263	-.204	.079
7	90	Tr	1	Hi	-.258	-.223	-.058
8	90	Tr	2	Hi	-.233	-.134	-.349
9	140	Sq	1	Lo	.232	.020	.318
10	140	Sq	2	Lo	.262	.229	.074
11	140	Sq	1	Hi	.228	.166	.167
12	140	Sq	2	Hi	.265	.342	-.397
13	140	Tr	1	Lo	.238	-.330	.023
14	140	Tr	2	Lo	.272	-.241	.087
15	140	Tr	1	Hi	.250	-.287	.120
16	140	Tr	2	Hi	.249	-.109	-.352

Note— ϕ_1 = fundamental frequency, ϕ_2 = waveform, ϕ_3 = number of formants, ϕ_4 = formant frequency: Lo = 600 and 1550 or 600 Hz and Hi = 940 and 2440 or 940 Hz.

Table 2
Correlations Between Physical Characteristics and Psychological Features

Physical Characteristic	Psychological Feature		
	ψ_1	ψ_2	ψ_3
Fundamental	.99*	.11	.02
Waveform	.01	.90*	.15
Formant Frequency	.00	.21	.62**
Number of Formants	.03	.30	.61**

* $p < .001$

** $p < .01$

parameters fundamental frequency and waveform, respectively. Sounds having a low fundamental frequency (90 Hz) cluster with negative values along ψ_1 , while sounds with a high fundamental (140 Hz) cluster with positive values. Similarly, square waves tend to have positive values and triangular waves tend to have negative values along ψ_2 . The interpretation of the third dimension, ψ_3 , is less obvious: Notice, however, that sounds having two high-frequency formants (940 and 1,440 Hz), signals S_4 , S_8 , S_{12} , and S_{16} , tend to be distinguished from the remaining sounds along this dimension. This suggests that the third dimension reflects a combined function of the two formant parameters.

These observations were confirmed in a statistical analysis of the scaling solution. Point-biserial correlation coefficients were computed between each of the four physical characteristics and the three psychological features. The results of this analysis appear in Table 2. The two source parameters, fundamental frequency and waveform, correlated significantly with ψ_1 and ψ_2 , respectively, and, as anticipated above, both formant parameters correlated highly with dimension ψ_3 . No other

correlations reached significance at the .05 level. In summary, it appears that ψ_1 corresponds in a direct way to fundamental frequency, ψ_2 to the signal waveform, and ψ_3 to a combined function of the two formant parameters.

Hierarchical Clustering Analysis

Shepard (1972) has suggested that a multi-dimensional scaling analysis combined with an *independent* hierarchical clustering analysis would lead to more complete understanding of the data. If the features obtained from the scaling analysis accurately reflect the subject's underlying perceptual structure, then the hierarchical structure revealed by the clustering analysis should be consistent with the scaling solution.

A mean, off-diagonal similarity matrix was obtained for the present stimuli by collapsing across individual subject matrices. These data were subjected to Johnson's hierarchical clustering analysis/connectedness method (Johnson, 1967). The results of this analysis are displayed in Figure 5, and the obtained clusters are displayed embedded in the multidimensional scaling solution for low-fundamental (S_1 - S_8) and high-fundamental (S_9 - S_{16}) sounds in Figures 6a and 6b, respectively. Specific stimuli are grouped according to the hierarchical structure indicated in the clustering analysis. Notice that the clustering and scaling analyses produced nearly identical structural descriptions of these data—in no case do the stimulus clusters overlap in the perceptual space. This observed consistency lends further support to the perceptual structure revealed by the scaling analyses.

Individual Differences Analysis

As indicated above, the INDSCAL model preserves individual subject information while extracting the underlying group perceptual space. Since complex nonspeech sounds differ widely in importance for different individuals (e.g., certain sounds and cues are extremely important for musicians and sonarmen), it is likely that large individual differences

Figure 5. Stimulus clusterings produced by Johnson's hierarchical clustering analysis/connectedness method.

Figure 6. (a) Representation of hierarchical clustering analysis embedded in the INDSCAL solution for 90-Hz signals. (b) Representation of hierarchical clustering analysis embedded in the INDSCAL solution for 140-Hz signals.

would occur in the perception of these sounds. Individual differences were considered in the present data by examining the dimensional saliency or weighting factors for the three psychological features for each of the 34 subjects. The individual feature saliencies for each of the three dimensions are presented in Table 3. Notice that, while many subjects (e.g., Subjects 5, 6, 7) relied almost exclusively on the ψ_1 dimension, some subjects (e.g., Subjects 20, 25, 34) used ψ_2 and ψ_3 to an equal or greater degree.

This finding raises the possibility that the group scaling solution discussed above is only partially representative of an individual subject's perceptual structure. In other words, the three psychological dimensions reported above appear to be distinctive features that subjects may use in perceiving these sounds, but any particular subject is likely to emphasize only some subset of these features. This possibility was examined further by computing Pearson product-moment correlations between the

individual subject saliency weights for each of the psychological dimensions. A high positive correlation between the weights on two dimensions would indicate that the dimensions tend to be emphasized together. That is, subjects emphasizing (or de-emphasizing) the one dimension would also tend to emphasize (or de-emphasize) the other dimension. On the other hand, a high negative correlation between the saliency weights for two features would suggest a different dimensional independence: Subjects stressing the one dimension would tend to de-emphasize the other, and vice versa. The results of this analysis appear in Table 4a. It is clear from this analysis that a significant negative relation exists between ψ_1 (fundamental) and the remaining dimensions, ψ_2 (waveform) and ψ_3 (formants), while ψ_2 and ψ_3 are positively related. These results suggest that there are at least two types of individual subjects: those who emphasize ψ_1 (fundamental) and de-emphasize ψ_2 (waveform) and ψ_3 (formants), and those who emphasize ψ_2 and ψ_3 and de-emphasize ψ_1 .

This finding was examined further by dividing the

Table 3
Individual Subject (S) Saliency Weights for Each Feature

S	Saliency Weight			S	Saliency Weight		
	W_1	W_2	W_3		W_1	W_2	W_3
1*	.752	.238	.235	18	.893	.137	.069
2	.458	.226	.464	19	.385	.052	.093
3*	.632	.178	.234	20*	.382	.248	.446
4	.400	.002	.213	21*	.597	.440	.255
5*	.900	.140	.081	22*	.888	.049	.125
6*	.819	.052	.263	23	.778	.232	.253
7*	.923	.097	.114	24	.706	.258	.295
8	.229	.626	.314	25	.217	.464	.366
9	.768	.003	.163	26	.935	.070	.106
10*	.912	.175	.162	27	.837	.080	.260
11	.281	.569	.371	28*	.588	.274	.250
12	.755	.210	.343	29	.451	.402	.421
13	.709	.194	.302	30	.742	.256	.330
14	.325	.302	.299	31	.873	.075	.131
15*	.199	.574	.449	32	.393	.507	.291
16	.742	.204	.248	33	.675	.224	.277
17	.232	.213	.140	34	.222	.421	.186

Note—* indicates musically experienced subjects.

Table 4
Cross Correlations Between Individual Subject Saliency Weights

Saliency Weight	Saliency Weight	
	W_1	W_2
A. All subjects (n = 34)		
W_2	-.68*	
W_3	-.52*	.60*
B. Musical subjects (n = 11)		
W_2	-.93*	
W_3	-.82*	.67**
C. Nonmusical subjects (n = 23)		
W_2	-.31	
W_3	-.64*	.57**

* $p < .001$

** $p < .01$

subjects post hoc into musically sophisticated and musically naive groups according to their responses on a postexperimental questionnaire. A musically sophisticated subject was defined to be anyone who had played any musical instrument for a period greater than 3 years, while a musically naive subject had less experience with a musical instrument. The above saliency correlations were recomputed on the separate groups. These data are presented in Tables 4b and 4c for the musical ($n = 11$) and nonmusical ($n = 23$) subjects, respectively. The results parallel the group findings; however, the correlations are somewhat larger for the musical subjects than for the nonmusical subjects. This suggests that the musically sophisticated subjects are more homogeneous with regard to feature saliency than the nonmusical subjects—as a group, the musical subjects are more likely to stress ψ_1 and de-emphasize ψ_2 and ψ_3 than are the nonmusical subjects.

These differences are evident in the plot of the individual subject saliency space for the ψ_1 (fundamental) and ψ_3 (formants) dimensions displayed in Figure 7. Each of the 34 subjects is represented as a point in the space, indexed by their saliency weights for the two dimensions shown. The distinction between musical and nonmusical subjects is obvious in the figure. Musical subjects tend to cluster with high saliences for ψ_1 and low saliences for ψ_3 , while the nonmusical subjects are distributed across the full range of saliency values. Similar plots for the ψ_1/ψ_2 and ψ_2/ψ_3 dimensions may be obtained from the saliency weights in Table 3.

In summary, an analysis of individual subject data in the present study indicated that subjects vary widely in the distinctive features they emphasize in perceiving complex sounds. It was found that some subjects tended to emphasize ψ_1 (fundamental) exclusive of the other dimensions while other subjects stressed ψ_2 and ψ_3 exclusive of ψ_1 . A breakdown of subjects into musically sophisticated and musically naive groups indicated that most musical subjects fell into the former category, while nonmusical subjects were divided between the two categories.

DISCUSSION

It is clear from the above analysis that multidimensional scaling provides a useful technique for determining the distinctive features involved in the perception of complex nonspeech sounds. As indicated in the introduction, multidimensional scaling procedures have proven helpful in the analysis of human speech perception, but the methods have not been systematically applied to auditory perception in the nonspeech realm (e.g., Wish & Carroll, 1974a). In the present study, much of the total variance in the subject's similarity judgments was accounted for by an interpretable, three-dimensional scaling solution.

Figure 7. Representation of individual subjects in a two-dimensional saliency space.

The three dimensions have been viewed as corresponding to the psychological characteristics or distinctive features that subjects used in perceiving the 16 stimuli used in the present study. A correspondence was observed between each of the psychological dimensions obtained in the scaling solution and the physical parameters varied to generate the 16 sounds. The ψ_1 dimension corresponds to fundamental frequency, ψ_2 to waveform, and ψ_3 to a combination of the two formant parameters.

We can speculate further that ψ_1 may reflect the common auditory dimension of pitch. It is likely, however, that the formant dimension, ψ_3 , also contributes to the subject's perception of pitch, but in a manner that is independent of fundamental frequency. This argument is supported by the finding that ψ_3 tends to separate sounds according to maximum formant frequency, and in particular, to separate the four sounds having a formant centered at the highest frequency (i.e., 2,440 Hz) from the remaining sounds. These findings are consistent with the argument that pitch perception depends on the spectral composition as well as on the fundamental frequency of an auditory signal (e.g., Plomp, 1967).

The high correlation between the second psychological dimension, ψ_2 , and the waveform parameter (i.e., square vs. triangle) suggests a straight-forward interpretation. The differences in spectral composition of square and triangular signals lead to a perceptual difference in tonal quality similar to that occurring in the sounds produced by different musical instruments. These perceptual differences are well documented empirically. However, in the present study, there is evidence that the ψ_2 dimension may

reflect signal loudness in addition to tonal quality. In generating the stimuli for the present study, stimuli were equated for RMS amplitude rather than for loudness or perceived intensity.² As a result, the square-wave signals had greater energy than the triangular signals—a difference likely to produce differences in perceived intensity.

In order to examine the possible role of signal loudness, the subjects were asked to rate the loudness of each of the 16 sounds on a scale of 1 (very soft) to 5 (very loud) immediately after completing their comparative judgments. A mean loudness rating was computed for each stimulus, and these data were correlated with each of the psychological dimensions obtained in the scaling solution. This analysis revealed Pearson product-moment correlations of .15, .87, and .07 between the mean loudness ratings and the features ψ_1 , ψ_2 , and ψ_3 , respectively. Only the correlation with ψ_2 reached statistical significance [$t(14) = 7.73$, $p < .001$]. This finding confirms the above speculation that the ψ_2 (waveform) dimension corresponds closely to loudness, and that the other two dimensions, ψ_1 (fundamental) and ψ_3 (formants), were independent of subjective intensity.

The 16 complex sounds examined in the present study were similar to those used by Webster et al. (1973) in an auditory classification task. In Webster's study, subjects were required to learn a classification for each of the 16 sounds using an arbitrary set of labels. Webster et al. attempted to determine the relative psychological importance of the four physical parameters by examining the confusion matrices generated by subjects during a 2-week learning period. Although the conclusion reached on the basis of this analysis roughly paralleled the findings of the present study, no precise quantitative estimates of featural saliency were provided. Therefore, in order to obtain a more precise comparison, an interstimulus similarity matrix was established from the Euclidean interstimulus distances in the three-dimensional stimulus space, and compared with the overall confusion matrix reported by Webster et al. A statistically reliable correlation was obtained [$r = -.53$, $t(118) = -6.78$, $p < .001$]. While the overall fit is not impressive, stimulus, subject, and task differences between the two studies would all serve to increase variability. In addition, Shepard (1972) has pointed out that the psychological processes involved in classification and similarity comparison tasks are likely to involve different stimulus characteristics and would therefore lead to different underlying perceptual structures. In general, however, the present findings compare favorably with Webster's.

The three-dimensional scaling solution described above accounts for approximately 59% of the total variance in the subjects' similarity ratings. While the overall variance accounted for appears small relative to the results reported for similar work with speech

(e.g., Shepard, 1972, accounts for 99% with three dimensions), the difference is not surprising in light of the differences between speech and the present nonspeech stimuli. First, the stimuli used in the present study were highly similar perceptually, resulting in relatively poor signal discriminability. In addition, the distinctive features involved in human speech perception are determined by socio-cultural and physiological (e.g., Eimas & Corbit, 1973) factors which, for obvious reasons, are uniform across individuals. In contrast, individuals need not extract precisely the same features in processing complex nonspeech sounds. As a result, the three-dimensional solution examined above was not adequate for all subjects, since it is likely that some subjects were using stimulus features not represented in the solution.

The present data revealed substantial individual differences in the features emphasized. Some subjects—especially musically sophisticated subjects—relied primarily on ψ_1 (fundamental), while others relied primarily on ψ_2 (waveform) and ψ_3 (formants). Such differences may result from an attentional process (e.g., Kinchla, 1973) that selectively enhances one or another of the distinctive features in the complex signal. For example, in turning a musical instrument, it is necessary to ignore the spectral characteristics of the sound (i.e., the instrument producing the sound) and attend to the fundamental of the sound (i.e., the note being played). Musically sophisticated subjects appear to be better at selectively attending to the most salient distinctive feature, ψ_1 (fundamental), than musically naive subjects. The issue of why subjects, musically experienced or not, would base similarity ratings primarily on pitch is an open question.

In conclusion, the present study has demonstrated the utility of multidimensional scaling methods in the analysis of complex auditory perception in the nonspeech mode. The methods may be generally useful in further clarifying the relation between various physical characteristics of complex sounds and their perceptual correlates. Such analyses can be of considerable heuristic and theoretical value for research on auditory perception. For example, the role of attentional mechanisms in determining featural saliency and the influence of experience on these mechanisms remain to be determined.

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NOTES

1. Because of the four-dimensional physical structure of the stimulus set, the four-dimensional scaling solution was examined in considerable detail. This analysis revealed that the first three psychological dimensions in the four-dimensional solution corresponded to the dimensions in the three-dimensional solution. The additional, fourth, dimension appeared to reflect the number of formants parameter, however, the correspondence was tenuous at best (the point-biserial correlation between the coordinates of this dimension and number of formants was .40). Consequently, the three-dimensional solution was accepted as providing the most parsimonious estimate of the underlying perceptual structure.
2. This procedure was followed in an attempt to approximate the signals used by Webster et al. (1973) as closely as possible.

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