



IDENTIFICATION OF PSYCHOLOGICAL FEATURES IN THE RECOGNITION OF COMPLEX, NONSPEECH SOUNDS

> James H. Howard, Jr. ONR CONTRACT NUMBER NOO014-75-C-0308

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Unclassified Block 20 continued tification of perceptual features, (2) aural feature selection processes, and (3) aural classification processes. The methods, substantive contritution and practical implications of the research are outlined. N ACCESSION for e Pottion 8 Saulion 🗖 NTIS DOC 1.1.1. \$ DISTRIBUTION ANALY ANY ITY CODES r.v SPLCIAL Unclassified SECURITY CLASSIFICATION OF THIS PAGE(When Date Entered) a talk all the short of -State And Alexander and the second

This report summarizes the research conducted under contract N00014-75-C-0308 between the Office of Naval Research, Engineering Psychology Programs and the Catholic University of America. The research investigated the perceptual processes involved in the recognition of complex nonspeech sounds, particularly those that resemble steady-state passive sonar signatures. The individual experiments conducted in this pursuit have been distributed in nine technical reports and ten additional papers (see Appendix A for a complete listing). The issues addressed in this work may be classified into three general areas: (1) identifying perceptual features, (2) aural feature selection processes, and (3) aural classification processes. The substantive contribution of each report is described below following this overall organization.

### (1) Identifying Perceptual Features

<u>Problem and rationale</u>. Recent years have witnessed major theoretical advances in our understanding of the perceptual processes involved in the detection and discrimination of simple acoustic stimuli. In contrast, relatively little is known about the psychological processes that underlie the classification of complex acoustic signals. A popular approach to the analysis of this problem assumes that human auditory recognition involves several distinct information-processing stages. In this view an unknown sound undergoes several transformations before it is recognized. First, an initial sensory representation of the signal is formed. Second, this preliminary representation is further transformed into a set of distinctive auditory features. This stage is referred to as feature extraction and is generally thought to involve the reduction of a stimulus to its essential characteristics. Third, this highly processed feature representation is compared with information stored in memory to determine its classification. The processes involved in this stage may be extremely complex

and are collectively referred to as the decision stage.

Although no single theoretical statement of the feature extraction process exists, recent research has stressed its importance in auditory perception. It is frequently argued that the feature extraction process is "tuned" to select perceptually important information from the output of the preliminary analysis stage, and discard information that is likely to be unimportant. Since aural recognition performance ultimately depends on the feature extraction process, a central objective of our research was to investigate techniques that would enable us to identify those acoustic cues that are of primary psychological importance.

The object of this investigation, the feature representation or output of the feature extraction stage, is obviously not directly observable and must therefore be inferred using indirect methods. Although a variety of techniques have been used in previous research, we selected multidimensional scaling for further investigation. With this method, listeners are asked to provide pairwise similarity judgments on the set of sounds of interest. A specific multidimensional scaling algorithm is then applied to decompose the resulting subjective proximity matrix into an n-dimensional metric space in which each signal is represented as a single point or vector. If a satisfactory scaling solution exists, we assume that the dimensions of the scaled stimulus space reflect those features that the listeners used to compare the stimuli. A comparison of the perceptual space and the known physical structure of the stimuli can reveal the specific psychophysical transformations involved in the feature extraction process.

Three experiments were conducted specifically to investigate these techniques. In the first, we confirmed the validity of the method by scaling a set of engine-like sounds that had previously been investigated using other methods. In the second study we extended these techniques to a new set of eight passive sonar signals. In the third study additional evidence relevant to the

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feature identification problem was obtained for brief-duration signals in a backward-masking task. The results of the first two studies clearly established the effectiveness of multidimensional scaling techniques for identifying the perceptual features used by listeners in a similarity rating task. In addition, the techniques we used enabled us to specify the relative importance of stimulus features and to characterize the differences between specific groups of listeners in a precise way. The third study revealed some interesting taskdependencies. These findings have been followed up in subsequent research. The three reports are abstracted below.

Report ONR-75-1. The INDSCAL multidimensional scaling model was used to investigate the distinctive features involved in the perception of sixteen complex nonspeech sounds. The signals differed along four physical dimensions: fundamental frequency, waveform, formant frequency and number of formants. Scaling results indicated that an individual's 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 fundamental frequency, waveform, and a combination of the two formant paramenters. These results were further explored with Johnson's (1967) hierarchical clustering analysis. Large differences in featural saliency occurred in the group data with fundamental frequency accounting for more variability than the remaining dimensions. Further analysis of individual listener data revealed large individual differences in featural saliency. These differences were related to past musical experience of the listener and to earlier findings using similar signals. It was concluded that (1) the INDSCAL model provides a useful model for the analysis of auditory perception in the nonspeech mode, (2) featural saliency in such sounds is likely to be determined by an unspecified attentional mechanism.

The implications of these findings for tactical sonar operations were discussed.

<u>Report ONR-76-2</u>. The potential usefulness of multidimensional scaling techniques in the perceptual analysis of "real world" underwater sounds was demonstrated. Nineteen observers (nine with musical training, ten without) used a five-point scale to judge the similarity of all possible pairs of eight passive sonar recordings. The eight signals were selected to represent a range of common natural and man-made underwater sounds. These data were analyzed using the INDSCAL multidimensional scaling model, revealing an interpretable two-dimensional psychological space. One of the psychological dimensions was interpreted as reflecting the overall shape of the 1/3-octave spectra of the eight signals, while the second was seen to reflect the prominence of a low-frequency periodicity present in some signals. Individual observer analysis revealed substantial differences between the musically trained and musically inexperienced observers in the relative importance or salience of the two dimensions. The relation of these findings to earlier work was discussed.

<u>Report ONR-77-3</u>. Three experiments investigated the effect of an interfering white noise on the recognition of brief-duration complex sounds. Listeners were presented with a 20-msec signal followed, after a variable delay, by a 500-msec white noise burst. Their task was to classify the signal into one of two categories on the basis of either its fundamental frequency, waveform or formant frequency. The main focus of the experiments was to investigate the relation between performance and the auditory features or cues present in the signal. Recognition performance improved with increasing inter-stimulus intervals up to an asymptote at approximately 200 msec. This finding is consistent with earlier results in suggesting that brief-duration signals are retained for a short time in a precategorical sensory memory for further processing. In addition, the data revealed that asymptotic performance level was determined primarily by the distinctiveness

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or discriminability of the relevant auditory feature and by the amount of listener experience with the relevant feature. It was concluded that practiced listeners have an improved ability to selectively focus their attention on specific auditory cues in a complex aural display.

## (2) Aural Feature Selection Processes

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<u>Problem and rationale</u>. In the research outlined above we focused on the problem of identifying the features that listeners actually use to compare complex sounds. Once the reliability of multidimensional scaling techniques had been established in this context, more fundamental questions could be addressed. In particular, the feature extraction process had not been wellspecified in the literature. No true psychological theory of feature extraction existed. When we say that a stimulus is reduced to its "essential elements," what do we mean? How do listeners determine these crucial elementary units of perception? Implicit in our approach to this problem was the understanding that a feature tuning process exists whereby the set of distinctive features was defined. We referred to this as the <u>feature selection problem</u>. The specification of a general feature selection theory will enable us to <u>predict</u> the features that listeners will use in perceiving complex sounds.

Two contrasting approaches to this problem have been suggested in the literature. First, the human auditory system may be equipped with a set of specific feature-detecting mechanisms that monitor incoming aural information for particular stimulus cues. Here it is assumed that the tuning process has occurred through natural selection, and that evolutionary mechanisms have provided us with the neural apparatus needed to detect these features. This approach emphasizes the importance of the feature detectors themselves. Each detector "looks for" an individual stimulus property, and a set of feature detectors determines a property list for the stimulus. Second, it is possible that the

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auditory system has an internalized set of rules and criteria for feature selection rather than a set of narrowly tuned feature detectors. These rules and processes enable the listener to determine what the comparison features should be in any particular stimulus context.

Our research has favored the latter view. While we are not prepared to deny the existence of specialized neural detectors for some attributes (e.g., for speech cues), the more flexible, process-oriented approach has seemed more appropriate for timbre perception on both logical and empirical grounds. In the first report on this research we carefully articulate the two contrasting positions outlined above and consider earlier findings (both from our laboratory and from others) in terms of this issue. In the second report, we propose a specific structure-preserving feature-selection model and demonstrate its ability to predict the features that listeners use to compare complex steady-state sounds. We see the proposed theory as a first step toward the specification of a general feature-selection model. The two reports are abstracted below.

<u>Report ONR-78-5</u>. Feature extraction plays a fundamental role in most theories of pattern recognition, but despite its importance, the extraction process is not well defined. Two contrasting views of feature extraction were identified in this review paper, one which emphasizes invarient feature detection and one which emphasizes flexible feature selection. The invariant detector approach assumes that the auditory system is equipped with finely tuned feature detectors that respond to specific stimulus properties. In this view, stimuli are described in terms of property lists of specific features. In contrast, the more flexible, process-oriented approach assumes that the auditory system is equipped with a set of rules and criteria for feature selection. In this view, the important perceptual features reflect the underlying structure of the stimuli. Research on timbre and pitch perception has supported a flexible, process-oriented approach. The flexibility of this approach offers particular advantages in that it can explain

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the effects of stimulus and task context on performance. Both types of context influence the perception of complex sounds. Stimulus context affects the structure of the stimulus space and consequently the features that would be extracted by a structure-preserving transformation. Task context affects the relative importance of features in making similarity judgments and classification decisions. The two approaches to feature extraction have important implications for the development of auditory pattern recognition theory.

Report ONR-78-6. A process-oriented feature selection model was proposed to characterize listeners' comparisons of the timbre of complex steady-state sounds. Specifically, the model assumes that the listener performs a structural analysis on the low-resolution spectra of the stimuli to be compared and then extracts a feature representation through a structure-preserving transformation resempling a principal-components analysis. This feature representation is subsequently employed to make similarity judgments between stimuli. Predictions of the model for a timbre-comparison task were examined using a set of sixteen complex sounds that varied in amplitude spectral shape. The subjective feature representation obtained from the ALSCAL nonmetric scaling program was generally consistent with the theoretical feature representation produced by the optimal structure-preserving transformation applied to the loudness-weighted spectra. The two comparison features as well as the relative importance of the two dimensions were successfully predicted by the model. Practical implications for the subjective evaluation of complex signals are discussed and refinements to the transformations in the model are suggested.

### (3) Aural Classification Processes

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<u>Problem and rationale</u>. In order to develop a complete understanding of the aural classification process, it is necessary to clarify the relation between the feature extraction and decision stages. How are the characteristic features

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that listeners extract used to determine signal classification? The overall question addressed in the third phase of our research concerned the relation between the perceptual features identified in a multidimensional scaling analysis and the decision stage of the aural classification process. In a classification task, the listener is required to distinguish among a specified set of acoustic patterns. Consequently, one would expect the decision process to selectively emphasize one or another distinctive feature, depending on the configuration of stimuli in the perceptual pattern space. For example, given a set of stimuli which differ in both pitch and loudness, listeners would likely use both features to evaluate pairwise similarity. On the other hand, if the same signals were then grouped into two categories based on only a single dimension (e.g., high and low pitch), then listeners learning this partition need only consider a single feature, pitch, to achieve optimal classification performance.

In our first study in this series we proposed and tested a specific, bottom-up model of the aural classification process. The model is bottom-up in that classification is based on a systematic and extensive analysis of loworder feature information. In the model we assumed that a decision processor estimates the perceptual distance between the to-be-classified stimulus and each of a set of category prototypes in the feature space. This is used to estimate the likelihood of each category given that stimulus. The stimulus is then classified into the category having the greatest likelihood. This model differs from earlier efforts in at least two respects: (1) it is oriented toward multidimensional rather than unidimensional stimuli, and (2) we propose that a feature-tuning process occurs whereby the relative importance of stimulus features are adjusted to optimize classification performance. The four experiments outlined in the first of these reports investigated classification using a set of synthetic cavitation signals. Overall, the data were supportive of the model.

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Our second study addressed an issue raised in the research discussed above. Specifically, we examined the long-term stability of our theoretical predictions. Can the model adequately predict the confusions that listeners will make after extended practice? Perhaps listener sensitivity changes or new features emerge for highly practiced listeners? The results of this study were generally consistent with the model. Although some listeners seemed to "discover" perceptually difficult features only after considerable practice, very little change occurred over the final twelve sessions in the experiment.

Another issue of some interest concerns the ability of our aural classification model to characterize individual listener performance. Large individual differences were frequently noted in our classification research. In this study we were interested in predicting an individual's confusion data in one classification task after observing his or her performance in another. The results revealed that an overall attentional effort parameter was similar for the same individual across very different classification tasks. This suggests that our aural classification model may be useful in characterizing individuals as "good classifiers" or " poor classifiers" as well as in predicting the specific confusions that will occur in a number of different classification tasks.

The final study undertaken in this series addressed a broader issue. Our previous experiments on the classification of complex sounds used categories defined by two exemplars. One objective of the present study was to test the generality of the model by examining classification performance in a four-exemplar categorization task. A second objective of this study was to obtain additional evidence regarding the classification rules that listeners use. Our classification model is based on the assumption that listeners compare a sound with each of a

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series of prototypes to determine its correct classification. Although this assumption has been supported in several experiments, other possible decision rules have not been considered explicitly. Two possible models of how category information is represented subjectively were examined in this study: the prototype-distance and attribute-frequency models. The prototype model argues that in a classification task a prototype or best example of a category is formed by averaging the distinctive features of the category members. In contrast, the attribute-frequency model assumes that the best example of a category is simply that item whose features or attributes occurred most frequently in the category exemplars. Our findings indicated that the classification model will adequately handle the four-examplar situation, but also indicated that the prototype assumption may not be the most appropriate in all conditions. Each of the four studies in this series are abstracted below.

Report ONR-78-4. The relation between the perceptual features identified in a multidimensional scaling (MDS) analysis and the decision stage of the auditory classification process was investigated in four experiments based upon a set of sixteen complex acoustic patterns. The sounds consisted of broad-band white noise, amplitude modulated by sawtooth waves of varying frequency and attack. A psychological feature representation of the stimuli was obtained in Experiment 1 using a MDS analysis (INDSCAL) of the listeners' pairwise similarity ratings. Two groups of listeners in Experiment 2 learned to classify each of the sixteen signals into one of eight categories (two sounds per category). The two groups learned eight-category partitions that emphasized different features of the stimuli. Confusion matrices were analyzed in terms of both the stimulus space obtained in Experiment 1 and a probabilistic model of the listener's decision process. The model provided a reasonable fit to the observed data. Experiments 3 and 4 further tested the assumptions of the

decision model. In Experiment 3, listeners were required to classify each member of a large set of amplitude-modulated signals that formed a "grid" over the perceptual feature space. Subjective probability density functions for the eight categories estimated from listener responses using potential function or Parzen estimator techniques were consistent with those assumed by the model. In Experiment 4, MDS techniques were used to investigate the "conceptual space" underlying the listeners' memory for each of the eight categories in both groups. Category coordinates obtained from the MDS analysis corresponded well to the category centroids computed from the perceptual space of Experiment 1. Overall, results of the four experiments indicated that listeners employed an optimumprocessor strategy to determine the relative importance of each feature in the decision process. The findings indicate that any theoretical treatment of auditory pattern recognition must address the interaction of the feature extraction and decision processes.

<u>Report ONR-78-7</u>. Four listeners were given extended practice in an eight-category classification task (3072 trials). The stimuli were sixteen amplitude-modulated noise patterns that varied in modulation frequency (Tempo) and attack (Quality). Two listeners learned an eight-category partition that was based primarily on stimulus Quality, and two learned a partition that was based primarily on stimulus Tempo. The resulting confusion data were analyzed in terms of our aural classification model. The theoretical analysis enabled us to specify the relative emphasis placed on the two stimulus features by each listener on each of the sixteen trial blocks. The results indicated that although large individual differences occurred, all listeners had more difficulty making use of the subtle stimulus differences along the Quality dimension than they did of differences along the Tempo dimension. Three of the four listeners placed a greater emphasis on Tempo than would be optimal. Although one listener only "discovered" the Quality dimension after 750 trials, very few changes occurred for any listener

after 1000 trials. It was concluded that extensive practice alone is not likely to improve a listener's ability to use difficult features in aural classification. The role of sensory factors in limiting performance was considered.

<u>Report ONR-78-8</u>. Our proposed classification model estimates attentional capacity and how it is allocated to the relevant dimensions. It was hypothesized that capacity will vary as a function of individuals, but that the allocation of capacity is a function of dimensional relevance. A classification experiment was conducted using amplitude-modulated noise with modulation frequency (Tempo) and waveform attack (Quality) as relevant dimensions. Listeners were required to classify sixteen sounds into eight categories emphasizing one of the dimensions for eight blocks (1536 trials) and then the other dimension for eight blocks. Capacity was estimated by the model and was equivalent for both classification tasks for individuals. Allocation of capacity reflected dimensional relevance.

<u>Report ONR-78-9</u>. Our proped classification model assumes that each category in a classification task is represented by an abstract prototype. Others have argued that the evidence for prototype representations can be explained by the indeterminancy of exemplar attributes. A test of these two models would require that attribute indeterminancy be measured. In a classification task, attribute indeterminancy can lead to overlapping category boundaries. In turn, this results in confusions, which can then be a measure of indeterminancy. An aural classification experiment was conducted where listeners classified sixteen amplitude-modulated noise patterns into one of four categories, each having four examplars. Results of a post-training recognition test indicated that an unexperienced prototype was rated as familiar, but this effect was

reduced with increased practice with the category exemplars. Neither model was supported unequivocally. Classification results did demonstrate that the classification model is applicable to four examplar categories defined in two dimensions.

#### (4) Summary

A number of general conclusions are justified on the basis of our findings. (1) Multidimensional scaling provides a set of useful techniques for identifying the perceptual features that listeners use to evaluate complex sonar-like sounds. These methods also permit a precise quantitative specification of individual and group differences as well as an assessment of the relative importance of specific features. (2) Caution must be exercised, however, in generalizing the aural features identified in one situation to other task contexts. Our research has demonstrated that considerable, task-related variability can occur in the relative subjective importance of individual features. The most important feature in one task is not necessarily the most important in another, even though both tasks may involve the same stimuli. (3) Our feature selection model provides a reasonable preliminary specification of how listeners determine which features to use when comparing complex, steady-state sounds. (4) The aural classification model proposed in the present research can successfully predict the specific confusion errors that listeners make in a wide range of classification tasks. When coupled with the feature-selection model, the classification model provides a potentially very powerful method for anticipating the "fine structure" of aural classification data. The contribution of such knowledge to the development of acoustic preprocessing devices or other performance aids is obvious.

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