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Human discrimination of complex acoustic signals typically cannot be predicted from the simple sum of the discriminabilites associated with individual components of the signal. Understanding such failures of additivity is central to our understanding of complex sound analysis. The goal of this project is to elucidate the rules and mechanisms whereby individual stimulus components combine to influence the detection and discrimination of complex sounds. The project is designed to answer specific questions regarding listeners' abilities to integrate information within and across acoustic dimensions, to extract information contained in the pattern of the acoustic signal, and to perform under conditions of stimulus uncertianty. The data are also used to determine how listeners weight the information provided by different components of the signal, and how best to package the acoustic information so as to be most effectively processed by the listener.

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ADDITIVITY AND AUDITORY PATTERN ANALYSIS

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Additivity and Auditory Pattern Analysis

Robert A. Lutfi, Principal Investigator

Project Summary

Human discrimination of complex acoustic signals typically cannot be predicted from the simple sum of the discriminabilities associated with individual components of the signal. Understanding such failures of additivity is central to our understanding of complex sound analysis. The goal of this project is to elucidate the rules and mechanisms whereby individual stimulus components combine to influence the detection and discrimination of complex sounds. The project is designed to answer specific questions regarding listeners' ability to integrate information within and across stimulus dimensions, to extract information contained in the pattern of the acoustic signal, and to perform under conditions of stimulus uncertainty. The data are also used to determine how listeners weight the information provided by different components of the signal, and how best to package the acoustic information in frequency and/or time so that it is processed most effectively by the listener. Finally, w[illegible]k is undertaken to develop a computational model to summarize and predict the results of these a[illegible] future experiments.

Statement of Work/Research Objectives

Can the perception of a complex event be reduced to the sum of its analyzable elements? This was one of the fundamental questions that occupied the minds of the earliest thinkers interested in understanding human perception. Today, of course, we are familiar with the Gestaltist's favorite illusions demonstrating that the perception of the whole is often greater than the sum of its separate parts. By demonstrating the importance of the relations among parts, the Gestalt psychologist redefined the study of perception as the study of patterns.

In contemporary psychoacoustics, the Gestaltist's influence has been made evident in pattern perception models of pitch (Goldstein, 1973; Terhardt, 1974; Wightman, 1973), localization (Searle, 1982; Perkins, Kistler and Wightman, 1986), and speech (Stevens and Blumstein, 1978). Now there is evidence that simple auditory detection, as well, frequently involves an analysis of the overall pattern of excitation produced by the signal and masker (Ahumada and Lovell, 1971; Ahumada, Marken, and Sandusky,1975; Green, 1983; Green, and Kidd, 1983; Green, and Mason, 1985; Hall, Haggard, and Fernandes, 1984; Hanna, 1984; Leek, and Watson, 1984; Lutfi, 1985, 1986; Spiegel, Picardi, and Green, 1981). The basic result of the detection studies is a failure of additivity; components of the acoustic complex affect threshold in ways that are not predicted by summing their separate effects. Failures of additivity impose severe constraints on our ability to predict the auditory system's response to complex stimuli, like speech, from the response to much simpler inputs. Thus, one of the greatest challenges confronting psychoacoustics in the years ahead is to understand the mechanisms and invariances that determine how stimulus components combine to influence auditory perception.

The present project adopts an approach to this problem which is both simple and direct. In all experiments, the unit of analysis is the discriminability, as measured by d', of single tone bursts that differ (on average) in level. The complex signals of these experiments are comprised of various combinations of 2 to 13 of these tone bursts distributed in frequency and/or time. On the basis of simple additivity, the discriminability of the complex is given by the vector summation rule, $d'_{complex} = (\Sigma d'^2_i)^{1/2}$, where d'_i is the discriminability of the ith tone component of the complex. The vector summation rule thus provides the referent for evaluating the discriminability actually obtained. This simple approach is used to address the following specific questions regarding the processing of complex sounds:

(1) How efficiently can human observers integrate information within and across different stimulus dimensions?

(2) What effect does uncertainty along relevant and irrelevant dimensions have on the ability to integrate this information?

(3) How efficiently can observers extract information contained in the pattern of level variation across the individual components of the complex?

(4) Which components of the complex are weighted most heavily in the decision process?

(5) What is the best way to package the acoustic information in frequency and/or time so that it will be processed most effectively by the observer?

(6) What are the mechanisms underlying the discrimination of these complex sounds? Can a computational model be developed to account for the results?

Summary of Research Progress

To summarize the research progress made in answer to these questions we list all scientific publications to accrue from the project along with a brief description of the research findings in each case. Further information pertaining to research progress can be found in these publications.

Lutfi, R.A. (1988b). "Complex interactions between pairs of forward maskers," **Hearing Research, 35**, 71-78.

The present study was conducted to determine to what extent the combined effects of two forward maskers can be predicted from addition of their individual effects. The masker were 50-Hz wide noise bands with center frequencies ranging from 1.8 to 2.2 kHz. The signal was a brief, 2.0-kHz tone burst. When the maskers were gated on and off together, the combination produced sometimes more and sometimes less masking than predicted depending on the particular pair and the relative amounts of masking produced by the individual maskers in the pair. The greatest discrepancy occurred however, when the masker pair was presented simultaneously with the signal or when the forward maskers were presented in sequence. In the latter case, the obtained threshold exceeded the predicted threshold by as much as 34 dB.

Lutfi, R. A. (1989). Informational processing of complex sound: I. Intensity Discrimination. **Journal of the Acoustical Society of America, 86**, 934-944.

This paper reports on some initial experiments using the sample discrimination paradigm to investigate normal-hearing listeners' ability to process information in complex, nonspeech sounds. An important feature of the sample discrimination experiment is that the value of the difference to be discriminated randomly varies from trial to trial. It is this variation that yields potential information. In the present study, listeners heard a pair of multi-tone complexes (or sequences) on each trial. The individual levels of the tones were drawn from two normal distributions differing only in mean. The listener's task was to identify the sound having the higher mean tone level. For an ideal observer in these experiments, performance in d' grows as the square root n, where n is the number of tones. Obtained d' grew more nearly as the cube root of n regardless of whether the tones were played sequentially or simultaneously; whether they were increased in number from high frequencies to low or from low frequencies to high. A preliminary model is proposed in which discrimination performance depends predominantly on the information content of the sounds and is largely independent of the physical dimensions along which the sounds vary. Information content is defined in terms of the variance of the underlying stimulus distributions and a stimulus equivocation factor which is derived from the data. Based on this model, transmitted information is estimated to be between 1.0 and 2.6 bits.

Lutfi, R. A. (1990a). Informational processing of complex sound: II. Cross-dimensional analysis. **Journal of the Acoustical Society of America, 87**, 2141-2148.

A series of experiments investigated listeners' ability simultaneously to process information across different acoustic dimensions. On each trial the listener heard a pair of brief n-tone sequences (n = 1 to 12). The frequency, intensity, and duration of each tone in the sequence varied randomly from trial to trial. On average the values of these three parameters were greater for one sequence, the target, than the other, the nontarget. The listener's task was to identify the target on each trial. For an ideal observer in this task d' performance grows as the square root n. Obtained d' grew at a rate slightly less than the square root of n. Close to cube root of n growth was observed when the average difference occurred in only one of the three tone parameter values within a block of trials. Although performance fell short of ideal, optimum weights were consistently given to each tone and each tone parameter. The results are consistent with a model in which performance depends predominantly on the information content of the sounds regardless of how the information is 'packaged' in the stimulus. Transmitted information is estimated to be 0.9-2.0 bits within a single acoustic dimension, 2.1-3.0 bits when distributed across dimensions.

Lutfi, R. A. (1990b). How much masking is informational masking? **Journal of the Acoustical Society of America, 88**, 2607-2610.

Tone-in-noise masking experiments have long served as a useful tool for measuring the limits of auditory frequency selectivity and temporal resolution. The general conclusion to be drawn from these measures is that tone detectability is largely determined by a small portion of noise *energy* falling within close spectral or temporal proximity to the tone (Fletcher, 1940; Green and Swets, 1966; Penner et al., 1973). Another source of masking, not often discussed in these studies, is that resulting from the uncertainty associated with trial-to-trial variation in the noise waveform. Pollack (1975) uses the term *informational* masking to describe this second type of masking. The effects of informational masking are well documented for highly uncertain maskers exceeding 40 dB in some conditions, even with masker energy far removed from the signal. Given the potential magnitude of these effects, it seems reasonable to ask how much informational masking might exist in more traditional experiments using noise. This paper provides an estimate based on a theoretical analysis of many of the existing data. The conclusion is that 22% of the masking observed in many traditional tone-in-noise detection experiments is due to uncertainty associated with trial-to-trial variation in the noise waveform.

Lutfi, R. A. (1991a). Comment on "Analysis of weights in multiple observation tasks" [J. Acoust. Soc. Am. 86, 1743-1746 (1989)]. **Journal of the Acoustical Society of America, 91**, 507-508.

Generally, we can identify two factors that limit an individual's ability to process information from multiple sources: internal noise associated with the observations, and undo reliance or weight given to particular observations. It is shown that Berg's (1989) proposed method for assessing weights is not independent of assumptions regarding internal noise.

Lutfi, R. A. (1991b). Informational processing of complex sound: III. Interference. **Journal of the Acoustical Society of America**, (in press).

In this study theoretical results from information theory and detection theory are applied to provide a formal analysis of the interaction of target and context uncertainty on the discrimination of brief multitone sequences. The experiments employ a sample-discrimination task in which the performance of an ideal observer is held constant while the relative variability of the target σ_T and context σ_C is varied. Listener performance in these experiments was less than ideal but increased monotonically with

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