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AUDITORY PATTERN MEMORY

Mechanisms of Temporal Pattern Discrimination by Human Observers

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Several studies of temporal pattern perception were conducted, using tasks where the listener discriminated whether or not two tonal sequences formed the same temporal pattern. Performance was modeled using the Pattern Correlation Model, which assumes that the listener estimates the correlation between the pattern of intervals marked by the tones in each sequence. The model was applied to experiments where the sequences were (a) compressed or expanded in time, (b) presented at different frequencies and to different ears, (c) onset delayed from 1 to 1500 ms, and (d) subject to cyclic repetitions within each sequence. Other experiments have concerned (1) the discrimination of rhythmicity, (2) visual information processing as a function of spatial position and time stress, and (3) modeling and computer simulation of systems for group signal detection.

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PROJECT SUMMARY

The primary goal of this research is to understand how human observers process temporally patterned, acoustic stimuli. We have been performing a series of studies of how listeners detect, encode, store, and compare sequences of tones. Several studies of temporal pattern discrimination were conducted. Listener performance in these experiments was evaluated using a mathematical model of temporal pattern discrimination called the Pattern Correlation Model. Analyses of these experiments allow specification of the temporal pattern discrimination mechanisms employed by the human auditory system.

Our experiments tested how listeners discriminate between arrhythmic, tonal sequences that were approximately one half-second in duration. According to the Pattern Correlation Model, the listener extracts a list of tone marker interonset times from each pattern, and then computes the correlation between the pattern of time intervals marked by the tones in each sequence; other information about the input waveforms (such as absolute timing or spectra) is discarded. The experiments tested how listener performance depends on basic parameters of the task, such as sequence correlation, and number, duration, and variability of pattern elements. Listener performance was consistent with the predictions of the Pattern Correlation model, but was limited by an internal time jitter or noise that was a function of the average intermarker interval.

A second study evaluated the human listener's ability to discriminate between word-length tonal sequences that were subjected to uniform temporal transformations, such as time compression and expansion. One of the most intriguing features of temporal pattern perception is the ability to recognize patterns as similar, despite such compression or expansion manipulations. Examples of such time normalization abound in speech and music perception and we are normally unaware of such temporal changes, even when they occur during relatively brief stimuli, such as words. These experiments tested how well the Pattern Correlation model could predict the effects of time compression and expansion on listener performance. The model proved useful in describing performance in a variety of different conditions that employed multiplicative and additive time transformations. Listener performance dropped when one of the sequences was compressed or expanded in time. In order for the model to describe performance, it was necessary to postulate an additional, internal noise component that was proportional to the magnitude of the difference between the sequence transformations.

A third study evaluated the possibility that different pattern comparison mechanisms operate in different task conditions. The experiments evaluated discrimination when the two patterns began at delayed starting times. The patterns were presented at different frequencies and to different ears, and were subjected to multiplicative compressions and expansions. Listeners performed well even when the patterns contained tones of different frequency and in spite of the patterns being presented to separate earphone channels. Performance was good when the sequences were presented either (near) simultaneously or at relatively long time delays. When the time between pattern onsets was less than 10-ms, discrimination was very sensitive to the expansion or compression manipulation, indicating that discrimination in this region was based on the process of waveform correlation. At longer time separations, performance was relatively insensitive to such transformations, consistent with the Pattern Correlation hypothesis. Thus the results support a two-phase mechanism: when the sequence delay is less than 20-ms, the binaural waveform correlator is the active mechanism; when the sequence delay is greater than 20-ms, the pattern correlator is the active mechanism. Moreover, the efficiency of the pattern correlation mechanism is very poor when the sequences overlap in time. It appears that the sequential presentation of stimulus patterns is a requirement for the pattern correlator to function.

We are now conducting experiments on the role of rhythm in the discrimination and perception of complex auditory patterns. Two experimental paradigms are being employed. In one, we are investigating the possible advantages of cyclic repetitions in the temporal patterns to be discriminated. Because the presence of cyclic repetition or pattern correlation (i.e. rhythm) reduces the amount of (independent) statistical information in the stimuli to be compared, this paradigm offers a way to extend the Pattern Correlation Model. A second experimental paradigm attempts to assess directly the listener's ability to discriminate rhythmicity as measured by the pattern correlation. This experiment offers the possibility that the Pattern Correlation Model may be useful for modeling the perception of rhythm.

In addition to auditory experiments on temporal pattern processing, we completed two studies of visual pattern processing. One continuing study employs a weighting analysis derived from signal detection theory; the goal is to specify how the observer's processing of information from different spatial positions, varies as a function of the stage of information processing and the time (and other) stress on the observer.

Finally, we have begun the development and computer simulation of group signal detection. Group signal detection systems are composed of m detectors, who must work together to detect a weak signal in noise. These analyses have already resulted in some very interesting comparisons of the relative efficiency of different detection schemes, including common systems such as the traditional jury.

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I. OBJECTIVES AND STATUS OF THE RESEARCH EFFORT

1. Discrimination of arrhythmic tonal sequences: Effect of temporal transformations. (Sorkin and Montgomery).

A basic aspect of our normal perception of speech and music, is the ability to discriminate and categorize temporal patterns. We have been studying the discrimination of brief tonal sequences. The observer is presented with two sequences of tones and asked to report whether or not the two temporal patterns are the same--ignoring any other differences between the two stimuli, such as frequency. On half the trials, the patterns are the same, and on half they are different. For most of our experiments, the sequences were composed of 8, 30-ms duration, 1000-Hz tones, and the mean intertone interval was set between 20 and 100-ms. The mean duration of a typical sequence was 600-ms and the time separation between the pair of sequences was 750-ms.

Subjects perform this task very well. The important variable controlling task difficulty is the correlation, ρ_{ex}, between the two series of tone interonset times. On SAME trials, ρ_{ex} is set to 1.0 and on DIFFERENT trials, ρ_{ex} is set to a constant value less than 1.0, depending on the condition of interest. The task is easiest when, on DIFFERENT TRIALS, ρ_{ex} is set to zero, and becomes more difficult as ρ_{ex} approaches one. The optimal way to perform this task is to estimate ρ_{ex} from the sequences of interonset times observed on a trial. We know how that statistic is distributed, and so we can compute how d' should depend on rho and the number of tones in the sequence. We assume that there is an internal noise or jitter on the subject's estimate of the times, and we factor that into our prediction of subject performance. For our previously reported data, this jitter was approximately 15-ms.

We tested sequence discrimination when the second sequence was time expanded or compressed by a multiplicative or additive constant. A mechanism that extracts the times and then computes the correlation between the two lists of intertone times, e.g. a temporal pattern correlator, will be relatively insensitive to such time transformations. (Imagine that you multiply each element in the second of two lists of numbers, by a constant. The correlation should not be affected by that multiplication.) We found that performance was good under the transformations, but was affected by the magnitude of the transformation to the second sequence. A satisfactory model of performance used two sources of internal noise: a fixed component of internal noise and a component dependent on the magnitude of the transformation difference between the sequences.

2. Discrimination of arrhythmic tonal sequences: Effect of delay in onset of second sequence. (Sorkin and Montgomery).

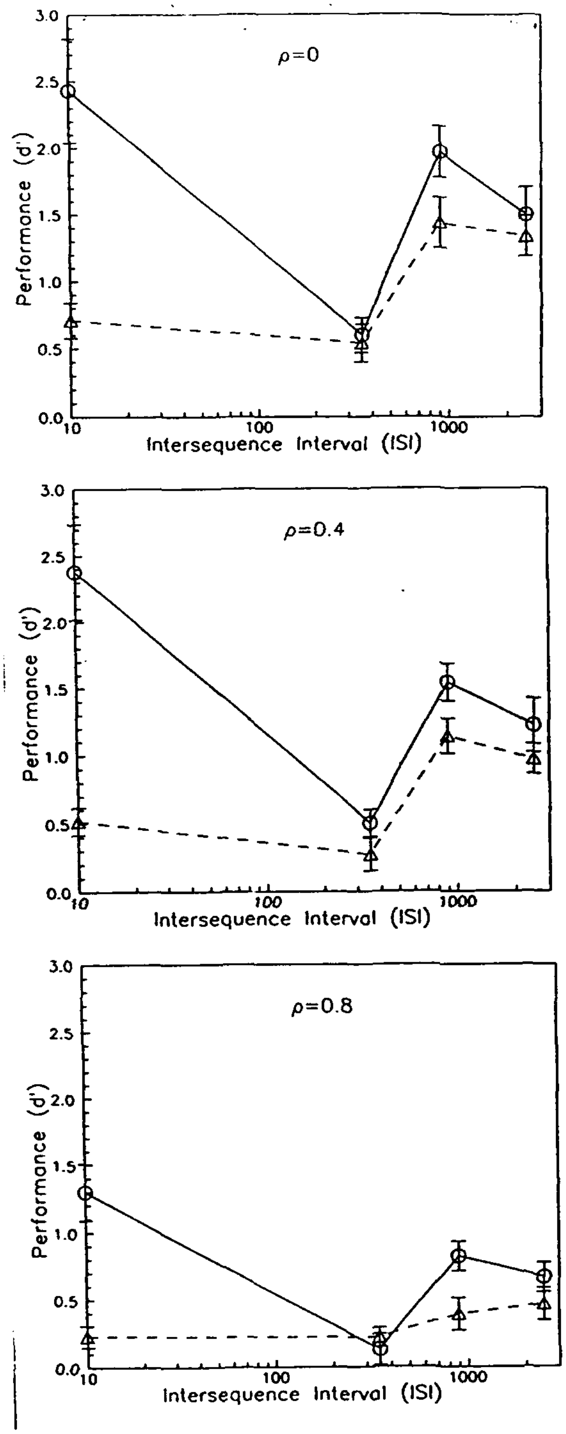
These experiments evaluated temporal pattern discrimination as a function of the time delay between the patterns. Listeners decided whether two arhythmic tonal sequences had the same or different temporal patterns. The patterns were determined by the sequence of successive time intervals between tones. According to the Pattern Correlation Model, listeners discriminate between arrhythmic tonal sequences by (a) extracting information about the time intervals between the tones and (b) computing the correlation between the serial pattern of time intervals in each sequence. We examined the effect of varying the time interval between onsets of the pair of sequences; we wished to evaluate delays of from a few ms--up to the relative long delays of our previous experiments. The sequences were presented at different frequencies and separately to the two ears.

Performance was quite good when the sequence onsets began within 1-ms and decreased as the delay between onsets exceeded 20-ms, approaching a minimum at 300-ms (when the sequences overlap by 50%) and then increasing again. The average duration of each sequence was about 600-ms. The moderately good performance at long delays is consistent with our previous experiments and with the idea that the task is performed by estimating the temporal correlation between the time patterns defined by the intertone time intervals.

We would expect very good performance at very short onset delays; because under these conditions, the binaural system can make very precise determinations of differences between stimuli presented to the two ears. Other investigators have reported that binaural comparisons may be performed when the signals are presented at high frequencies (e.g. above 2,000 Hz), and at different frequencies in the two earphone channels. A delay in the second signal of more than about 15 milliseconds would be expected to exceed the limits of the binaural system. We would expect that a mechanism that simply correlated the two input waveforms would be very sensitive to the time expansion manipulation, because temporal misalignments that occurred early in the sequence would produce even greater decorrelations at later times.

In order to examine the interaction between these manipulations, we combined the two manipulations of temporal expansion and intersequence delay. That is, we added a condition in which all time intervals in the second sequence were expanded by a small uniform factor between 0.8 and 1.2. Over trials, we multiplied all tone durations and gaps in the second sequence by either 0.8, 0.9, 1.0, 1.1 or 1.2, chosen randomly over trials. The results are shown in the figure: The solid curves are the conditions with no time transformations. The dashed curves show the random time transformations. In the latter case, performance at very short delays dropped almost to zero. It is tempting to conclude that the mechanism operating at short onset delays is a waveform correlation process; and the mechanism operating at long delays, is a temporal pattern correlation process.

Why is neither mechanism effective at intermediate delays? These delays are clearly too long for the binaural system, so the temporal pattern correlator is left to do the job--and apparently it cannot. In order for the relevant time information to be extracted from the stimuli, the sequences may need to be presented to the system-one sequence at a time-that is, in a "single-channel" mode. It may be that this mode of processing requires the observer's attention to the individual stimuli to be compared.



Performance (d') as a function of intersequence interval, under two temporal transformation conditions: no transformation (solid lines), and random-transformations (dashed lines). The panels show data for three values of intersequence correlation.

3. Effects of rhythm on temporal pattern discrimination (Sorkin and Sadralodabai).

This ongoing project assesses the effects of the rhythmic properties of the temporal patterns on the listener's ability to discriminate between patterns. The success of the pattern correlation model suggested that its ability to describe a listener's temporal pattern discrimination behavior may be generalizable to "rhythmic", e.g. repeating, non-random patterns. In this experiment, we use the pattern correlation model to characterize the rhythmicity of a sequence; that is, the temporal correlation between repeated sequences of length k, is taken as a first approximation to a measure of stimulus rhythmicity. The hypothesis under study in this experiment is whether two rhythmic (or partially rhythmic) patterns are more easily discriminated than are non-rhythmic patterns.

One difficulty in performing this experiment is to insure that any difference in the rhythmicity of the two sequences to be discriminated does not itself signal a difference between the sequence patterns. We have designed and are currently running, an experiment in which these variables are controlled. If pattern rhythmicity is found to affect temporal pattern discrimination, we will attempt to model the process and define what factors, such as memory, mediate those effects.

4. Discrimination of Pattern Rhythmicity: Extended Temporal Correlation Model (Sorkin and Sadralodabai).

The initial results of the rhythmic pattern discrimination experiment have led us to study the listener's ability to discriminate the extent of rhythmicity in a temporal pattern. Using the temporal pattern correlation model to provide an objective measure of pattern rhymicity, we have begun experiments assessing a listener's ability to discriminate this aspect of a temporal stimulus. Essentially, the listener is provided with two temporal patterns (each is a sequence composed of 3 repetitions of 4 intertone intervals) and must discriminate which pattern is more rhythmic. We will employ the pattern correlation model, augmented by assumptions about an additional source of internal jitter, to model this discrimination process.

5. Analysis of Group Detection Systems (Sorkin and Crandall).

In this study, we are using the theory of signal detectability to predict how the performance of grouped detection systems depends on the size of the group, the group decision rule, and the characteristics of the group members. These systems are assumed to have m individual detectors, each with a specified detection sensitivity and response criterion. Four types of groups are considered: (1) the Ideal Group, (b) the Standard Jury, (c) the Limited Interaction (Delphi) Jury, and (d) the Single Ballot Group. Decisions of the Ideal Group are determined by weighting and summing the likelihood-ratio observations of the individual detectors; this strategy defines the upper bound of performance achievable by any group detection system. Lower performance is obtained when the group decisions are based on the binary outputs of the individual detectors. The Standard Jury is assumed to function as follows: After the observation is made, each detector makes an initial decision and then recomputes its response criterion as a function of the initial decision, sensitivity, and criterion, of the other detectors. This cycle repeats until unanimity (or other majority decision rule) is reached or time runs out.

We have performed computer simulations of these group detection systems for a variety of conditions, group member parameters, and majority voting rules. The Standard Jury exhibits the best performance of the non-optimal (binary combination) groups. We shall consider the implications of the analysis for the design of group detection systems.

6. Integration of information from multiple element displays (Sorkin, Mabry, Weldon, and Elvers).

This experiment examined the processing of information from multiple element visual displays, using techniques derived from the theory of signal detectability. The method allows one to specify how observers integrate information from individual elements of a display. The experiment tested numerical and graphical displays having different display sizes, durations, and arrangements of elements. Observer performance increased with the number of display elements (m), but at less than the ideal $\sqrt{m}$ rate. Observer performance was consistent with a model of information integration constrained by internal noise. Linear arrays of elements resulted in better performance than did square arrays. Graphically coded elements resulted in better performance than did numerically coded elements. Observer decision weighting of element information from graphical displays was approximately uniform across spatial positions, but the weighting of information from numerical displays was concentrated on elements near the fixation point.

7. Information integration under processing limitations (Montgomery).

Three experiments were performed to determine the effects of time stress on the selection and use of visually displayed information in a 2-alternative-forced-choice decision task. Observer time stress was varied by altering the stimulus duration, complexity, and time to respond. The stimulus consisted of a horizontal array of nine, three-digit numbers. Each number was independently sampled from either a signal or noise probability distribution, depending on the type of trial. Observers had to decide whether the display was generated from the signal or noise distribution. A technique developed by Bruce Berg, provided the means for characterizing changes in observer performance from ideal performance as (1) changes in the relative decision weights for the different spatial positions or (2) changes in the observer's internal noise.

In the first two experiments time limitations were imposed during sensory processing and response selection. Limitations in capacity or bandwidth at the sensory processing stage were expected to reduce the number of allowable fixations, leading to a reduction in the information available from different spatial positions. Limitations imposed later in processing , closer to response selection and execution, were expected to force observers to use whatever information was available for a rapid decision, interpretable as a non-spatially specific loss in performance due to internal noise. Evidence from both experiments supported the early stage effect: neither limiting the answer duration nor forcing and immediate response produced significant effects on performance. In the third experiment, stimulus complexity was manipulated by altering the mean and variance of the two signal distributions. Changes in these parameters did not produce significant changes in performance.

II. PERSONNEL ASSOCIATED WITH THE RESEARCH PROJECT

Crandall, Christian S., Visiting Assistant Professor of Psychology, University of Florida. Professor Crandall has been assisting with the group detection study.

Montgomery, D. A. (Widman). Graduate Student, Department of Psychology, University of Florida. Ms. Montgomery has been on the project since May, 1989.

Sadralodabai, Toktam. Graduate Student, Department of Psychology, University of Florida. Ms. Sadralodabai joined the project in August, 1991.

Sorkin, R. D. Principal Investigator, Professor of Psychology, University of Florida.

III. ADVANCED DEGREES

Montgomery, D. A. Information integration under processing limitations: A weight analysis. M.S. Thesis, University of Florida, August 1991.

IV. INTERACTIONS

Associate Editor, International Journal on Human-Computer Interaction.

Member and Chair, Acoustical Society of America Long Range Planning Committee.

Member, Research Advisory Council, Center for Applied Human Factors in Aviation, Orlando, Florida.

Sorkin, R. D. and Montgomery, D. A. Psychophysical analysis of visual information processing. Invited paper presented at the Conference on "Human Error". Indiana University Institute for the Study of Human Capabilities, March 20-23, 1991, Bloomington, Indiana.

Montgomery, D. A. and Sorkin, R. D. The effects of time stress on visual spatial selectivity. Paper presented at the 35th Annual Meeting of the Human Factors Society, San Francisco, California, Sept. 1991.

Sorkin, R. D. and Widman, D. A. Discrimination of arrhythmic tonal sequences: Effect of temporal transformations. (Paper presented at 120th Meeting of the Acoustical Society of America), Journal of the Acoustical Society of America, 1990, 88, S147.

Sorkin, R. D. and Montgomery, D. A. Discrimination of arrhythmic tonal sequences: Effect of delay in onset of second sequence. (Paper presented at 121st Meeting of the Acoustical Society of America), Journal of the Acoustical Society of America, 1991, 89, 1913.

V. PUBLICATIONS

Sorkin, R. D., Mabry, T. R., Weldon, M., and Elvers, G. Integration of information from multiple element displays. Organizational Behavior and Human Decision Processes, 1991, 49, 167-187.

Sorkin, R. D. and Montgomery, D. A. Effect of time compression and expansion on the discrimination of tonal patterns. Journal of the Acoustical Society of America, 1991, 90, 846-857.

Sorkin, R. D. and Robinson, D. E. Computer-aided detection and classification. (in preparation).

Sorkin, R. D. and Montgomery, D. A. Effect of stimulus delay interval on the discrimination of tonal patterns. Journal of the Acoustical Society of America, (in preparation).

Sorkin, R. D. and Crandall, C. S. Detection Theory Analysis of Juries and Other Groups. Psychological Science. (in preparation).