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A series of experiments testing the discrimination of random temporal patterns (single frequency tone sequences) was performed. The observer's task was to discriminate whether two sequences of tones contained the same or different patterns of temporal gaps. Half of the experimental trials contained gap sequences that were perfectly correlated across the two sequences (e.g. the temporal patterns were identical), and half the trials contained gap sequences that were partially correlated (the correlation was controlled by adding the outputs of two normal deviate generators). A model of discrimination, based on computation of the sample correlation between the gaps, and limited by a fixed source of internal (independent) temporal noise, allowed good prediction of observer performance. Some additional sources of variance were due to encoding or memory limitations. The correlation model makes specific predicitions aobut the consequences of sequence time compression and expansion on performance; experiments are under way to evaluate the effects of these transformations. (continued)

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ABSTRACT (continued)

Two channel, two frequency, versions of the basic pattern discrimination experiment were begun. In these experiments the frequency of the tones in the second sequence was different from the first (by more than a critical band) and these tones were presented in the contralateral earphone channel. Little decrease in pattern discrimination performance was observed compared to experiment 1. Performance dropped as the time separation between the two sequences was reduced. Performance was worst when the two sequences began to overlap. When there was only a very small time delay, t, separating each tone of the two sequences, performance was exceedingly good. The latter result is explained by the presence of periodicities generated on trials when the sequences are correlated. As t gets increases, the frequency of the prominent periodicity becomes too low for the system and observer processing shifts from a spectral to a trace-dependent and then to a context-coding basis. This transition is very interesting because it may provide a bridge between elementary psychophysical experiments on noise correlation discrimination (or binaural detection), and results with longer stimuli such as tonal sequences. The experimental paradigm may support a model of performance that is applicable over three different modes of processing-spectral, trace, and context-as a function of the single task parameter, sequence offset time.

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AUDITORY PATTERN MEMORY

Mechanisms of Tonal Sequence Discrimination by Human Observers

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I. Temporal Pattern Discrimination

A. Introduction

The goal of this research is to understand how human listeners encode, store, and compare the temporal patterns defined by two tonal sequences. The general experimental paradigm requires the listener to decide whether two arrhythmic tonal sequences have the same or different temporal patterns. This comparison process appears to be accomplished in different ways, depending on the relative timing of the sequences. In one case, listener behavior is described by a process that computes the correlation between (encoded and stored) lists of intertone onset intervals. In the second case, listener performance is modeled as a running computation of the correlation between the whole waveforms of the filtered input sequences. In a later section, we expand these descriptions and summarize some preliminary data.

Several investigators have studied the perception of partially unstructured or arrhythmic temporal sequences. Lunney (1974) showed that the discrimination of irregularity in tempo, introduced into the fourth click of the output of a metronome, was an exponential function of the period, in a range of period durations from 30 ms to 3200 ms. Pollack studied the perception of temporal gaps within trains of very brief pulses (Pollack;1967,1968a,) and the perception of periodicity and jitter in pulse trains (1968b,c,d). Pollack found that the threshold for gap discrimination increased with the interpulse interval, for interpulse intervals greater than 10 ms. In general, performance was best when the pulse trains contained large numbers of intervals and had very short interpulse intervals. Pollack suggested that the processing of trains with very short interpulse intervals involved a spectral mode of processing, while long interpulse intervals (> 10 ms) probably required a temporal processing mode.

Sorkin, Boggs, and Brady (1982) studied the perception of tone sequences with randomly jittered temporal patterns. Their subjects heard two sequences of n tones: one sequence had a fixed intertone interval and the other had jitter added to the intertone intervals. Subjects had to detect which sequence had the added jitter. Sorkin et al. found that discrimination improved with the number of intervals and decreased with the average duration of the intervals (the durations ranged from 20 to 110 ms). Their results were consistent with temporal discrimination data employing single, marked time intervals (Creelman, 1962; Getty, 1975; Divenyi and Danner, 1977; Divenyi and Sachs, 1978; and Allen, 1979).

Sorkin et al. (1982) proposed a statistical model of jitter detection, in which the timing of different frequency tones was monitored (and compared) across separate critical band channels; discrimination of time jitter within a critical band channel was much better than across channels. Performance increased in the expected way with the number of tones in each sequence and with the different regular frequency patterns employed. However, when the frequency patterns were random, listener performance was well below the model's predictions.

In a similar experiment, Halpern and Darwin (1982) presented subjects with a sequence of four clicks which marked three intervals; their subjects had to indicate whether the last interval was shorter or longer than the preceding two. Halpern and Darwin tested base durations ranging from 400 to 1450 ms. Discrimination performance, as measured by the standard deviation of the resulting psychometric functions, was an increasing function of the base duration; the resulting Weber fraction was about 0.05, consistent with that reported by Getty (1975) and Sorkin et al.(1982).

Recently, Schulze (1989) reported a variation of the Halpern and Darwin experiment in which subjects were asked to report whether the last of n intervals marked by tones, was longer or the same as the n-1 preceding intervals. Schulze used base durations of from 50 to 400 ms and from 2 to 6 intervals in each sequence. Schulze tested an hypothesis similar to that of the Sorkin et al. model about the expected improvement in discriminability with number of intervals. For most of the subjects, discrimination improved with the number of intervals. Schulze failed to find evidence for a Weber's law effect; for his subjects, the discrimination limen was between 5 and 15 ms and independent of the base duration.

B. Single Channel Sequence Discrimination

We have completed experiments (Sorkin, submitted) in which the listener was asked to compare two arryhthmic tonal sequences and report whether the temporal patterns were the same or different. The two sequences were either identical or had partially correlated temporal envelopes. This task is a generalization of the Sorkin et al. (1982) jitter detection paradigm. An advantage of these paradigms is that the information carrying aspects of the sequences is distributed throughout the sequence, rather than concentrated on one judged interval as in the Halpern and Darwin (1982) and Schulze (1989) experiments. The goal of our experiments was to test whether a listener's ability to perform sequence comparison can be described by a process in which the listener computes the correlation between the sequence temporal envelopes.

In these sequence discrimination tasks, listeners compared two tone sequences, each composed of n, 1000 Hz tone bursts of 35 ms duration at a sound pressure level of approximately 71 dB. Tone bursts were shaped by a 4 ms linear rise and decay envelope. After listening to the pair of tone sequences presented on each trial, the subject had to respond whether or not the temporal pattern of tones was the same or different. There were two types of experimental trials: trials on which the identical sequence of tones and intertone intervals (gaps) were presented (SAME trials), and trials on which the pattern of intertone gaps was different in the two presented sequences (DIFFERENT trials). On trials when the sequences were different, the only difference between the sequences was in the pattern of intertone gaps and tone onsets. The first part of figure 1 illustrates a SAME trial; the second part illustrates a DIFFERENT trial. The type of trial was chosen at random, with p(SAME) = .5.

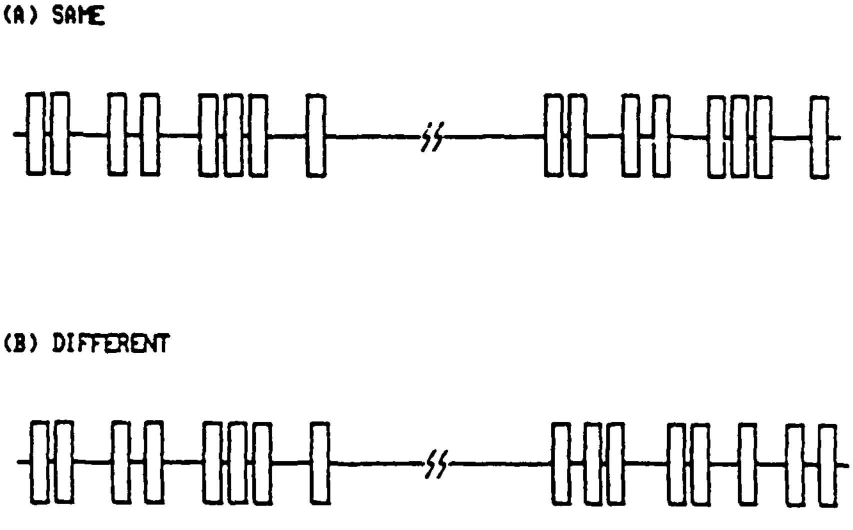

Figure 1. The envelopes of typical tone sequences are shown for same and different trials.

The intertone gaps were generated by a process that enabled us to control the mean gap duration, μ_{gap}, the standard deviation of the gaps, σ_{gap}, and the correlation, ρ_{ex}, between the two gap sequences on trials when the sequences were different. The intertone gaps were constructed by combining three independently generated normal deviates, with one deviate common to the two sequences. Gap durations of less than 2 ms were not allowed. The sequence correlation is given by the ratio of two variances, the variance common to the two sequences divided by the sum of the common and unique variances (Jeffress and Robinson, 1962):

$$\rho_{ex} = \sigma^2_{com} / [\ \sigma^2_{com} + \sigma^2_{un}\ ] \qquad (1)$$

and

$$\sigma^2_{gap} = [\ \sigma^2_{com} + \sigma^2_{un}\ ] \qquad (2)$$

where com and un refer, respectively, to the common and unique portions.

Correlation Model of Pattern Discrimination

A simple model of observer performance in the temporal pattern discrimination task follows from the assumption that the observer computes the correlation between the two sequences of gaps (or tone onsets) presented on each trial. Suppose that the observer's response is based on the value of the Pearson product-moment correlation coefficient statistic, r_{12}, computed on the sample of intertone gaps defined by the pair of sequences,

$$< t_{1,1}, t_{1,2}, \ldots t_{1,n} > \text{ and } < t_{2,1}, t_{2,2}, \ldots t_{2,n} >.$$

A transformation of the correlation coefficient, known as the Fisher r to Z transformation, is defined as:

$$Z = \frac{1}{2} \ln \left[\frac{1 + r_{12}}{1 - r_{12}} \right] \qquad (3)$$

The sampling distribution of Z is distributed approximately normally, for gaps drawn from a normal distribution and for n of at least moderate size ($n \sim 10$). If ρ is the population correlation coefficient, the mean and standard deviation of Z are then given by (Brunk, 1960):

$$\mu_Z \cong \frac{1}{2} \ln \left[\frac{1 + \rho}{1 - \rho} \right] + \frac{\rho}{2n - 1} \qquad (4)$$

and

$$\sigma_Z \cong (n - 3)^{-1/2} \qquad (5)$$

Discrimination performance can be obtained from the normalized difference between the means of the Z statistic, given the possible hypotheses on a trial: SAME, when $\rho = 1.0$ and DIFFERENT, when $\rho = \rho_{ex}$. The discriminability, d', is given by the difference between the means of the Z statistic divided by the standard deviation of Z. (The contribution of the right hand term of equation 4 is very small.)

For a human observer, the effective correlation between the sequences on DIFFERENT trials will depend on ρ_{ex}, σ_{gap}, and the magnitude of internal variability in the observer's encoding and storage of the gaps. We assume that the observer's observation of the gaps is subject to a temporal jitter, σ^2_{in}, and that this jitter is uncorrelated across the gap sequences. Adding this uncorrelated jitter σ^2_{in} to equations (1) and (2), yields:

$$\rho_{DIFF} = \frac{\sigma^2_{com}}{\sigma^2_{com} + \sigma^2_{un} + \sigma^2_{in}} = \frac{\rho_{ex}}{1 + (\sigma_{in} / \sigma_{gap})^2} \tag{6}$$

and from equations (1) and (2) and # = 1.0, the effective correlation on SAME trials,

$$\rho_{SAME} = \frac{1}{1 + (\sigma_{in} / \sigma_{gap})^2} \tag{7}$$

The magnitude of the internal temporal jitter σ_{in} is the single parameter of this model. Because the internal jitter is independent between the two sequences, it acts to reduce the effective correlation of the sequences.

Discrimination performance can be calculated using equations (4), (6) and (7) to compute the difference between the means of the Z statistic on DIFFERENT and SAME trials divided by the standard deviation of Z:

$$d' = \frac{\frac{1}{2}\ln\left(\frac{1+\rho_{SAME}}{1-\rho_{SAME}}\right) + \frac{\rho_{SAME}}{2n-1} - \frac{1}{2}\ln\left(\frac{1+\rho_{DIFF}}{1-\rho_{DIFF}}\right) - \frac{\rho_{DIFF}}{2n-1}}{(n-3)^{-1/2}} \tag{8}$$

Effect of Sequence Correlation and Variability

We examined how discrimination performance depended on the correlation between the sequences ρ_{ex} (as specified on DIFFERENT trials, since $\rho = 1$ on SAME trials) and the standard deviation of the intertone gaps σ_{gap}, and we estimated the magnitude of the internal noise, σ_{in}.

Figure 2 shows the data from four observers at a mean gap duration of 50 ms and a gap standard deviation of 20 ms. The vertical bars in the figures indicate plus and minus one standard error of the mean. The solid lines in figure 2 are least square fits of the model to each observer's average data; the value of the internal jitter parameter is shown in each section of the figure. The observed drop in performance with increases in the correlation of the sequences is consistent with the model. The value of the (single) internal temporal jitter parameter was 14.75 ms, for the fit of the model to the average data from the four listeners. This value for internal jitter is at the high end of the range of values obtained in duration discrimination experiments employing single and multiple judged intervals (Lunney, 1974; Getty, 1975; Divenyi and Danner, 1977; Halpern and Darwin, 1982; Sorkin, Boggs, and Brady, 1982; and Schulze, 1989).

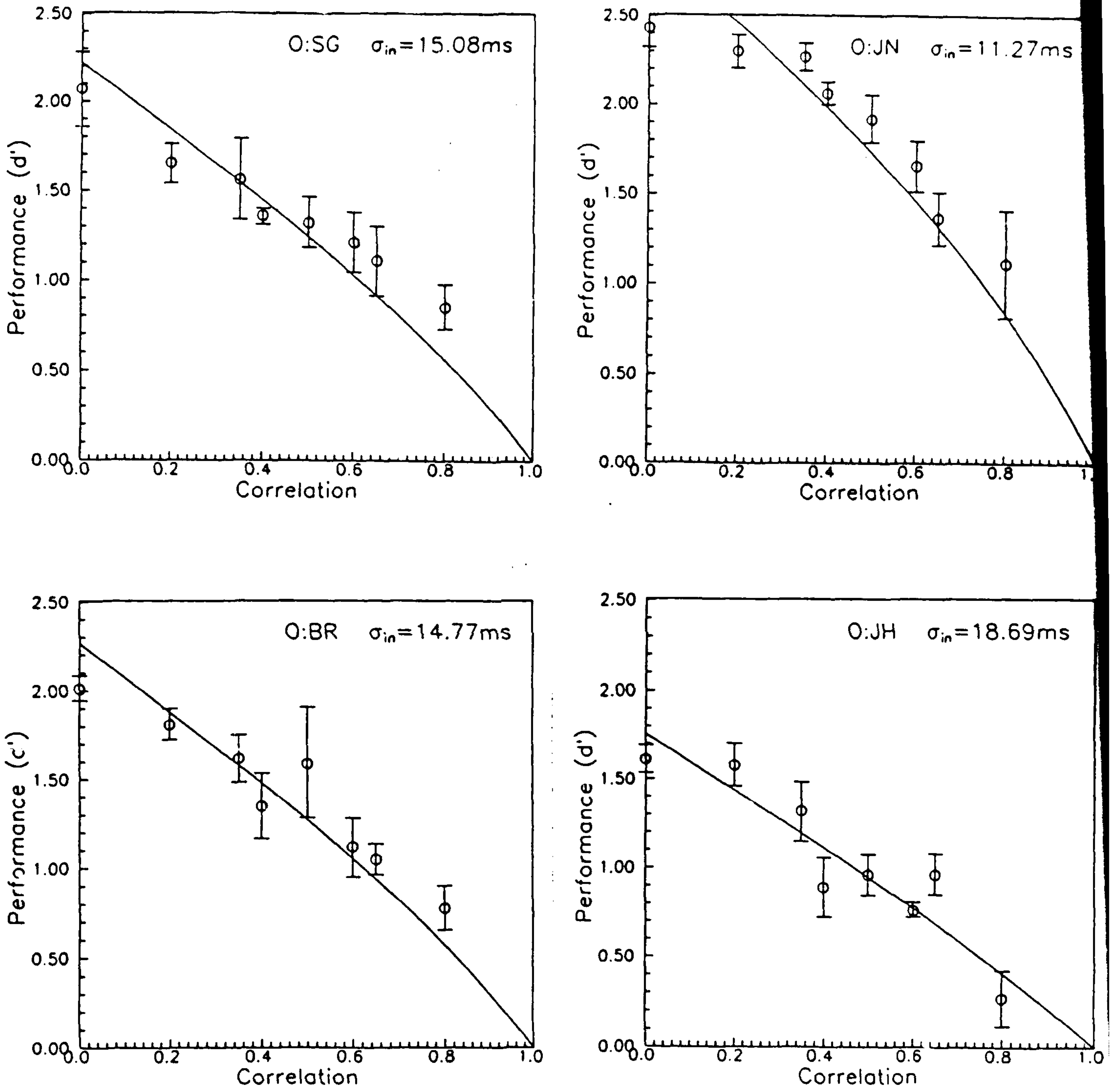

Figure 2. Performance (d') is plotted as a function of the sequence correlation, for each of four observers. The solid lines show the performance of the correlation model with the internal noise standard deviation shown.

Figure 3 shows how average performance depended on the standard deviation of the gap duration. The vertical bars indicate plus and minus one standard error of the mean; the average standard errors for the four observers are shown for each condition. The solid line is the prediction of the correlation model, using the value of the internal jitter based on the average data of figure 2. As the level of external variability in the gaps increases, the contribution of internal and (assumed) uncorrelated variability is reduced, and performance should improve. It is apparent that the model overestimates performance at high gap standard deviations.

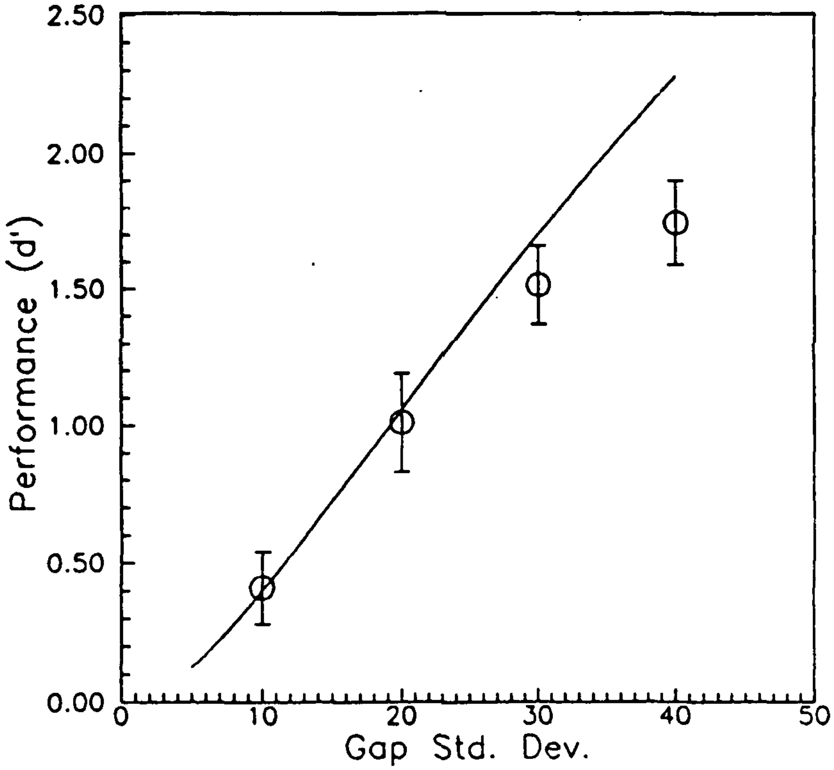

Figure 3. The average performance of four observers (d') is plotted as a function of the standard deviation of the gaps. The solid line is the prediction of the correlation model with an internal noise of 14.75 ms.

We also examined how discrimination performance depended on the mean gap duration μ_{gap} and on the number of intertone gaps, n. As the mean gap is increased, server performance decreased at an increasing rate. The model, as defined by quations (6), (7), and (8), was modified to incorporate this effect, by assuming a Weber's Law type of dependence of the internal jitter on the magnitude of μ_{gap}. Such a relationship, where σ_{in} increases in proportion to μ_{gap} has been found by Lunney (1974), Getty (1975), Divenyi and Danner (1977), Halpern and Darwin (1982), and Sorkin, Boggs, and Brady, (1982).

The modified model did well at predicting performance as a function of the mean gap; however, the model's decrease in performance with increasing gap size was less than that shown by the human observers at mean gaps of 80 ms or more. Some part of the drop at long gaps may be attributable to the fact that spans of 1 s or longer exceed the capacity of the observer's auditory memory and hence the effective number of intervals being processed is much smaller than assumed by the model (see Watson, 1987). Similar effects occurred when the number of intertone gaps was manipulated. Good fits with the model's predictions were obtained as long as the number of intertone gaps did not exceed 12 or more.

These experiments support the idea that the discrimination of temporally perturbed tone sequences may be described as a process in which the listener computes the correlation between the temporal envelopes of the sequences. This computation appears to be limited by an internal temporal variability (of approximately 15 ms.) in the listener's encoding and storage of the stimulus information. This variability is about 10 ms higher than difference thresholds obtained using two-interval duration discrimination tasks, depends on the magnitude of the base duration to be discriminated, and increases when the time span of the sequences is longer than 1 s. or when the sequences have more than 12 intervals. These latter effects probably are related to encoding and memory limitations.

C. Extensions to the Theory and Ongoing/Planned Experiments

In this section we discuss some implications of the above results for correlation theories of pattern discrimination. We argue that different realizations of the correlation mechanism may hold under different task conditions. We describe some experiments to specify the nature of the mechanism under those conditions.

Possible Mechanisms

The idea that a listener can compare auditory patterns by computing the correlation between temporal or spectral aspects of the patterns, is not novel. Models of the binaural detection mechanism have typically involved the assumption of a process that involves computation of the interaural correlation between the left and right auditory channels (Durlach, 1963; Osman, 1971; Lindemann, 1986; and cf. Sorkin, 1965, and Pohlmann and Sorkin, 1974). Several investigators have studied the binaural discrimination of changes in the interaural whole-waveform correlation of the signals (e.g. for wideband noise: Pollack and Trittipoe, 1959; for pulse train polarity agreement: Pollack, 1971; and for wideband, narrowband, and low-pass noise: Gabriel and Colburn, 1981). These studies have reported a dependence of discrimination on interaural correlation that is consistent with the hypothesized correlation process.

Recently, Richards (1987) reported an experiment on the discrimination of differences between simultaneously presented noise stimuli having partially correlated amplitude (and spectral) envelopes. Richards postulated a correlation discrimination process that is essentially identical to the one we have proposed to describe sequence comparison. Her noise stimuli had bandwidths of 100 Hz and center frequencies of 2500 and 2750 Hz. For any given stimulus, these two noise bands had, on average, a specified correlation. The observers had to discriminate which of two such stimuli contained the higher correlation across the spectral bands. Richards tested her observers' ability to discriminate between a reference stimulus, containing either a zero or unit noise correlation, and target stimuli having a range of noise correlations. In general, her results supported the model: the observers' sensitivity to changes in envelope correlation was a monotonic function of the computed z statistic and was essentially independent of the specific reference correlation.

In the binaural studies and in Richard's noise study, one assumes that the listener can compute the correlation between the transduced, critical-band filtered signals; the signals are assumed to undergo minimal processing prior to the correlation operation. It is possible that a similar process is operating in the sequence discrimination task: The signals in each sequence are transduced, subjected to windowing and filtering operations, and then stored; finally, the correlation is computed between the resulting waveforms.

A more cognitive mechanism may be appropriate for describing the listener's correlation computation in the sequence discrimination task. Using this mechanism, the listener (behaves as though he/she) encodes and stores only the magnitudes of the time intervals between the tone onsets. The listener then computes the correlation between the resulting two lists of interonset times. This view of the correlation process implies quite different relationships between the task characteristics and performance. For example, the computation of correlation based on two lists of stored numbers should be relatively insensitive to certain transformations of the sequences such as temporal compression or expansion. This is in contrast to the whole-waveform correlation mechanism, which might be expected to be highly sensitive to such transformations. This distinction between an input or waveform-based process, and a more highly processed mode is similar to the trace and context processing modes postulated by Durlach and Braida and their colleagues, and discussed in a number of studies (see Durlach and Braida, 1969; also cf. Sorkin, 1987).

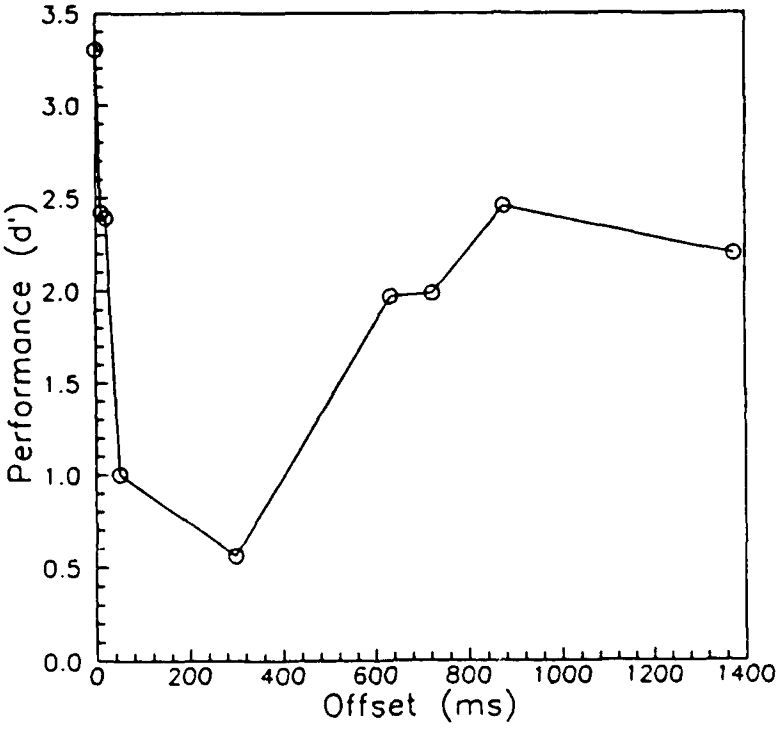

Figure 4. Average performance plotted as a function of the time between the onset of each sequence in the two channel experiment. (Average sequence duration = 630 ms.)

Two Channel Sequence Discrimination

We are attempting to distinguish between these alternative mechanisms, in ongoing experiments. The discrimination task was modified so that the tones within each sequence were presented at two different frequencies (all of the tones in sequence 1 were at 1000 Hz, all tones in sequence 2 were at 2300 Hz) and the two sequences were presented to different earphone channels. When the sequences were presented dichotically and at different frequencies, essentially the same performance was obtained as in the previous sequence experiments (see Figure 4). The point plotted in figure 4 at a sequence offset of 1375 ms shows that performance in the dichotic, separated frequency, condition was similar to performance when the frequencies were the same and presented in the same ear. As the time separation between the two sequences was reduced, performance fell. As the sequences began to overlap in time, performance dropped markedly until at approximately 50% overlap, performance was lowest. These results indicate that listeners can process sequence temporal pattern information across two frequency (and ear) channels at time separations and performance levels similar to those when the frequencies and channels were identical.

Notice that subjects could perform the two-channel discrimination task extremely well when the two sequences were presented at the same time--so long as the sequences are not offset by more than approximately 20 ms. Without invoking specific binaural mechanisms, it is clear that a great deal of spectral information about the relative similarity of the patterns is potentially available to the listener, when the sequence offset is less than 20 ms. Suppose that the offset were 5 ms and that both channels contained the SAME sequence pattern: all tones would result in cross-channel pairings having a 5 ms separation. If the channels contained DIFFERENT temporal patterns, there would be a distribution of cross-channel pairings, with a reduction in the prominent periodicity (at 1/offset), depending on the correlation between the channels. As the offset were increased from 0 to 10 ms and greater, the peak in the (same sequence) cross-channel spectrum would decrease to 100 Hz, eventually reaching a point where spectral processing was not feasible. As the offset was increased beyond that point, the alternative "temporal" processing mode would be invoked and performance would be similar to that observed in the long delay, single channel, sequence experiment.

The two channel, sequence discrimination task is interesting because it may provide a bridge between psychophysical experiments on correlation discrimination with noise or binaural stimuli, and more context sensitive or "cognitive" sequence experiments. An intermediate mode of processing may be operating as well: As the time between sequences is increased beyond the limit of the whole waveform correlation mechanism, the listener may try to (briefly) store the whole waveforms for later comparison. Thus, a short term memory requirement is imposed at offsets longer than 20 ms. As the offset becomes very long, memory trace noise becomes excessive, and there is sufficient time for the interonset intervals to be encoded and stored as representations of the time pattern. The system then performs its correlation computations in the interonset timing or "context" mode. Thus, an exciting aspect of the two channel sequence paradigm is that it may support a model of performance that is applicable over three different modes of processing-spectral, trace, and context-as a function of the single task parameter, offset delay.

Temporal Manipulations

We have begun to examine performance in single channel, long offset delay, sequence discrimination experiments in which the second sequence has been scaled in time (compressed or expanded) by a factor of from 0.6 to 1.4. The preliminary results of these manipulations are consistent with the predictions of the correlation model; the effect of the time transformation is small and is approximately a symmetric function of the time scaling factor. These manipulations should have a smaller effect on the interonset time mode than on the whole-waveform mode. The former mechanism, based on encoded and stored lists of numbers, should be relatively insensitive to uniform scaling of the lists (or any paired portion of the list). The whole-waveform mechanism, however, should be very sensitive to such temporal transformations, since the computed correlation (on SAME trials) will be greatly reduced. It would be necessary for this mechanism to compute the correlation at a number of delays in order to make a decision about whether the sequences were the same or different.

These temporal manipulations will be applied to the two-channel sequence task. In the two channel task, the compression or expansion will be applied randomly over trials, limited to a smaller range (10-15%), and uniformly applied over each sequence. We will compare the effects of the temporal scaling manipulations on performance at very brief offsets, at intermediate offsets, and at long offsets. Our expectation is that, at long offsets, the results will be similar to those described in our preliminary single channel experiments, supporting the interonset time mechanism. At short offsets, we expect that performance will be much more sensitive to the scaling manipulation, indicating a whole waveform, spectral type mechanism.

Frequency Manipulations

The listener's subjective impression of the single-frequency sequence discrimination task, is of trying to recall and compare two briefly heard rhythmic patterns. That observation, the relatively long interonset intervals employed in the task, and the small effect of changing the frequency of all of the tones in the second sequence, support the argument that the listener is using a temporal rather than spectral processing mode. We have characterized this mode as the interonset timing mode. Because this mode requires encoding and storage of the timing information, it is likely that it will be dependent on contextual factors such as the nature and distribution of different frequency tones in the sequences and within- and across-trial variation in the frequency of the tones.

The literature on the perception and production of temporal patterns includes many studies that demonstrate the influence of sequence temporal structure on spectral pattern discrimination (Deutsch, 1980; Jones, 1981; Jones, Kidd, and Wetzel, 1981; Jones, Boltz, and Kidd, G., 1982; and Monahan, 1987) as well as the influence of sequence spectral pattern on temporal pattern discrimination (Woods, Sorkin, and Boggs, 1979; Handel and Lawson, 1983; Espinoza-Varas, and Jamieson, 1984; Espinoza-Varas and Watson, 1986; and Sorkin, 1987). The model of temporal jitter detection supported by Sorkin et al. (1982) assumed that best performance would occur when the tones marking the intervals were within a critical band in frequency. In that experiment, the detection of jitter in sequences containing different frequency tones was predictably poorer than with equitone sequences. A similar assumption may enable the correlation model to describe pattern comparisons between multiple frequency tone sequences. For example, the listener might compute the correlation between the temporal envelopes of tone subsequences defined only within a single critical band. Correlations computed within separate critical bands then could be combined, in order to arrive at a composite estimate of the temporal similarity of the sequences.

We have indicated that changing the frequency of all tones in the second sequence does not degrade performance when the offset is either very short or very long. However, this manipulation did not involve the presence of uncertainty about the frequency of the tones within a sequence (or pair of sequences). If both sequences on a trial have the same pattern of tone frequency, we should be able to predict performance based on the results from single frequency sequences at those frequencies. Relative, rather than absolute timing accuracy should be important in the interonset timing mode; a reduction in timing accuracy due to timing intervals across critical bands, should not produce large effects on performance. Such a manipulation should not affect the whole waveform mode because only the envelope information is relevant to the computation. Similarly, the effect of a random frequency condition, so long as the same random sequence pattern occurs in each sequence, should be small.

The preceding predictions apply to cases when the frequency pattern of each sequence on a trial is the same (or when there is no frequency uncertainty over trials). The effect of frequency pattern uncertainty within an experimental trial is potentially more complex. How well can a listener discriminate between two temporal patterns on a trial, when the frequency patterns of the sequences vary within the trial? We would expect this manipulation to have a small effect on processing in the whole waveform mode and a large effect on the interonset timing mode. The effect on the whole waveform mode would be minimal for the reasons cited in the previous paragraph. However, this type of contextual uncertainty should interact with the encoding and storing operations required by the interonset timing mode. The goal of the experiments is to evaluate these effects over a range of timing manipulations and to incorporate the results into a general model of sequence pattern discrimination.

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II. Information Processing with Multi-Element Sources

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A detection theory theorem (Starr et al., Radiology, 1975, 116, 533) predicts performance in a recognition-detection task (subject responds whether signal `a` or `b` or `c` or **`no signal`** was present) from data obtained in the component detection tasks (respond whether signal `a` or **`no signal`** was present). The theorem was evaluated in a visual display processing task employing nine-element linear arrays of analogue gauges. The subject's task was to decide which signal had occurred on each trial. The gauge values were generated by statistical processes having different mean values depending on whether a signal or noise was present; the signals were defined by different patterns of mean gauge values. The signals were designed to be equally detectable and mathematically orthogonal. The subjects detected each of the three signals separately, as well as all combinations of the three signals. The Starr Theorem provided good predictions of performance in the recognition-detection tasks based on performance in the component detection tasks. This work was reported at the annual meeting of the Human Factors Society, in Denver, October, 1989, and in Elvers (1989).

A second study, using the same types of stimuli, but in a single-signal detection version only, was run under conditions in which the statistical properties of the display elements were non-uniform. That is, the means of the display elements, given signal and noise, varied depending on spatial position; thus the diagnosticities of the display elements varied. Performance in this task was analyzed using a theorem derived by Dr. Bruce Berg for computing the observer decision weights in a task involving the detection of auditory sequences (Dr. Berg is in Dr. David Green's laboratory at Florida). The results of these experiments indicate that it is very difficult for the observer to employ optimal weights in the processing of display information having variable diagnosticity (reported in Elvers, 1989).

III. Other Activities

Member, National Research Council Committee on Hearing, Bioacoustics, and Biomechanics (CHABA).

Panelist, CHABA Working Group on Classification of Complex, Non-Speech Sounds.

Associate Editor, International Journal on Human-Computer Interaction.

IV. Project Personnel

Elvers, G. C., Assistant in Psychology, Department of Psychology, University of Florida. While at Florida, Dr. Elvers completed his Ph.D. dissertation and received his Doctor of Philosophy degree from Purdue University. He left the project to take a position at the University of Dayton.

Pezzo, M., Graduate Student, Department of Psychology, University of Florida. Mr. Pezzo left the University of FLorida in August, 1989, to continue his graduate studies at Ohio University.

Widman, D., Graduate Student, Department of Psychology, University of Florida. Ms. Widman began work on the project in May, 1989.

Sorkin, R. D., Professor and Chair, Department of Psychology, University of Florida.

V. Publications, Reports, Manuscripts, Dissertations

Elvers, G. C. (1989). *Detection of visual signals consisting of multiple information sources: A signal detection analysis*. Unpublished doctoral dissertation, Purdue University, West Lafayette, IN.

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Barfield, W., Salvendy, G., and Sorkin, R. D. Judgments on the angular orientation of three-dimensional (3D) images displayed in virtual 3D space. *Ergonomics* (manuscript submitted).