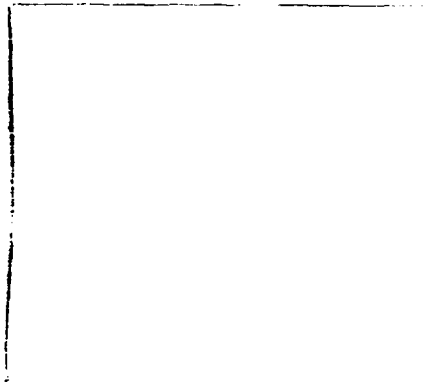


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Final Technical Report

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Table of Contents

Abstract	1
Specific Aims	2
Scientific Significance	3
Research Accomplishments	4
References	19
Publications	23
Manuscripts in Preparations	25
Oral Presentations	26
Personnel	28

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Abstract

This progress report describes work completed in the first two years of a proposed three-year study of the discrimination and identification of complex sounds. Support was terminated at the end of the second year. Projects number 2 and 4 in the "Research Accomplished" section were initiated with NMRDC funds. The remaining projects are part of ongoing investigations with partial funding from AFOSR and NIH.

Much of the effort in the first year was devoted to the installation of a multi-user PDP 11 computer system to be used for program development, data analysis, and synthesis of complex sounds. This installation involved the integration of the PDP 11 with existing computer facilities as well as with newly acquired Apollo workstations. Considerable effort was also devoted to the development of programs for experimental control and data analysis. In addition, experiments were completed in four topic areas:

- (1) Work on auditory processing capacity limitations was extended using threshold values of $\Delta f/f$ and ΔI (dB) as dependent measures. New experiments revealed that the proportion of the total pattern duration occupied by a target component accounts for large-scale changes in frequency discrimination performance previously attributed to variation in the number of components within a pattern.
- (2) New experiments on the discriminability of noise samples have shown that the discriminability of differences in pairs of noise samples depends on the duration and location of the deviant portion of noise within a noise sample, replicating a similar finding obtained earlier with tonal patterns.
- (3) Internal noise is assumed by signal detection theories to account for less-than-perfect detection and discrimination performance. A model has been developed in which the internal noise has been partitioned into peripheral and central components. That model was tested in experiments in which the external stimulus distributions were rigidly controlled.
- (4) Preliminary studies with complex stimuli developed for use in vigilance experiments have shown that listeners are able to integrate information across multiple components of multidimensional sounds, with little or no loss due to increasing the number of components over a range of from 1 to 7. These experiments have also shown large individual differences in subjects' tendencies to base their decisions on specific dimensions of complex sounds. Initial attempts to train listeners to attend to dimensions that were initially unattended (by giving listeners extended practice under conditions in which only the to-be-learned dimension could vary over trials) resulted in little or no improvement for most listeners. These experiments have generated several forms of useful information for operational applications. They provide a large amount of data on the level and range of performance that can be expected of highly trained human listeners whose assignments require them to detect, discriminate, or identify complex sounds. They provide "benchmarks" for the selection of unusually salient or identifiable acoustic signals. Last, they provide theoretical models of auditory discrimination and decision making which are not limited to the classes of acoustic events used in the laboratory experiments conducted to develop and test these models.

Specific Aims

Four experimental projects were proposed, each dealing with a different aspect of listeners' abilities to detect or identify complex sounds. The purpose of this work was twofold: (1) to ascertain those properties of acoustical waveforms which determine performance limits for human listeners and (2) to determine optimal training procedures for auditory "monitoring" or watchstanding tasks. The general approach is that of contemporary psychoacoustic research, oriented by the Theory of Signal Detectability (Robinson and Watson, 1972).

1. *Pattern discrimination and identification.* These studies continued a series of experiments on the total amount of information listeners are able to extract from complex sounds. Experiments extended previous work in order to quantify the informational limits, or "channel capacity" of the human listener, toward the development of a general model of complex auditory processing. Such a model could be useful both for the selection of optimal preprocessing of SONAR signals, and to predict the limits of listeners' performance from the acoustic properties of a signal catalog.

2. *Detection and Discrimination of Noise Signals.* Listeners' abilities to detect, discriminate between, and identify Gaussian or pseudo-Gaussian noise samples were examined using procedures similar to those used with multi-tone patterns. The experiments were designed to test a preliminary model based on an assumed bank of critical-bandwidth filters, wherein the output of each filter is given specific weightings by individual listeners. It is also assumed that various temporal portions of the waveform are similarly weighted. Models based on responses to noise samples are more likely to characterize the actual transfer characteristics of the human auditory system than are those based on more constrained stimuli.

3. *Detection and Identification without Defined Observation Intervals.* The free-response testing procedure of Watson and Nichols (1976) was to be used to study the detection and identification of noise signals presented at random times. Preliminary testing with complex sounds was completed, but funding was terminated before these experiments could be carried out.

4. *Optimization of Training Procedures.* Training procedures that have led to perceptual enhancement of specific spectral-temporal regions of multi-tone patterns (i.e., reducing trial-to-trial stimulus variation or allowing the listener to directly control the acoustic properties of the signal in an early phase of auditory training) were to be applied in an effort to minimize the time required to learn to detect and identify specific classes of noise signals and other complex sounds. Only preliminary training studies with complex sounds were completed before funding was terminated. These early results demonstrated changes in sensitivity that often ranged from near-chance performance in early testing to near-perfect performance following training.

Scientific Significance

This research has provided needed information about the limits of hearing for complex sounds. Most of what is known about normal hearing has been learned through experiments with simple stimuli: pure tones, noise bursts, or clicks. Our practical concerns with human hearing, however, are based in the difficulty listeners exhibit in extracting information from complex sounds. Knowledge of the ability to detect information in complex sounds may reduce some of the mystery that surrounds the human listener's ability to process special classes of sounds (e.g., speech, music, SONAR).

These experiments are part of an ongoing investigation of the perception of complex sounds (see the original proposal for a brief review) utilizing various types of stimuli, such as rapid, multi-tone patterns, bursts of reproducible Gaussian noise, and other synthetic multidimensional sounds, including speech. These experiments have allowed us to identify some of the critical stimulus parameters that limit listeners' abilities to detect various aspects of complex sounds, such as the degree of uncertainty involved in a listening condition and the spectral-temporal location of information to be detected within a complex sound. New experiments are helping us to more precisely define the stimulus parameters that influence the perception of complex sounds. In addition we have begun to study listeners' ability to integrate information in sequences of multidimensional sounds and have documented certain striking individual differences in the ability to base judgments on specific dimensions of multidimensional stimuli. This information has contributed to the development of a general model of auditory pattern recognition and discrimination that will have relevance beyond the domain of simple, isolated sounds.

Research Accomplishments

1. Auditory processing capacity for tonal sequences

A series of experiments on the informational capacity of the auditory system for temporal patterns has now been completed. These experiments were originally conceived as a means of determining the optimal combination (for information transmission) of total-pattern and pattern-component durations. The total information in a pattern is considered to be proportional to the number of independently varying components. The patterns in each of these studies consisted of a series of 75-dB tone pulses, whose frequencies were randomly selected from the range 300-3000Hz. Successive tones in the sequences were never closer than 1/3 octave, and were gated on and off with a 2.5 msec rise-decay.

An earlier series of studies conducted in our laboratory used an adaptive-tracking procedure in which the number (n) of components in fixed-duration tonal patterns was increased or decreased from trial-to-trial, in a S/2AFC discrimination task. (S/2AFC: A paradigm in which a standard pattern is followed by two test patterns, one of which is different from the standard.) Patterns with six total durations, from 62.5 to 2000 msec, were presented in random order, while an independent adaptive-tracking history for each duration converged on the n 's (number of components) required for 71% discrimination. As the numbers of components in the patterns were varied, the duration of the individual components was always the total duration/ n . This procedure was repeated in seven separate experiments.

Results of these experiments suggest that when tonal patterns can be discriminated by the presence of a silent gap, or by a change in gap position, performance is determined by a critical component duration (25-50 msec, depending on the specific task). In those cases, the threshold values of n , for each total pattern duration, are approximately the total durations divided by a constant. In experiments in which discrimination requires some degree of resolution of the actual pitch contour, performance seems to reflect a fixed informational capacity for pattern discrimination, in the range of 6-9 components per pattern. No clear optimal combination of total and component duration can be seen in these data, since the same 6-9 component limit is found for a 32-fold range of total durations (62.5-2000 msec).

1.1. Isochronous vs. anisochronous patterns (Watson, Foyle)

The results of the above experiments were obtained with isochronous patterns (duration of each component = total duration/ n). The relative constancy of the total information in discriminable patterns ranging from 62.5 msec to 2000 msec might be a property only of patterns which have the very salient rhythmic quality associated with isochronous temporal structure. A major difference in discriminability for isochronous and anisochronous patterns might be predicted by the results of a recent experiment reported by Sorkin (*J. Acoust. Soc. Am.* 75, S21, 1984). To investigate that possibility, a new experiment was conducted, in which the random sequences of patterns

included three levels of temporal "jitter" of the non-target component durations. In the resulting anisochronous patterns the target-component durations (the component whose frequency was incremented) were still total duration/ n , while the non-target components were each randomly increased or decreased in duration by a fixed percentage of their isochronous value. The "jitter" percentages were 0%, 30%, or 50%, in separate conditions. It was found that threshold values of n were unaffected by the two levels of anisochrony, although the perceptual quality of the patterns was markedly changed by these manipulations. Sorkin's study differed from this experiment, in that he studied the effects of within-trial variation in the temporal structure of patterns, thus these results do not directly contradict his.

1.2. Capacity estimated in a true frequency-discrimination paradigm (Watson, Kidd)

In the above experiments, the dependent variable was n (the number of components in a constant-duration tonal pattern – an unusual psychophysical procedure that is, to our knowledge, unique to these experiments. While we know of no theoretical reason that this paradigm would yield aberrant results compared to more traditional methods, it nevertheless seemed reasonable to attempt to estimate the pattern-discrimination "capacity" using a more traditional psychophysical approach. Another experiment was therefore conducted, in which the dependent variable in the adaptive-tracking variable was $\Delta f/f$, the proportional change in the frequency of a mid-temporal position, mid-frequency component. Threshold values (71% correct) of $\Delta f/f$ were determined for various numbers of components, for total pattern durations of 125, 500, and 1500 msec. Although there is some reduction in threshold as total pattern duration (and therefore component duration, in these isochronous patterns) is increased, that effect is extremely small compared to the changes associated with variation in n .

Taken together, the results of these experiments suggest a limit on pattern processing in terms of the total amount of information contained in tonal patterns, rather than in terms of critical values of some physical parameters. Such a processing limit is reminiscent of Miller's (1956) "magical number 7 ± 2 ," and of the results of some of Pollack's (1953) experiments on the information in multi-dimensional auditory displays. It extends that earlier work to complex temporal auditory stimuli. These limits appear to be general at least for stimuli in the range of pattern durations thus far investigated (62.5-2000 msec), but only for cases in which discrimination must be based on the contents of immediate memory. When the listener has some long-term basis for focusing attention on a restricted portion of a complex pattern, then these informational limits do not yield accurate predictions of performance. When the information-processing demands are reduced, as by permitting successful use of top-down direction of attention (e.g., Spiegel and Watson, 1981) considerably greater amounts of stimulus information may be included in discriminable patterns. The predictability of the waveforms of speech (or of most music) thus affects the applicability of the limited-capacity hypothesis to such familiar and highly constrained stimuli.

1.3. Detection of level changes in multi-tone patterns (Watson, Kidd, Washburne)

The experiments on listeners' processing capacity have now been extended to the detection of changes in the level of individual tones in multi-tone patterns. Listeners' abilities to detect increments and decrements of the intensity of tones were examined with a range of sequence lengths (1 to 9) and of total pattern durations (125 to 1500 msec). We found that, in contrast to our data for the detection of changes in frequency, performance is primarily affected by individual component duration with very little influence of number of tones or of total pattern duration. This is very much like the results of our earlier experiments on the detection of gaps in multi-tone patterns. These cases have in common that it is not necessary to attend to the series of pitch changes in order to detect the change in the pattern. As a working hypothesis, it appears that "saturation" of the processing capacity for pitch changes has little or no degrading effect on listeners' abilities to detect changes in other stimulus dimensions. This result is consistent with Pollack's findings of an increase in information transmitted through the use of multi-dimensional encoding.

1.4. Proportional target-tone duration as a factor in the discriminability of tonal patterns (Watson, Kidd)

A series of experiments on listeners' abilities to extract information from patterns with varying total durations and numbers of tonal components has previously been reported [J. Acoust. Soc. Am. Suppl. 1 **73**, S44 (1983); **77**, S1 (1985)]. In those experiments listeners were tested in high-stimulus-uncertainty, same-different pattern discrimination tasks, in which the tonal patterns to be discriminated differed by changes in the frequency of one or more components. Discrimination performance in those tasks was consistent with previous measures of the frequency resolving power of the auditory system when the patterns contained one to three equal-duration components, for total pattern durations from 62.5-2000 ms. As the number of components was raised, discrimination thresholds increased by large amounts, often by factors of 10-100 for patterns with more than seven-eight components. While this result might imply an informational limit on pattern processing, it is also consistent with the hypothesis that *target tones are equally well resolved if they occupy equal proportional durations* of the patterns in which they occur. Results of a new experiment, in which the proportional durations of target tones and the number of tones per pattern were independently varied, suggest that proportional duration of the target tones is in fact the primary determinant of pattern discriminability for tonal patterns ranging from 100-1500 ms in total duration. [Abstract of paper presented at the 114th meeting of the Acoustical Society of America; Miami, Florida; November, 1987.]

2. Detection of pattern repetition in continuous tone-patterns (Kidd, Watson, Washburne)

The existence of a general processing-capacity limitation, as suggested in the previous studies, does not mean that all pattern discrimination tasks would necessarily reflect that same limit. We have therefore investigated listeners' abilities to detect the repetition of multi-tone patterns as a function of tone duration and number of tones in

the pattern. In this experiment, generally modeled after that reported by Guttman and Julesz, 1963), subjects are presented with repeating or non-repeating tonal patterns using a tracking paradigm that increases or decreases the number of tones in a pattern, depending on a subject's performance. Because of the possibility that successful performance of the task might be strongly influenced by detection of the repetition of perceptually unique events within a pattern, we chose patterns designed to have few such events. In one series of tests we investigated the effects of decreasing the bandwidth, intended to reduce the likelihood of the occurrence of unique events that result from frequency-based auditory stream segregation. Preliminary data collection has been completed, utilizing 50-msec and 200-msec tones with 1/3-octave and 1-octave pattern bandwidths (centered on 1000 Hz) with 9 subjects participating in all conditions. These data showed strong effects of tone duration and bandwidth, as well as a significant interaction (due to a slightly greater effect of bandwidth at the 50 ms tone duration). The number of components for which each subject could correctly detect repetitions 70% of the time was estimated for each condition. The mean number of components for the 9 subjects for each condition is shown in Table 1. In general it can be seen that listeners are able to detect the repetition of patterns consisting of more tones with the shorter tone duration and the wider bandwidth. Interestingly, the effect of tone duration is not simply an effect of total pattern duration: subjects are able to detect the repetition of patterns with longer total durations (but fewer tones) at the 200-msec tone duration.

Table 1. Mean number of tones for 70% correct detection of repetition (total duration of detectable repeating patterns, in seconds, shown in parentheses).

Bandwidth	Tone Duration	
	50ms	200ms
1/3 Octave	62.9 (3.16)	30.7 (6.14)
1 Octave	94.1 (4.71)	35.5 (7.10)

Despite our attempts to minimize the occurrence of unique events, subjects' reports indicated that judgments were often based on the reoccurrence of particular events rather than detection of whole-pattern repetition. To further reduce the occurrence of unique events, a new version of this experiment was developed in which the sequences of pitches of consecutive tones approximated a sinusoidal series. Tones deviated randomly from strict sinusoidal variation by $\pm 6\%$ and a single repeating pattern spanned three cycles. This procedure reduces the possibility of unique events by constraining adjacent tone relations while eliminating the problems of pattern-restart discontinuities and gross changes in pattern macrostructure.

Initial data collection with this new procedure revealed that unique events were still being used as a basis for repetition judgments. We are currently testing a new

procedure that tracks on the deviation around the sine wave with a variable number of tones per cycle. The goal of this series of experiments is to devise a class of tonal sequences for which listeners must attend to the microstructure of an entire sequence to detect the repetition of a series of tones within the a sequence.

3. Perception of salient auditory events or figures (Kidd, Watson, Washburne)

In several studies Bregman and his colleagues (reviewed in Bregman, 1978) have described the factors associated with the emergence of auditory "streams" (sets of elements within a sequence of sounds that are more salient than their context). Similar effects have been noted in listening to repetition of the multi-tone sequences used in our experiments. A new series of experiments has been designed to more objectively measure the subpatterns (or auditory "events" or "figures") that listeners report hearing when patterns are repeated.

In an auditory figure-identification procedure (AFI), listeners work at computer terminals, where they are given one-key control over the presence or absence of each of the components of a tonal pattern (generally 10 tones). They check each tonal component by turning it on and off, to determine whether that component is a part of an auditory "figure" that emerges after the pattern has been repeated several times. When a component is identified as part of a figure, it is marked (by depressing another key), and when all components have been checked the listener can confirm his choices by a single key which turns on and off all non-marked components (ie. the "ground"). Another keystroke causes the selected subpattern and the time required to identify it to be recorded.

Results of a first experiment using the AFI procedure show excellent agreement among the figures identified by five well-trained listeners within a set of 120 patterns. In general, listeners identified figures within one frequency range (either high or low) more reliably as the range of figural components is relatively more compact and more distant from the non-figural components. The absolute frequency range of the elements that form a figure was not significantly related to its salience.

In a second experiment, the accuracy with which the figural and non-figural (ground) components are resolved was measured, using the method of adjustment described by Watson (1976). The frequency of single components was adjusted in a comparison pattern, until the listener decided that it had the same pitch as the corresponding component in a standard pattern.

In general, the adjustments of figural components are either slightly more accurate than for those that form the ground, or, in some cases, are made with the same accuracy, but require more pattern repetitions before the listener is satisfied with the match.

The primary goal of these preliminary experiments was to devise a rapid and reliable means by which listeners can identify the elements of a pattern which they perceive as a discrete auditory "figure" or "event". The AFI method is a very convenient means of achieving that goal. In future experiments, we plan to use that method to study other factors that may be systematically related to the emergence of auditory figures or "targets" from various backgrounds.

4. Perception of multidimensional complex sounds (Watson, Kidd, Washburne)

4.1. Information integration with multidimensional complex sounds

Listeners' abilities to perceive information independently encoded in different dimensions of complex sounds were examined in experiments that required simultaneous attention to three dimensions. Stimuli consisted of sequences of 1, 3, 5, or 7 brief pulses that were generated by adding five 100-msec sinusoidal components. Each pulse had one of two values on each of the following complex dimensions: 1) harmonicity (harmonic vs inharmonic relations among the components), 2) spectral shape (linearly decreasing amplitude vs a two-peaked amplitude profile), and 3) amplitude envelope (slow vs rapid rise and decay times). Stimuli were selected such that the two values on each dimension were highly discriminable.

Two types of stimuli were generated by designating one value on each of the dimensions as the "target" value (harmonic spacing of sinusoids, the double-peaked power spectrum, and rapid rise/decay), and the other as the "non-target" value. The selection of dimensions for each component of a sequence was probabilistically determined and was adjusted to yield maximum possible (ideal) performance of 90% correct for all sequences.

Two groups of listeners were tested for 10 days. One group had four days of training in a single-dimension control experiment in which they identified target and non-target values for each of the individual dimensions while the other two dimensions varied randomly. The other group had no prior training but was tested in the single-dimension control experiment after completion of the main experiment.

Performance in the training experiment for the first group revealed very substantial differences among listeners' abilities to attend to the individual dimensions, even after 4 days of training (240 trials per day per dimension). All listeners were able to correctly detect differences at least 70% of the time for each dimension, and close to 100% for at least one dimension.

Both groups of listeners showed an impressive ability to integrate information over pulses within sequences of up to 7 pulses, with identification performance at about 5% to 10% below that of the ideal (90%). The similarity in performance of the two groups, even at early stages of the experiment, indicates that the type of training we have used did not have a significant effect on listeners' ability to perform the information-integration task.

Performance of the second group of listeners in the single-dimension control experiment after 10 days of listening to the stimuli in the multi-pulse task was quite similar to that of the group tested prior to the multi-pulse task. There appears to be little or no effect of exposure in the integration task on discrimination ability as tested in the single-dimension control experiment.

In order to better understand listeners' attentional strategies in the integration task and how they might differ from those in the control experiment, responses to various stimulus configurations (i.e., multi-component stimuli with different numbers of target values on each dimension) were examined. The result of this analysis can be summarized as follows:

1. Although performance levels are often similar to levels that could be achieved by attending to a single dimension (approximately 80%), listeners were clearly attending to more than one dimension. Correlations between the number of stimuli with target values on a given dimension and listeners' responses were computed for each dimension and combination of dimensions. Correlations between responses and values on each individual dimension were higher than would be predicted on the basis of the correlation among the components, and correlations with the sum of all three dimensions were generally higher than with any single dimension or pair of dimensions. In other words, the listeners' decisions were in fact multi-dimensionally based.

2. Substantial individual differences were observed in the extent to which listeners attended to each of the dimensions. However, the allocation of attention suggested by the results of the single-dimension control experiment did not always agree with the apparent attentional distribution observed in the integration experiment. In some cases, the dimensions that influence listeners' responses most were not those that yielded highest performance in the control experiments (when feedback was based on a single dimension). It thus appears that a listener's ability to attend to a given dimension while others vary randomly is not a good predictor of his ability to use that same information when making decisions based on the combination of multiple dimensions.

4.2. Individual differences in the allocation of attention to specific dimensions

The existence of large individual differences in the allocation of attentional resources to various dimensions of sound sequences has recently been confirmed in another version of this experiment. Twenty-seven additional listeners were tested in a four-session "screening" protocol in which they were trained and tested in the classification of the three-dimensional target and non-target sounds. Approximately the same number of subjects displayed a preference for each of the three dimensions: Ten preferred spectral shape (the "profile" in Green's (1983) terms), nine preferred harmonicity, and eight preferred amplitude envelope. There were subjects who were skilled at processing each of the dimensions but could not seem to simultaneously process the other two, while a few subjects could reliably detect all three dimensions. The unsatisfactory generalization from these data was that there were many substantially different patterns of allocation of attention to the three dimensions and very little evidence of clusters of listeners with similar patterns.

At this point, this research has yielded two primary results concerning listeners' ability to categorize complex multidimensional sounds. One is that listeners can integrate multidimensional information in sequences of sound pulses, with little or no loss of efficiency with increasing sequence length, for sequences of one-two-seven components. The other is that they are often not very good at allocating attention to all three features (or "dimensions"), even though their absolute efficiency in this task is fairly high. In fact, comparable levels of performance are achieved with a variety of patterns of attention to the features of the stimuli. One possible interpretation of this result is that performance is limited in terms of the amount of information the listener can extract from complex sounds. The existence of small negative correlations between weightings for two of the three pairs of dimensions gives some support to this interpretation.

New experiments have been planned to determine (a) how well listeners can learn to process features they appeared to initially ignore, and (b) how well they can be taught to integrate information across all three dimensions. Initial attempts to train listeners to attend to previously unattended dimensions (utilizing training techniques that encourage listeners to attend to each of the individual features in the context of different stimulus configurations) have had limited success. It would seem very likely that this task can ultimately be learned, given that each of the features *can* be discriminated easily.

5. Discriminability of complex waveforms (D. E. Robinson and S. M. Fallon)

Watson and his colleagues have provided a large amount of data concerning the discriminability of individual components within sequences of tonal patterns (Watson, Wroton, Kelly, and Benbassat, 1975; Watson, Kelly, and Wroton, 1976; Spiegel and Watson, 1981; Leek and Watson, 1984; Watson and Foyle, 1983; 1985a, 1985b; Watson and Kidd, 1987). We are now investigating the relationship between such relatively deterministic tonal sequences and essentially random waveforms. There appear to be some striking similarities between the two, apparently quite different, types of waveforms.

The research described under this heading is directed toward a better understanding of the processes by which listeners discriminate between pairs of complex auditory waveforms. The waveforms are, in all cases, samples of broad-band, white, Gaussian noise, and all experiments made use of a same-different paradigm. [Portions of the work described here have been reported in Fallon and Robinson (1985) and in Fallon and Robinson (1987).]

5.1. Models of auditory masking

Results from experiments in which hit proportions and false alarm proportions for detecting a 500-Hz tone at each of four starting phase angles in each of 25 reproducible noise samples were modeled by fitting the general form of the electrical analog model of Jeffress [J. Acoust. Soc. Am. 48, 480-488 (1967)] to the diotic data. The best-fitting configurations of this model do not correspond to energy detectors or to envelope detectors. A detector composed of a 50-Hz-wide single-tuned filter, followed by a half-wave rectifier and an integrator with an integration time of 100 to 200 ms fits the data of all four subjects relatively well. Linear combinations of the outputs of several detectors that differ in center-frequency or integration window provide even better fits to the data. These linear combinations assign negative weights to some frequencies or to some time intervals, suggesting that a subjects' decision is based on a comparison of information in different spectral or temporal portions of the stimulus. [Gilkey, R.H., & Robinson, D.E., J. Acoust. Soc. Am., 79, 1499-1510 (1986)]

5.2. Effect of random variations in level

If the discrimination between pairs of noise bursts is based on a statistic such as total power, average power or energy, the discrimination should be impossible if overall level is randomized between the two bursts in the same-different paradigm. The effect of

such a change was investigated at each of two durations using bursts which were either identical ("same" trials) or completely independent ("different" trials). Within a block of trials, the noise bursts were either 25- or 150-msec in duration and the level of the sample presented in one observation interval was held constant while the level of the sample presented in the other interval was randomly varied. In one experimental condition, the level of one of the samples in the pair was 3 dB greater than, 3 dB less than, or equal to the level of the other sample. The effect of a variation in level of ± 6 dB was also examined.

The data indicate that varying the level of one of the samples in a pair caused a only slight decrease in discriminability. When the bursts were 150-msec in duration, the average value of d' without variations in level was 2.98; with a ± 3 dB variation, it was 2.46; and with ± 6 dB, 2.09. For 25-msec bursts, the corresponding values of d' were 3.13, 2.79, and 2.49. Thus, although there is a slight decrease in performance with randomized levels, the samples are still quite discriminable. We conclude that the basis of the discrimination cannot be average power or energy.

5.3. Effect of temporal position of appended noise

Hanna (1984) demonstrated that samples of wide-band reproducible noise are highly discriminable over a large range of durations. We have found that discriminability can be reduced by increasing the similarity between the pairs of samples to be discriminated. During "different" trials of the same-different procedure, the second sample of the pair was generated by repeating a temporal segment of the sample presented in the first interval and combining it with a new sample of noise. The total duration of the second sample of a pair is equal to the duration of the new sample plus the duration of the repeated sample of noise. The total duration, as well as the duration and position of the new segment of noise was varied. The three total durations examined were: 150, 50, and 25 msec. The new segment of noise was either placed at the beginning, in the middle, or at the end of the repeated sample of noise.

The degree of similarity between the two samples presented during a "different" trial may be expressed in terms of the inter-pair correlation (r): the duration of the repeated sample of noise divided by the total duration of the sample. When the data are expressed in terms of correlation, the threshold value of r is independent of duration, but is highly dependent upon the position of the appended segment. Although discriminability was not affected by the total duration of the sample, the temporal position of the new segment had a large and consistent effect: segments placed at the end were more discriminable than those in the middle which were more discriminable than those at the beginning.

The effect of temporal position on discriminability also occurs with tonal sequences. Watson and his colleagues (Watson et. al., 1975, 1976) showed that discriminability increases as the location of the test tone is moved from the beginning to the end of a 450 msec tonal pattern. Hanna (1984) also determined that the discriminability of two samples of reproducible noise was dependent on the temporal positions of the repeated and appended segments. Hanna's data indicate that discriminability is best in the end condition, decreases in the beginning condition, and is worst in the middle

condition. Based on the results of the present experiment as well as on the research of Watson and his colleagues, one would have predicted the middle condition to be more discriminable than the beginning condition. The discrepancy may be attributable to procedural differences such as the duration of the samples of noise or the degree of stimulus uncertainty.

The results of this experiment and the data of Watson's group indicate that the processes underlying the discriminability of sequences of tonal patterns and the discriminability of samples of reproducible noise are very similar. The just-detectable segments of "different" noise in these experiments tend to be a constant proportion of the total stimulus duration. This result is very similar to the performance described for various duration tonal patterns, in the "capacity" experiments discussed by Watson and Foyle (1985a) and by Watson and Kidd (1987). The fact that two distinctly different types of complex waveforms appear to be processed in the same manner suggests that discriminability is dependent on the more global characteristics of the complex waveform rather than on the fine structure of a specific waveform.

5.4. Effect of decorrelation: autocorrelation

This experiment investigated the discriminability of noise-samples which differed in their autocorrelation. As in the previous experiment, "same" trials were generated by repeating in the second interval the sample presented in the first interval. On "different" trials, however, the sample presented in the second interval was generated by deleting the first T-msec of the sample from the first interval and appending T-msec of independent noise to the end. In the experiment described in Sec. 6.2, new noise was appended at the beginning, middle, or end. The data from the "end" condition of that experiment are very similar to those from the present experiment. The two conditions are similar in that in each, independent noise is appended at the end of the 150-msec burst. The two conditions differ, in that, for the 'end' condition, samples in the two intervals are identical for the duration T_c , while for the autocorrelation experiment, the beginning segments differ. Since, as was pointed in Sec. 6.2, differences between samples which occur at the beginning or in the middle have only a small effect on discriminability, it is not surprising that the 'end' and the autocorrelation conditions are similar.

5.5. Effect of decorrelation: added noise

The correlation between pairs of noise samples may also be reduced by reducing the proportion of variance common to the two samples. In this experiment, "same" trials were generated by presenting identical samples of noise in both observation intervals. "Different" trials were generated by adding a new, independent, sample of noise to the sample which had been presented during the first observation interval. The relative levels of these two samples determined the Pearson product-moment correlation coefficient between the samples presented in the two intervals. The overall level of the samples in the two intervals was maintained at 50 dB SPL/Hz.

For all four of the durations examined, discriminability decreased as the correlation increased. The decrease was slight for correlations between 0.00 and 0.75, and very rapid for correlations greater than 0.75. This is to say that two samples are easily discriminable when they have less than about 50% common variance.

5.6. Effect of the temporal position of a decorrelated segment

In this experiment "different" trials were generated by decorrelating, as in Sec. 6.4, only a portion of the 150-msec waveform presented in the second interval. The decorrelated portion was located at either the beginning, the middle, or the end of the waveform. As expected from previous experiments, discriminability is highly dependent on the temporal position of the decorrelated segment. When the correlation was 0.00, threshold durations were approximately 25-, 60-, and 90-msec for segments at the end, middle and beginning. When the correlation was 0.75, these values had increased to approximately 50-, 90-, and 120-msec. The large effect of temporal position which we reported previously is still maintained as correlation is increased.

5.7. Effect of gap duration and position

In this experiment, the overall duration of the bursts of noise in a pair was 150 msec and either a 25 msec segment of new noise was appended to the end of the burst or a 50 msec sample was appended to the beginning of the burst. A silent interval or gap replaced a portion of the repeated segment either immediately following or immediately prior to the appended segment. The duration of the gap was gradually increased until only 5 msec of the repeated segment remained. Although discriminability increased as gap duration increased the presence of a brief repeated segment temporally separated from the appended segment by 90-120 msec caused a large decrement in performance. For example, when each burst in a pair consisted of a 5 msec repeated segment followed by a 120 msec gap and a 25 msec appended segment, the average $P(C)$ is 0.72. If the 5 msec repeated segment was not present and the pair of 25 msec bursts was presented in isolation the overall $P(C)$ increased to 0.88. It would appear, then, that interactions occurring after such a long silent interval are unlikely to be peripheral sensory interactions, as was suggested by Hanna (1984).

6. Information integration: multiple observations and internal noise (D. E. Robinson and B. G. Berg)

The work described in this section began with two major goals. The first is to understand the processes by which humans integrate information over time or over channels. The "multiple look" problem is the basis for our initial work in this area. The basic question is, "How much additional information is gained by allowing observers more than one observation in a detection or discrimination task?" The second goal is to develop and evaluate models of "internal noise." The amount and rate of improvement in performance with an increasing number of observations will depend not only upon the amount of internal noise, but upon the level of processing at which the internal noise is added. The following section describes our attempts to describe the improvements that occur with multiple observations and to model the processes that lead to such improvements. [Portions of the work described here are reported in Robinson and Berg (1986), in Berg and Robinson (1987), Berg (1987), and Sorkin, Robinson, and Berg (1987).]

6.1. Internal noise model

Previous research has demonstrated that performance in signal-in-noise detection tasks improves as listeners are allowed more observations (Swets, et al., 1959; Swets and Birdsall, 1978). According to signal detection theory, the rate of improvement is a function of the square-root of the number of observations:

$$d'_n = (m_2 - m_1) / (v_{\text{ext}}/n + v_{\text{int}}/n)^{1/2} = (n)^{1/2} d'_1 \quad (1)$$

where: d'_n , d' after n-observations
 d'_1 , d' for one observation
 m_1 , the mean of the noise-alone distribution
 m_2 , the mean of the signal-plus-noise distribution
 v_{ext} , the common variance of the N and SN distributions
 v_{int} , the variance of the internal noise.

Internal noise is assumed to be added prior to the formulation of a decision statistic. This derivation of the square-root-of-n rule assumes that the decision statistic is the mean of the n likelihood ratios (or any monotonic transformation of the likelihood ratios) obtained from the n observations. Previous research has supported this square-root-of-n prediction. However, the earlier work provided only a limited test of the model, since n never exceeded six. Our research has extended this work by using several paradigms and a greater number of observations.

6.2. Sequential presentation of n tones

Consider the following task. There are two probability density functions on frequency, one with a mean of 1000 Hz, one with a mean of 1100 Hz, and both with a common standard deviation of 100 Hz. On each trial, n independent samples are selected from one of the distributions and presented sequentially over headphones as n, 50-msec tone bursts, separated by 50 msec silent gaps. The listener's task is to decide from which of the two distributions the n tones were sampled. Our results indicate that listeners can approach the theoretical d' for $n=1$, but do not follow the square-root-of-n rule, even for small n. Representative data for one subject are shown in Figure 6.2a. The solid line represents the predictions of Equation 1.

One interpretation of the model, described by Equation 1, is that some amount of internal noise is added to each observation prior to generating a decision statistic. Once the decision statistic is obtained, no additional variance is assumed. This model allows no parsimonious account of variance introduced by uncertainty of the decision criterion, changes in response bias, or memorial factors associated with the decision statistic. The model can be extended by allowing additional variance after the generation of the decision statistic. This "partitioned variance" model is represented by the equation:

$$d'_n = (m_2 - m_1) / (v_{\text{ext}}/n + v_p/n + v_c)^{1/2} \quad (2)$$

where: v_p , the variance of the peripheral noise
 v_c , the variance of the central noise.

In this model, internal noise is added at two stages: (1) at the periphery, before a decision statistic is formed and (2) centrally, after the statistic is formed. The dashed line in Figure 6.2a represents the function obtained for subject KN by a least-squares estimate of the two parameters. Similar fits were obtained for the three other subjects.

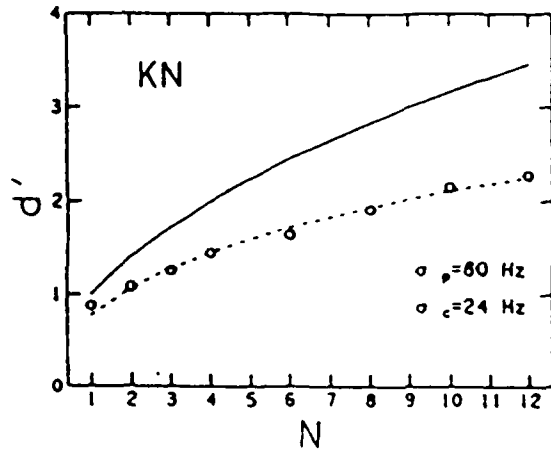
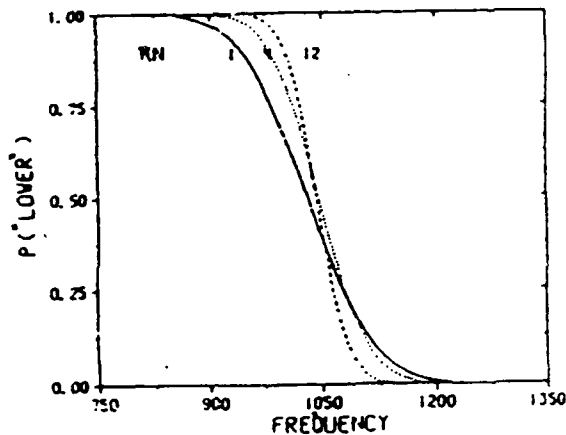


Figure 6.2a



6.2b

There is a second method of estimating the two parameters. Consider the function relating the probability of reporting "lower distribution" to the mean frequency of the sample. An ideal observer would generate a step function; when the mean frequency was less than the criterion, the ideal would report "lower", and would report "higher" when the mean exceeded the criterion. Within the model, any deviation from this step function can be attributed to internal noise. The variance of this internal noise can be estimated by fitting a normal ogive to the obtained data. Figure 6.2b shows the best fitting functions for subject KN for sample sizes of 1, 4, and 12.

The slope of the functions increase with increasing n , indicating that the total internal variance is decreasing. In this manner, estimates of the total internal variance were obtained for each sample size ($n=1,2,3,4,6,8,10$ and 12). Estimates of the peripheral and central variance were obtained by a least-squares fit to the equation:

$$v_{\text{tot}} = v_p/n + v_c . \quad (3)$$

A comparison of the parameter estimates obtained with Equations 2 and 3 showed remarkably good agreement for all four subjects. The partitioned variance model thus provides a reasonably good account of the data, and represents an improvement in the formal treatment of internal variance.

6.3. Simultaneous presentation of n tones

This work was conducted in collaboration with Dr. Wesley Grantham of the Bill Wilkerson Hearing and Speech Center, of Vanderbilt University. Grantham conducted an experiment similar to that described in Sec. 7.1, with the exception that the n tones were added and presented simultaneously, rather than sequentially. Data could be reasonably described by Equation 1. That is, little or no central variance was required. Preliminary conclusions seemed to indicate a fundamental difference between the processing of information presented sequentially and information presented simultaneously. However, this difference can be attributed to a procedural difference between the two studies. For technical reasons, tones were sampled without replacement for simultaneous presentation, whereas sampling was done with replacement for sequential presentations. Equation 1 assumes independent sampling and is valid for the sequential tones study, but a correction factor is required to obtain predictions when sampling is done without replacement. Obtaining fits to Grantham's data using this correction factor indicated a less than optimal growth rate in d' for all three subjects, and required the addition of central variance. A comparison of estimates of peripheral and central variance across the two studies showed relatively good agreement.

6.4. Distribution of internal noise over the tonal sequence

An important question raised by our general model is whether information from each tone in a tonal sequence is equally weighted in determining an observer's decision. We have developed a technique for assing how internal noise is distributed over the N-elements of a tonal sequence. In terms of the model as described in Eq. 2, the amount of information obtained from different tones in an N-element sequence will be reflected in the variance of the internal noise added at each temporal position. If a particular temporal position contributes little to the final decision, that position will be found to have a large amount of internal noise associated with it. If, on the other hand, a particular element contributes a great deal, that element will have less internal noise associated with it. Data from an auditory experiment were analyzed to assess how internal noise is distributed over successive temporal positions. Over many thousands of trials we store the frequency of the tones actually presented in the i th temporal position ($i = 1, 2, \dots, n$; where n is the number of tones in the sequence). We then partition these stored frequencies into bins of arbitrary width. The purpose of our analysis is to keep track of the number of trial events on which the frequency of the i th element was in each frequency bin. For each bin and each temporal position, we then compute the probability that the subject responds that the sequence came from the lower distribution. Cumulative normal distributions are then fit to the resulting ogives. The standard deviation of the best fitting normal distribution is then an estimate of the

standard deviation of the total internal noise limiting performance at each display position.

Figure 6.4 shows the standard deviation of the internal noise as a function of temporal position. The parameter on the figure is the total sequence length, n . If each element in the sequence contributed equally to the final decision, the lines in Figure 6.4 would be horizontal. It is clear that the last tone in a sequence contributes more to the final decision than do tones in the middle, which contribute less than those near the beginning of the sequence.

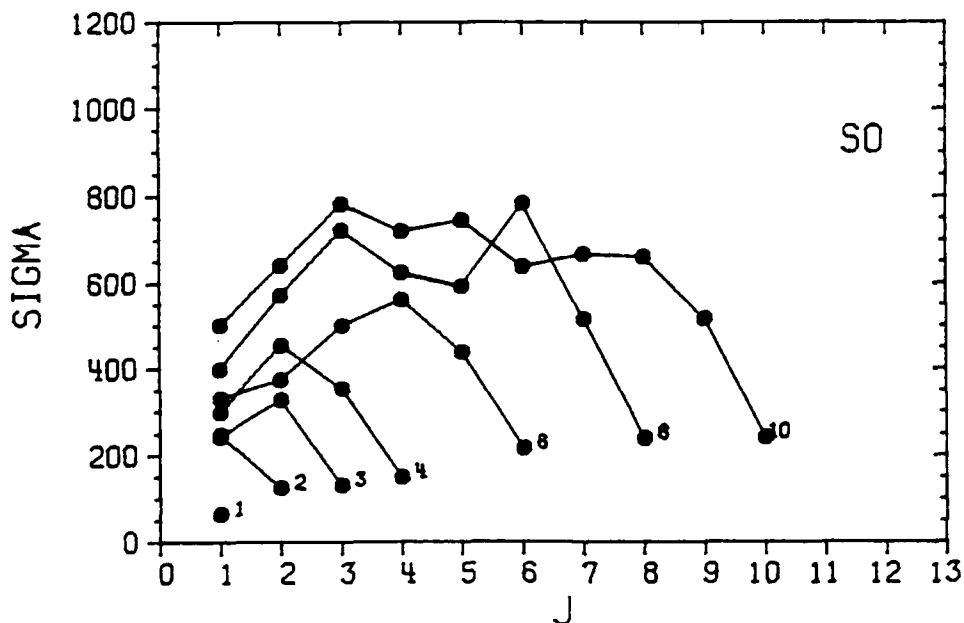


Figure 6.4

6.5. Additive or multiplicative internal noise?

A common assumption of the models discussed above is that external and internal variance are independent and additive. This assumption was tested by using a within-subjects factorial design consisting of two levels of external variance

$$(v_{\text{ext}})^{1/2} = 100 \text{ Hz or } 150 \text{ Hz}$$

and two levels of the mean frequency difference between the two distributions.

$$m_2 - m_1 = 100 \text{ Hz or } 150 \text{ Hz.}$$

For each of the four conditions, the experimental procedure was identical to the sequential tone paradigm described previously. Data obtained from four listeners indicate that estimates of internal variance are not affected by changes in the mean frequency difference for a fixed level of v_{ext} . However, estimates of internal variance

increase when v_{ext} is increased. This increment in internal variance is obtained for both levels of the mean frequency difference. These data violate the assumption of additivity, and suggest that internal variance increases as a function of the external variance.

7. Facility Development

During the present grant period the experimental facilities in the Hearing and Communication Laboratory have been substantially improved. Originally HCL had a single 11/23 computer which was (and still is) heavily committed to running on-line experiments. A PDP 11/83 was installed to assist with off-line support of laboratory activities such as stimulus generation, data analysis, program development and signal processing. A Digisound-16 D/A, A/D converter was installed and software was developed, so that synthesis of the sounds for the vigilance experiments could be done on the 11/83.

In addition, the grant provided savings that, together with other funds, allowed us to purchase two Apollo workstations. These workstations are each powerful mini-computers which run UNIX. We participated in establishing Apollo Domain ring at Indiana together with an interdisciplinary group of investigators in Computer Sciences, Linguistics and Mathematics, all of whom had interests in speech and auditory processing. We have been able to share software applicable to the needs of this group, in particular statistical and signal processing packages, digitizing facilities, and speech recognition tools and algorithms. Several new workstations have now been added to this network by the AFOSR supported Institute for the Study of Human Capabilities. Interests between our labs and the Institute overlap considerably, and the communication with these additional investigators has further enhanced the usefulness of the Apollo system. We are fortunate to have been able to build a state-of-the-art psychoacoustic and speech laboratory over the past few years. That system now enables us to conduct a wide range of extensions of the research supported here, without need for additional apparatus, at least in the near future.

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Advanced Degrees Awarded

David A. Geddes, M.A.; May, 1986; "Estimation of Hearing Loss in Elementary School Children using Acoustic-Reflex Thresholds."

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