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A COMPARISON OF SINGLE- AND MULTI-BAND

ATTENTION MODELS BY USE OF SHORT

DURATION NOISE PULSES

by

Stephen R. Harris

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Two experiments were conducted to compare the single- and multi-band models of selective attention. Previous work cited in the literature had shown conflicting results both confirming and discrediting the models. Some of the data may be accounted for by assuming a change in the subject's (S's) response criterion. Therefore, the present study examined the concepts of time-sharing and Theory of Signal Detectability (TSD) in relation to auditory selective attention.

The stimuli were two narrowband noise pulses 74 Hz wide with low (L) and high (H) center frequencies of 713 and 966 Hz, respectively. These stimuli were presented either separately (H or L) or simultaneously (HL condition). When two signals are presented simultaneously, the intensity of the resulting combined signal is greater than that of either of the component signals (H or L) presented separately. Two different HL presentations were used in the experiments to eliminate this intensity problem. One HL presentation was simple combining of the two component signals (HL_I). The other was when the two component signals were combined again; however, this time the intensity of the resultant HL presentation was lowered to that of the most intense component signal (HL_D). Stimuli were presented at 15 dB SL with

a 40 dB SPL white noise background. Responses were recorded automatically and dependent variables (d' and false alarms) were based on at least 600 trials for each stimulua condition.

Three males served as trained Ss. [In a two alternative forced choice (2AFC) paradigm], the Ss were asked in Experiment I to indicate (by pushing one of two microswitches) their decision as to which interval contained the signal. This was studied under four stimulus conditions (H, L, HL_I and HL_D) and three signal durations (0.5, 2.0, and 3.5 msec). Experiment II examined the same stimulus conditions; however, these were presented at the Temporal Recognition Threshold (TR) which reflects the "minimum dwell-time" required to differentiate between the two signals (H and L) 75% of the time. The S's task was to indicate (by pushing one of three microswitches) his decision as to which signal condition had been presented in the second interval of a modified 2AFC paradigm. In this modified 2AFC paradigm, the first interval contained one of the three stimulus conditions (H, L or HL).

In Experiment I, it was found that under the HL conditions the multi-band model predictions closely resembled the obtained data, which showed an increase in detectability for the HL_I condition compared to a single component signal (H or L) and equal detectability for the HL_D

condition compared to the most detectable single component signal.

In Experiment II, it was found that when both noise pulses were presented simultaneously (either HL_I or HL_D conditions), recognition was less than when either the H or L pulses were presented alone. Analysis of the false alarm (F/A) rates showed that the different signal conditions produced significantly different ($p < 0.01$) F/A rates.

The results were discussed in relation to attention theories, selective attention models, and differences between recognition and detection analysis of auditory signals. The experiments indicated that auditory information processing and selective attention is a two step process involving: (1) a detection process in which this study could not determine whether single- or multi-band models were functioning; and (2) a recognition process using a single-band model (stimulus selection) of selective attention.

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CHAPTER 1: INTRODUCTION

Much work has been performed in the past two decades in the area of selective attention. Recently, the work in this area has been applied to the concept of auditory frequency analysis. During the same period of time, a psychophysical technique has been developed from decision theory which has aided in the study of both the former phenomena. This relatively new psychophysical method is the Theory of Signal Detectability (TSD). The following discussion reviews the relevant literature in selective attention from an auditory frequency analysis and TSD point of view. Data from experiments in these fields are examined and contrasted in order to reveal relationships which may be beneficially explored.

Selective Attention

The concept of attention is central to psychological work. Although it was a position for contention in early scientific psychology between the Structuralists (Titchner, 1908) and the Functionalists (James, 1890), both schools agreed that attention was central to psychological thought. However, in the early parts of the 20th century with the advent of the Gestalt, psychoanalytic, and behavioristic schools of psychology, interest in attention diminished.

Then in the 1950's, a rebirth of scientific interest in attention occurred. With this increase in interest, more investigations and theories have been generated and attention has been broken down into more specific categories (Moray, 1969, p. 6), such as mental concentration, vigilance, search, activation, set, analysis by synthesis, and selective attention. The present review will discuss pertinent theoretical and experimental work on this latter category of attention; viz., selective attention, from its rebirth (i.e., the 1950's) to the present.

Theories of Selective Attention

Cherry (1953) stimulated work in the area of selective attention with his now classical "cocktail party effect" experiment. His investigation introduced the phenomena of selective attention by showing that an individual could attend to one of two dichotic messages while ignoring the other. The extent of this attention was such that often a Subject (S) could not report whether the ignored message was in a foreign language or not.

Broadbent's filter theory. About the same time as Cherry's experiment, Broadbent (1958) reviewed the work in this area and developed an influencial theory of attention in his comprehensive book, Perception and Communication. Broadbent's theory was mainly developed and tested by experiments using speech stimuli, which permitted the inference that information entered the organism through parallel sensory pathways and was filtered into a single central channel. His model is illustrated in Figure 1. A single filter is posited so that the central channel would not be overloaded. This hypothesized filter, which blocks all but one of the sensory inputs at any instant in time, makes Broadbent's theory one which uses <u>sensory selection</u> to explain attentional processes. The central channel may sample more than one input but the single filter can only sample one input at a time. Broadbent (1958) hypothesized this switching of attention from one input to another would take a finite time period (approximately one second). This has been called the "filter theory" and was modified by A. Treisman (Treisman, 1964, 1967, 1969; Treisman & Geffen, 1967) from the concept of an absolute filter to that of a partical filter which attenuates unwanted incoming signals rather than completely removing (filtering) unwanted incoming signals. The reason for hypothesizing a new theory was, of course, because Broadbent's single channel theory could not explain all the data. Among the results obtained by Cherry (1953) was that <u>S</u>s required to attend to a message in one ear could perceive their names when they were presented to the non-attended ear. Also, Moray (1969) reported that <u>S</u>s required to attend to redundant (and therefore easily followed) messages would tend to report perceiving material from the

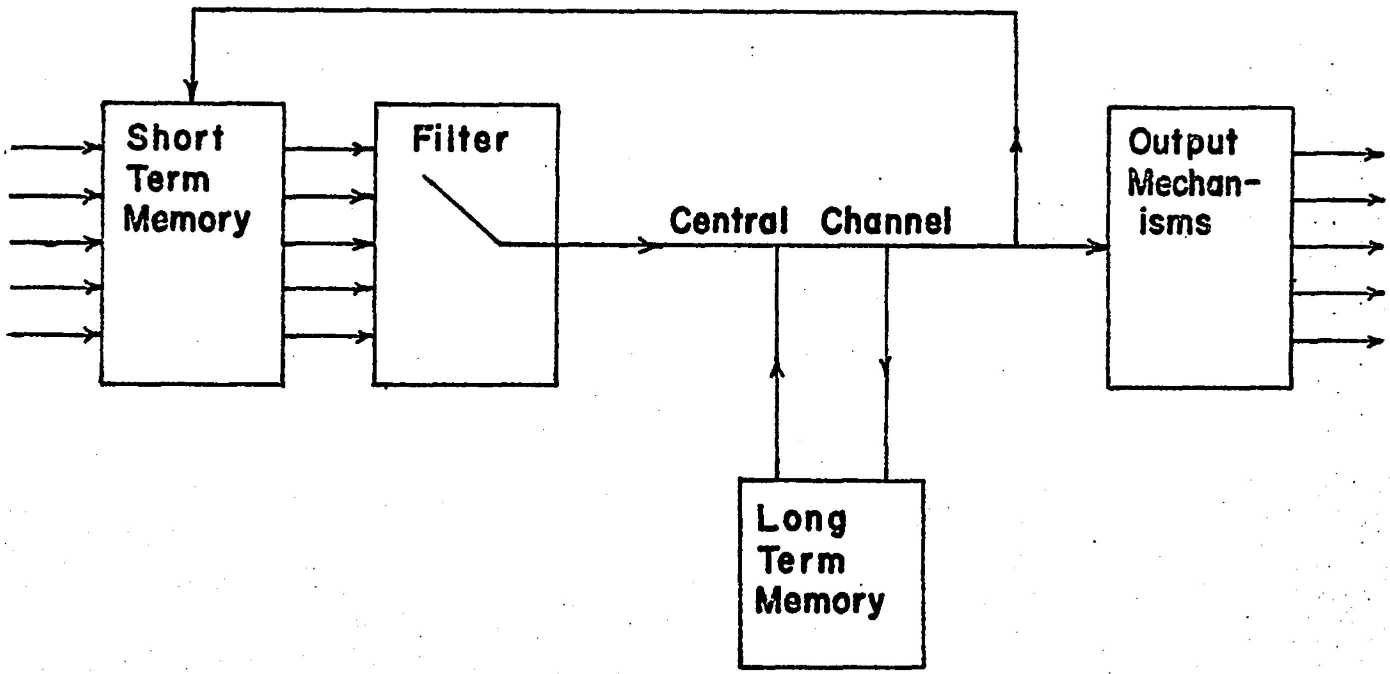

FIGURE 1. Broadbent's Filter Theory (after Broadbent, 1958)

non-attended message. These, and similar data which indicated faster switching times than, Broadbent proposed, led A. Treisman into hypothesizing an alternative theory of attention using the partial filter idea.

<u>Treisman's input selection theory.</u> Treisman postulated that the basic concepts of Broadbent's "filter theory" were correct, but the filter was not absolute; rather, it was a partial filter (Treisman, 1964, 1967, 1969; Treisman & Geffen, 1967). This view has since been incorporated by Broadbent in the recent discussion of his theory (Broadbent, 1971). Treisman's view can be seen in Figure 2 in which one message is selected for recognition (S_1) and all others are rejected (r_1-r_4); however, this rejection is not a total rejection (or filtering). This means that the non-attended stimulus information from the rejected messages is transmitted further along the nervous system in addition to the selected message. This information is then analyzed by the pattern recognition network (prn) located beyond point A in Figure 2. In this network there are hypothetical units, with differing thresholds, for specific types of stimuli. The stimuli that reach threshold for these hypothetical "dictionary" units are then responded to (the response may be either to attended or non-attended stimuli, or both). The differences between the alternative theories to the Broadbent "filter theory" seem to be the emphasis on whether selection of stimuli is a

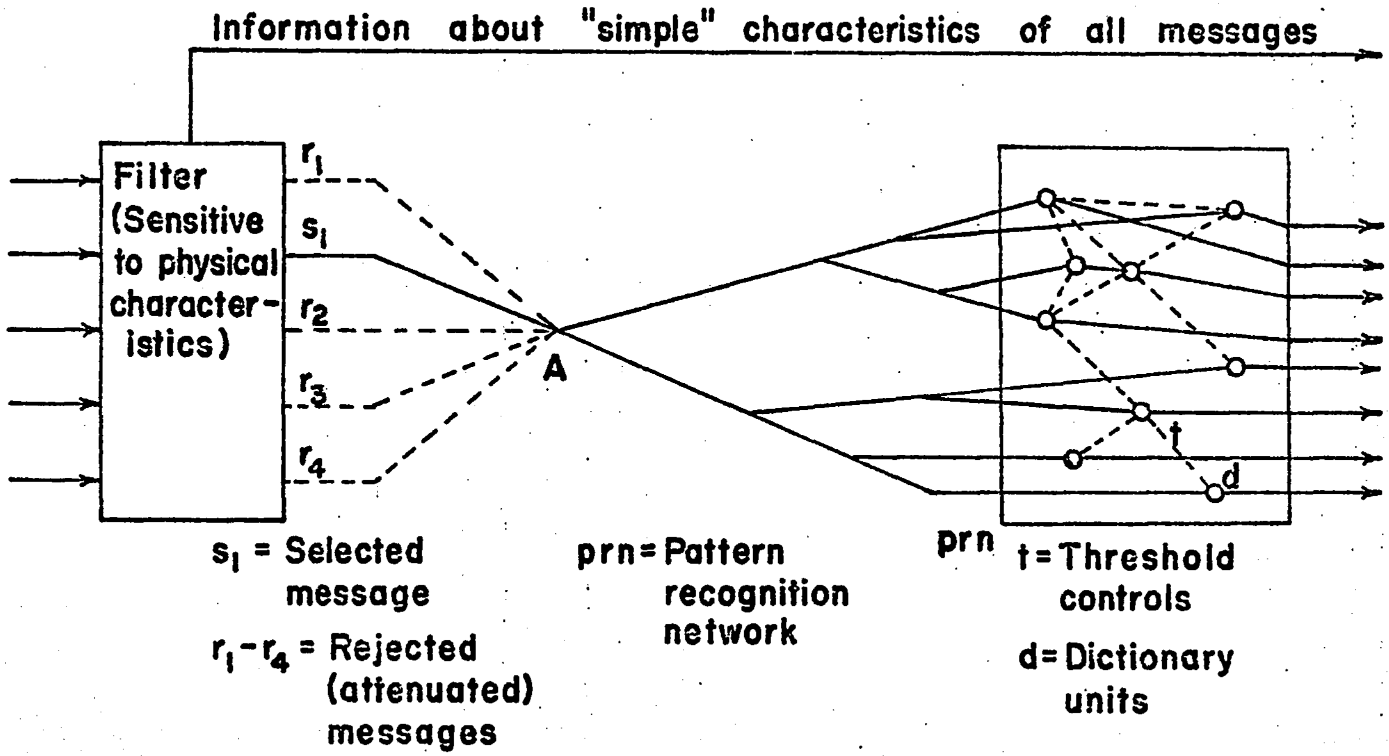

FIGURE 2. Treisman's Input Selection Theory (after Moray, 1969)

sensory (as described by both Broadbent and Treisman) or a response selection, as stated in the Deutsch and Deutsch theory to be discussed later (Deutsch & Deutsch, 1967; Lindsay, 1967; Treisman, 1967; Treisman & Geffen, 1967). Moray (1969), using a time-sharing concept, has also taken a sensory selection viewpoint to be discussed below.

Moray's time-sharing theory. Moray (1969) gave an excellent review of attention literature and theorizing up to 1969 in his short book, Attention: Selective processes in vision and hearing. In addition to these discussions, he also has developed his own sensory theory of selective attention as illustrated in Figure 3. He advocated time-sharing between two information channels (Listening Channels A and B of Figure 3), and proposed that the internal information analyzer (as illustrated in Figure 3) can share time between the two listening channels by switching from one to the other alternately at much shorter intervals than Broadbent had hypothesized. Moray postulated that the switching time may possibly be instantaneous (as illustrated in Figure 3 by the rectangular switching from Listening Channel A to Listening Channel B, and vice versa), with the analyzer switching back and forth between "attended" and "non-attended" stimulus conditions, while Broadbent posited that there was a definite time lapse of perhaps a second or more for switching time. Moray further stated that attended stimuli, if difficult to follow, would retain

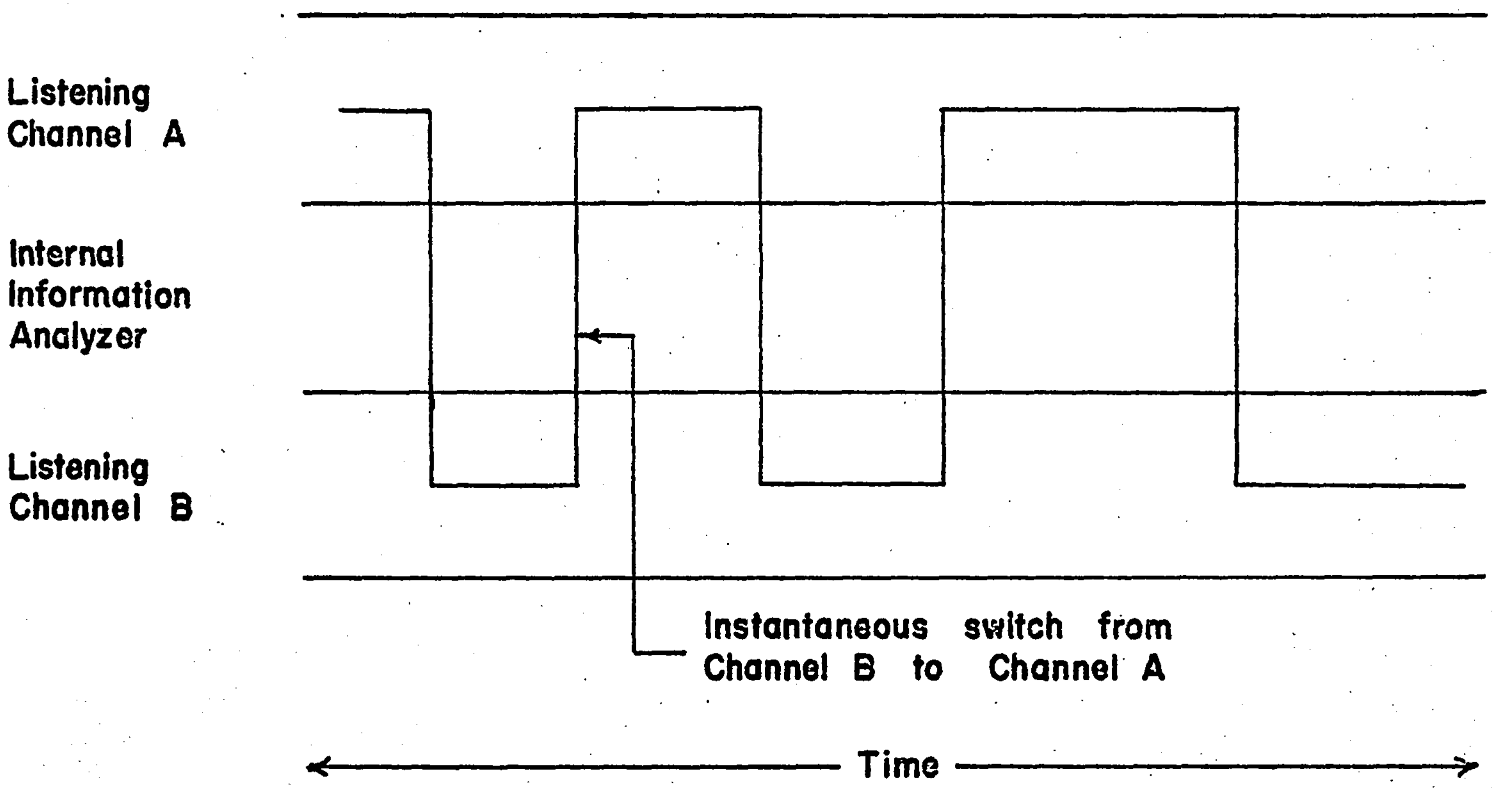

FIGURE 3. Moray's Time-Sharing Theory

the analyzer for longer periods of time (a "dwell time") and thereby eliminate processing of information from non-attended stimulus conditions by the analyzer. However, when the attended stimulus condition was easily followed, the analyzer could switch more often and thereby process information from both attended and non-attended stimulus conditions. As can be seen from the above discussion, this latest theory (Moray's Time-Sharing Theory) is only a variation of Broadbent's original theory. The former theory includes instantaneous switching time and the latter a slow switching time.

Deutsch and Deutsch's response selection theory. A third alternative theory was devised by Deutsch and Deutsch (1963) which stated that there was no sensory filter (absolute or partial) but that selection was based on the response. Thus, this theory would allow more than one stimulus to be processed at any one time. In addition, Deutsch and Deutsch (1963) stated that three stimulus characteristics determine the attentive state; viz., the amount of stimulation, the requirement of attending to a stimulus or not, and the importance of the stimulation. The third characteristic, the importance of the stimulation, could be considered a characteristic which possesses qualities of basic importance to the S, (i.e., the S's name, or impending physical harm). Therefore, the sum total of the three stimulus characteristics combined would determine which stimulus is selected to be attended and responded to at any one time. Hence in a response selection theory, as can be seen in Figure 4, all sensory information is processed, by channels S_1 through S_5, and the sensory information which has the greatest total stimulus value (i.e., the summated value of the three stimulus characteristics) is responded to first.

In summary, the difference among the above theories is that a sensory selection theory (i.e., Broadbent, Treisman, and Moray Theories) asserts that there is a sensory filter at some point which attenuates the non-attended signals, while the response selection theory (i.e., Deutsch and Deutsch Theory) states that the signal responded to is selected because it has more signal strength (i.e., stimulus characteristics) than any other at that time. The sensory selection theories are differentiated by their interpretation of the sensory filter; viz., a partial filter (Treisman) or a total filter (Broadbent and Moray). A further differentiation between the latter two theories is the concept of switching time. One theory (Broadbent) considers switching time to be relatively slow, while the other (Moray) asserts that switching time is extremely rapid or possibly instantaneous.

Simple stimuli and auditory selective attention. A recent review of attention literature (Swets & Kristofferson, 1970) has shown that data on auditory selective

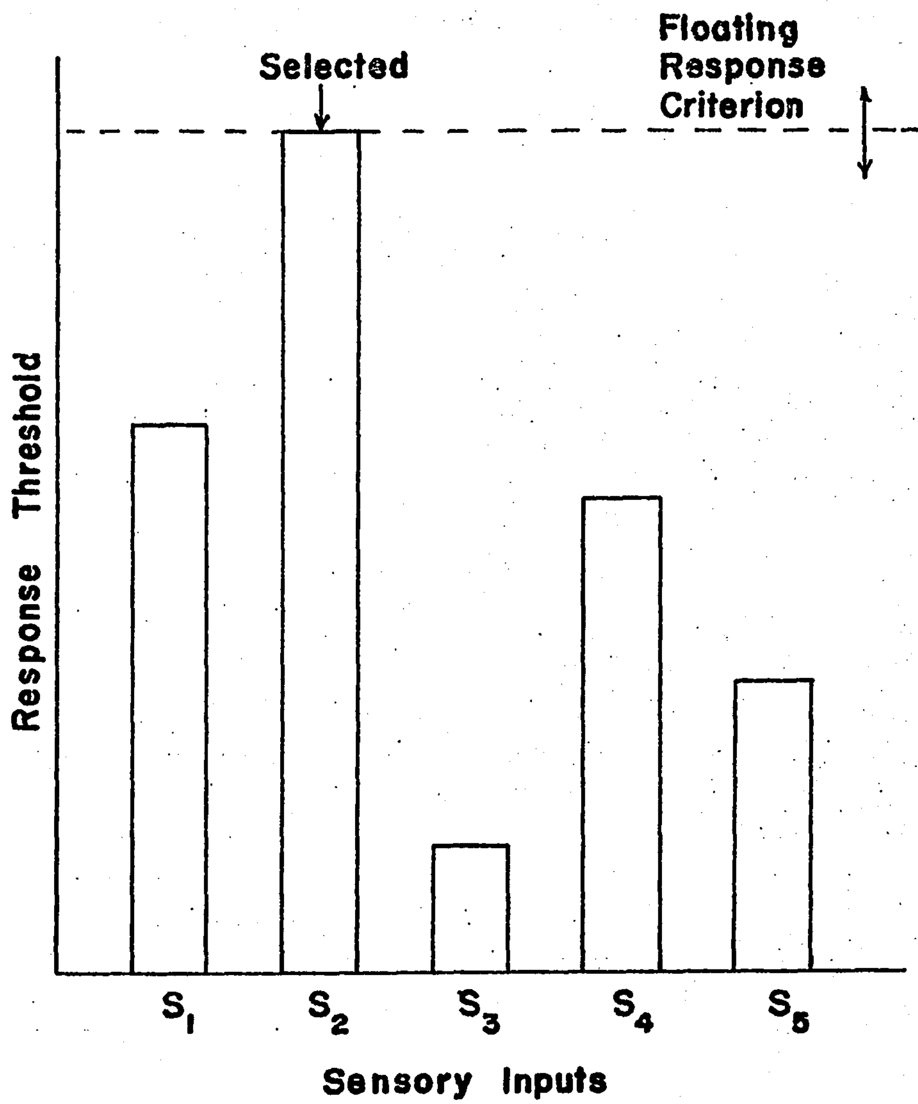

FIGURE 4. Deutsch and Deutsch's Response Selection Theory (after Deutsch and Deutsch, 1963)

attention may be partitioned into two parts; experiments concerning speech stimuli and those concerned with simple stimuli (i.e., sinusoids). Experiments using speech stimuli are extensive and the previously discussed theories of attention depend heavily upon these results. In addition, the studies of selective attention using simple stimuli are concerned with two types of experimental paradigms; viz., the Uncertain Frequency (UF) and the Multicomponent Signal (MS) paradigms. Moreover, the most frequently cited theoretical models of selective attention, based on simple stimuli, are those which are derived from signal detection experiments and depend in some manner upon the Critical Band (CB) concept of Fletcher (1940). Consequently, a brief review of the CB idea and the associated data is necessary and will precede the discussion of simple stimuli and the two prominent selective attention models currently extant in the literature.

Critical Bands

The ability of the auditory system to analyze complex sound into its components has been a central area of concern since the 19th century. It was explored in the work of Ohm, which culminated in the formation of Ohm's Psychoacoustic Law, which states that the ear is capable of analyzing sound in a Fourier manner. Helmholtz, in 1863, developed an influencial theory on hearing based on Ohm's

Psychoacoustic Law. He hypothesized a mechanism which could perform a frequency analysis on the periodic waveforms. Furthermore, masking experiments produced evidence for the concept of a limited frequency analyzer in the ear along the lines of Ohm's Psychoacoustic Law (Plomp, 1964; Soderquist, 1970). Several years after Helmholtz had outlined his theory, Mayer (1876) reported that masking of pure tones was non-symmetrical (low frequency signals mask higher frequency signals easier than higher frequency signals mask low frequency ones). However, it was not until 1924 when Wegel and Lane (1924) produced quantitative results with respect to pure tone masking, that these latter experimenters confirmed Mayer's earlier qualitative results. Concomitantly, they found that masking occurred primarily near the frequency of the signal. These results were not of great interest to auditory workers until Fletcher (1940) investigated the extent of masking using a sinusoid as a signal and wideband noise as the masker. He found that decreasing the noise bandwidth symmetrically around the sinusoidal signal would produce no effect on signal detectability until a critical band width was reached. After reaching this critical width, further decreases in the noise bandwidth were accompanied by increases in signal detectability. Fletcher argued that his experiment showed that the effective masker for a specific sinusoidal signal was solely the noise energy within a critical frequency range centered at the signal frequency. This frequency range is what Fletcher called a "critical band." He also found that the CBs varied in size dependent upon the signal frequency (the higher the frequency, the larger the critical bandwidth). Much work has been done in the field of CBs since Fletcher's effort. An excellent review is presented by Scharf (1970). The most acceptable estimates of the CBs are found in an article by Zwicker (1961).

As reviewed by Scharf (1970), CB investigations have shown that stimulus parameters other than signal frequency may affect the size of the CB. Recently, debate has developed concerning a variable or adjustable CB (Green, 1960; Jeffress, 1964; Sorkin, Pastore, & Gilliom, 1968; Swets, 1963; van den Brink, 1964). These later studies, consequently, brought a new direction to the study of auditory frequency analysis; i.e., the study of attentional control of peripheral mechanisms (CBs) which presumably underlie auditory frequency analysis (i.e., the ability to analyze or select parts from a stimulus waveform). This attentional control could be hypothesized to be either a response selection or a sensory selection type of theory. In light of physiological experiments in selective attention (Galambos, 1956; Hernandez-Peon, Jouvet, & Scherrer, 1957) which show a suppression of sensory neural activity at the cochlear nucleus, or at the peripheral organ itself (via Rasmussen's tract), it seems that the attentional control could easily be sensory in function.

The argument for adjustable CBs has been advanced due to the results of recent research. The first supporting data have been reported by experimenters who have used TSD to demonstrate that human Ss use relevant information about the stimulus parameters to approach a theoretical ideal level of performance (Swets, 1961; Tanner & Swets, 1954; Swets & Sewall, 1961). Closely related to these findings were the results showing that the S may be able to adjust the size of his CB to reflect the probability characteristics of signal presentation (Sorkin, Pastore, Gilliom, 1968; Schulman & Greenberg, 1960; Markowitz & Swets, 1967). In these experiments, it was found that Ss would attain detectability scores reflecting the probability of stimulus presentation in an uncertain frequency paradigm (i.e., the S does not know which of two or more signals is to be presented on any one trial). However, when the probabilities of signal presentation were changed, the detectability scores of the Ss changed in the same manner [i.e., when stimulus probability was changed from 50-50 (probability is .50 that a signal will occur) to 70-30 (probability of a signal is .70), the detecability of the signals changed from equal detectabilities to those of approximately 70%]. This may possibly be interpreted as a "cognitive" or response selection type of selective attention.

Another aspect of recent research which indicated attentional factors in frequency analysis was the inability of data to consistently confirm either of the two models of auditory selective attention hypothesized to account for the data. The failure to confirm either of the two models (single-band or multi-band) forced experimenters into a tentative conclusion that the auditory system was able to function under either or both of the two modes of processing [i.e., selecting the method (model) most suitable to the contingencies of a specific experiment]. It is important, therefore, to delve into the description of these two models and discuss research aimed at differentiating between them.

Models of Auditory Selective Attention

In 1963 Swets presented a description of the two competing models of auditory selective attention and a review of empirical evidence up to that time. Swets' conclusion was that both models were partially supported. A more recent review (Swets & Kristofferson, 1970) presented the same two theories with further empirical evidence for both views, but again no convincing data were found to determine which theory explained the data more accurately. A brief overview of these two theories and their data are discussed below.

Single-band Scanning Model

The first model of auditory selective attention to be discussed is called the single-band scanning model which was introduced by Tanner, Swets, and Green (1956). This model assumes the basic tenets of the CB concept; viz., that the ear is sensitive to energy within a limited frequency range for any given signal frequency. This model, however, also assumes that the center frequency of the CB is under intelligent (i.e., deliberate) control and that the center frequency may be changed by sweeping it through intervening frequencies to a new and different CB having a different center frequency. Therefore, if a measure could be made of the time required to change center frequencies one would expect increases in time as a function of the frequency separation between the centers of the CBs. This model follows the earlier discussion concerning Broadbent's single channel theory of attention and Moray's time-sharing theory, if switching time is not instantaneous.

The single-band model, then, assumes that there is a summation of energy within each critical band and the signal to noise ratio (S/N) within the attended CB determines a _S_'s report. Assuming that some time factor is involved in switching from one CB to another, it is apparent that if two signals were simultaneously presented, each within non-overlapping CBs, the duration of the signals must exceed the switching time if both signals are to be detected. Recent experimentation (Kristofferson, 1967a, 1967b) has shown that this switching time may be extremely fast (from 0 to 50 msec.). These short switching time estimates (short relative to Broadbent's original estimate) suggest that the duration of the signal is an important parameter. The basic premise, however, of the single-band model is that at any one time only one CB is monitored and signal detectability is dependent upon the S/N within the CB.

Multi-band Model

The second theory of auditory selective attention was developed by Green (1958) and called the multi-band model. This model also assumed the basic tenets of the CB concept; but in addition, the multi-band model assumes that a S can combine linearly the energy of several CBs simultaneously. The detectability of the signal, then, is assumed to be based upon the summated S/N ratio of several CBs. Just as Broadbent't theory seemed to foreshadow the single-band model, the multi-band model parallels the theories of Treisman (Treisman, 1964, 1967, 1969; Treisman & Geffen, 1967) and the Deutsches (Deutsch & Deutsch, 1963). Green's (1958) model states that there is a summation of all the energy produced by the CBs being monitored, and the total S/N ratio will determine whether a S detects a signal. This, then, is an energy summation model, just as is the single-band model; however, in the multi-band model the energy summation extends over the several CBs rather than a single CB. It should also be clearly noted that the multi-band model does not require a switching time in order to monitor more than one CB; hence, the duration of the signals are of little importance in the multi-band model.

Support for the Two Models

Many attempts have been made to differentiate between the two models. Some data favor one model; whereas, data favoring the other model are also abundant. As mentioned previously, the two paradigms used to study selective attention with simple stimuli are the Uncertain Frequency (UF) and the Multicomponent Signal (MS) paradigms. These experimental paradigms and the resulting data have been reviewed extensively in two recent publications and thus will only be briefly summarized here (Swets & Kristofferson, 1970; Gilliom, 1971).

Uncertain frequency paradigm. In the UF paradigm, the S is to detect one of two or more specified frequencies (sinusoidal signals) in a noise background. When there are only two specified frequencies, the signal may be presented on various occurrence schedules (signal probabilities); for example, the signal may be presented on half the trials ($p = .5$). Furthermore, when a signal occurs, the probability is .5 that it is one of two frequencies. If the frequency separation between the two possible signals is small enough to place both "within" one CB, the predictions of both models would be equivalent. Swets, Shipley, McKey, and Green (1959) and Green and Swets (1966, pp. 283-291) have described methods for making quantitative differential predictions between the two models. The single-band model would predict performance in a UF paradigm by the following formula:

$$d'_c = (d'_i)(1/n_{cb}) + \left[(n_{cb} - 1)/n_{cb}\right](d'_{cb}) \qquad (1)$$

where d'_c is the detectability when there are n possible frequencies, d'_i is the detectability (assuming all possible signals are equally detectable) of a signal under conditions when the frequency of the signal is known, d'_{cb} is the chance detectability of a signal in a non-monitored CB, and n_{cb} is the number of CBs in which the signals fall. In this formula, (again assuming that all signals are equally detectable) it can be seen that the detectability of a signal under uncertain conditions d'_c (i.e., any one of several signals falling in different CBs may occur on any one trial), would be less than the detectability for a known signal presentation, d'_i. This formula simply follows the basic tenet of the single-band model; namely, that one CB is monitored at a time and the probability of any particular CB being monitored is $1/n_{cb}$. Further, the single-band model assumes that the probability of a signal occurring in an unmonitored CB is $(n_{cb}-1)/n_{cb}$ at any instant. Thus, the detectability of a signal at any instant in time, in any one of the "non-attended" CBs, would be at chance level ($d' = 0$). This reduces formula 1 to:

$$d'_c = (d'_i)(1/n_{cb}) \qquad (2)$$

In turn this yields the maximum detectability a S could obtain in a UF paradigm if the single-band model is correct and he can monitor only one CB on any one trial.

The multi-band model, on the other hand, would predict performance in a UF task as follows:

$$d'_c = d'_i \; / \; \sqrt{n_{cb}} \qquad (3)$$

where d'_c is the detectability when there are n possible frequencies, d'_i is the detectability of any one component sinusoid (once again assuming that all component sinusoids are equally detectable), and n_{cb} is the number of CBs being monitored. In this formula, it can be seen that d'_c is again <u>less</u> than d'_i when more than one CB is monitored. Thus, both models predict a decrement in performance under uncertain frequency conditions (when compared to the situation where a signal is a known frequency and when the frequency separation between the component sinusoids exceeds one CB).

The predictions of both formulae 2 and 3 are in the same direction (a decline) but the theoretical assumptions are different and the <u>amount</u> of decline is different. The multi-band model states that the decrement in detectability is due to a linear summation of the noise energy in <u>all</u> the CBs monitored. That is, there is an increase in noise due to the linear summation of two or more CBs. However, there is only one signal, so the S/N ratio decreases. This lower S/N ratio would be reflected in the <u>S</u>'s performance by a decrease in detectability. However, the lowered performance using the multi-band model explanation would not be affected by switching time as the single-band model would be.

In the single-band model, it is assumed that only one CB is monitored on any one trial; or, if a S attempts to monitor more than one CB, there is a switching time introduced which may prevent the S from increasing his performance. If the switching time is longer than the signal duration, the S obviously cannot shift from one CB to another and increase his detection rate. However, if the switching time is short, relative to the signal, then it may be possible to increase performance (detectability) by rapid switching between (or among) CBs. This latter possibility is one of the factors which makes the differentiation between the two models difficult. The multi-band predicts (formula 3) a decrement in detection just as the single-band model does (formula 2). However, the multi-band model predicts a smaller decrease than the single-band model. Thus, if data appear to support the multi-band model, the single-band theory is in no trouble because a single-band theorist simply invokes the assumption of a short switching time and states that the S could monitor several CBs and thus increase his performance accordingly. Hence, it is evident that switching time and signal duration are important factors in terms of differentiating the models under UF conditions if one is to differentiate between the two models.

<u>Multicomponent signal paradigm.</u> In the MS paradigm, the <u>S</u> is to detect the presence of a complex signal embedded in a whitenoise background. A complex signal is defined as any soundwave containing more than one sinusoidal component of different frequency. When the component sinusoids all lie within one CB, both models again predict the same result, an energy summation. However, as the frequency separation between component sinusoids exceeds the width of the CB, the single-band model predicts that, at a specific instant in time, detectability of the MS signal will be no better than the most detectable signal in the complex. In contrast, the multi-band model predicts that detectability will be a linear energy summation of the CBs involved.

The formulae for predicting results between the single- and multi-band models in experiments using the MS paradigm are based upon the same assumptions as those for experiments using the UF paradigm (Green & Swets, 1966, pp. 283-291; Swets, et al., 1959). The single-band model states that the components "within" one CB may be processed at any one time and the energy "within" that CB will be linearly summated. The sinusoids "within" the attended CB would be summated linearly to produce the formula:

$$d'_c = (\sum d'^{\,2}_{cb})^{\frac{1}{2}} \qquad (4)$$

where d'_c is the detectability of the complex signal, d'_{cb} is the detectability of each sinusoid (assuming that each sinusoid is equally detectable) "within" the monitored CB when the signal is a single known sinusoid. An example of this prediction is in Appendix A. Since the MS paradigm assumes that all component sinusoids occur simultaneously, there is no adjustment for probability of occurrence of a signal in any one CB as there is in the UF paradigm. Therefore, formula 4 predicts an <u>increase</u> in detectability, if there are more than one component sinusoid in a CB. In the single-band model, there is an even larger <u>increase</u> in detectability above the predicted value, if the signal duration is sufficiently long so as to allow switching between monitored bands. Note, however, that if each signal in the Multicomponent Stimulus is within <u>different</u> CBs (not overlapping) and signal duration is extremely short, then, the model would predict that detectability of the MS would be no better than the detectability of the <u>most</u> detectable single component. That is, since the single-band model assumes that only one CB can be monitored (attended) at any single instant in time, and if the signal is extremely short or the switching time very long, the <u>S</u> will be able to monitor only one CB per trial; hence, detectability will be the same as the most detectable component.

The formula to predict performance in a MS task using the multi-band model would be:

$$d'_c = \left(\sum d'^2_i \right)^{\frac{1}{2}} \qquad (5)$$

where d'_c is the detectability of the complex signal, and d'_i is the detectability of each component sinusoid (assuming that each sinusoid is equally detectable) of the complex signal when the sinusoid is to be presented singly. This formula then is a linear energy summation of all component sinusoids of the complex signal and the accompanying noise. Both predictive formulae indicate an increase in detectability greater than that of a single component sinusoid. The multi-band model predicts an increase because it is monitoring all CBs constantly, thereby additional component signals will produce an increase in the S/N ratio and in turn produce an increase in detectability. The single-band model, on the other hand, is monitoring one CB at any instant in time and therefore would only summate the signals "within" one CB and detectability would increase only in relation to the S/N ratio of one CB. The single-band model assumes that only one CB is monitored because of either a long dwell time or a long switching time relative to the duration of the signal. However, if this assumption is invalid, then the single-band model can predict an increase in detectability commensurate with that of the multi-band model. If the assumptions of the single-band model are correct, the difference in predicted d' between the two models could be substantial enough to aid in determining which of the models better reflects auditory selective attention.

In summary, the experiments in these two areas have shown results which both support as well as refute the two models. Perhaps this conflict is due to differing experimental conditions in the various experiments; e.g., response criteria, signal intensity, undetected individuality in S response criteria, and signal duration (Creelman, 1960; Gässler, 1954; Green, 1968, 1961; Green, McKey & Licklider, 1959; Marill, 1956; Schafer & Gales, 1949; Swets, 1963; Swets & Sewall, 1961; Swets, Shipley, McKey, & Green, 1956; Veniar, 1958a, 1958b). Furthermore, a major problem in the research has been the inconsistency within individual experiments. In an attempt to distinguish between the two models, one must evaluate the data among experiments as well as within individual studies and the evaluation must be done by using the prediction formulae and the associated assumptions of the two models.

Experimental Background. By using the single-band and multi-band differential prediction formulae for asymptotic levels of performance, several conflicting results appear which will be reviewed at this point. In Tanner, Swets, and Green's (1956) original work, three of their four Ss were consistent with single-band predictions, while the fourth followed predictions of the multi-band model. Swets, Shipley, McKey, and Green (1959) also show conflicting results when only two of their three Ss followed the single-band prediction. Veniar (1958a, 1958b) showed similar conflicts but to even a greater degree. In a UF experiment, she showed one S to be superior to a second S in detecting a sinusoidal signal of an unknown frequency. However, in a MS detection task the second S was superior to the first. This again showed one S operating within the realm of the single-band prediction and the other consistent with the multi-band prediction. Green (1961) found even more perplexing results. When detectability was studied with extreme uncertainty (i.e., the signal could be any frequency between 500 and 4,000 HZ), he found a smaller decrement than predicted by either model.

The results of experiments using the MS paradigm have been even more obscure because the qualitative results, once again, do not consistently confirm one or the other model. Schafer and Gales (1949) while studying the detectability of complex signals, composed of two, four, and eight component sinusoids, found that detection of the complex signal would increase with the addition of more sinusoidal components. All the components used in this study had frequencies which separated the sinusoids by more than 2 CBs. Gassler (1954), also using a MS paradigm, presented signals composed of varying numbers of component sinusoids spaced at intervals of 20 Hz. This means that he deliberately began with signals contained "within" a CB and added component sinusoids until the CB was exceeded. His results showed that the energy required for signal detection remained constant so long as the component sinusoids were all confined to a single CB. Further addition of signal components, making the complex signal exceed a single CB, indicated that the energy required to maintain the same signal detectability had to increase. This result is in disagreement with the earlier study by Schafer and Gales (1949), but does agree with the single-band model in that there is an energy summation for the signal within one critical bandwidth and not when there are large frequency separations. Marill (1956) modified Gässler's technique by using only two components but varying the frequency separation for his complex signal. The results were consistent with Gassler's, showing a complete energy summation with small frequency separations, while detectability of the pair of sinusoids with a frequency separation of 600 Hz (i.e., 500 to 1100 Hz) was no better than the most detectable member of the pair. In contrast to the Marill (1956) and Gässler (1954) studies, two studies by Green and his colleagues (Green, 1958; Green, McKey, & Licklider, 1959) are consistent with the earlier study by Schafer and Gales (1949) and support the multiband model. In the first experiment, Green (1958) found that the complex signal (composed of two sinusoids) was more detectable than either member sinusoid. This proved to be the case in fifty-three out of fifty-four possible combinations of frequency and duration used in the experiment, including separations up to 1500 Hz, a separation exceeding the CB in the experiment. The second study (Green, McKey, &

Licklider, 1959) was designed specifically to force a difference in the predictions of the single-band and multi-band models. The experimenters matched the first sixteen harmonics of 250 Hz for level of detectability, and used these as the components for a complex signal. Green and his colleagues used formulae 4 and 5, described earlier, to predict the detectability for each model. Since d' is roughly proportional to signal energy, the complex signal's detectability could be converted to signal energy. This in turn can be used in a ratio of d'_c/d'_i, assuming that the component signals are all equally detectable, to determine the ratio of signal detectability of the complex signal to detectability of a single component. They found almost an exact 6 dB improvement as predicted by the multi-band model. However, the formation of the signal and the analysis of the data assumed that none of the harmonics used fell within the same CB. At the higher frequencies, this view is doubtful especially in view of the Zwicker (1961) estimates of critical bandwidth. The larger CBs at the higher frequencies may include more than one of the components and thus could also explain the 6 dB improvement in performance. This would salvage the single-band model because it could predict a higher detection level due to energy summation "within" a single bandwidth in the higher frequencies. This contradictory and confusing state of affairs for a central point in psychoacoustics seems to be the present situation.

In summary, as can be seen in the above discussion, a real differentiation between a single-band and a multi-band model of selective attention has not been completely delineated. The most convincing arguments perhaps favor the multi-band model of selective attention as the better predictor, although this conclusion is tenuous at best (Green, 1958; Green, McKey, & Licklider, 1959).

Recent Theory and Data

As noted previously, Moray (1969, 1970a, 1970b) has proposed that attention is an all-or-nothing switching mechanism. This theory, you will recall, is essentially a reintroduction of Broadbent's single channel theory and the single-band switching model of selective attention. Moray's theoretical view supposedly explains the fate of "nonattended" signals by assuming that those which are attended are the only ones causing effects. As has been discussed earlier, Moray's view is not the only possible position. Treisman (Treisman, 1964, 1967, 1969; Treisman & Geffen, 1967) and the Deutsches (1963) believe that shadowing experiments show some "nonattended" inputs do get through to cause effects. To explain the ability to analyze "nonattended" stimuli, the single channel advocates (Broadbent, 1958, 1971; Moray, 1969) state that there may be some switching during an attentional task and thereby some sampling of the "nonattended" channels. If this switching concept is correct, the multi-band model of auditory selective attention may be in difficulty because single channel theory could then explain the detection of more than one signal in the shadowing experiments noted above.

Tulving and Lindsay (1967) have supported the all-or-nothing hypothesis (Moray's theory) in attentional mechanisms using simple stimuli rather than the usual speech stimuli. They showed that when presented simultaneously, simple visual and auditory stimuli could not be attended or responded to simultaneously. They concluded that attention may possibly be an all-or-nothing process with extremely fast switching time, perhaps instantaneously. This experiment, even though using simple stimuli, may have produced a complex situation by using two sensory modalities (i.e., attention may only be focused on one sensory modality at a time; however, within a sensory modality more than one signal may be monitored). If the results from the Tulving and Lindsay (1967) experiment held true within a single sensory modality then the multi-band model of selective attention would possibly be in jeopardy.

The issue of all or none switching between channels has been examined recently by Moray (1969, 1970a, 1970b). He studied the ability of observers to detect a signal presented in either ear or both ears simultaneously. If the signal were presented to the right ear, the S would press the "right" button; if to the left, the "left" button; and if to both ears, the "both" button. In these experiments, the S was tested under four conditions: first, he was to respond to the signal, while the signal was presented to one ear and the second ear received no signal; second, he was to respond to the signal only if it occurred in one ear but not the other (signals in this condition may randomly be presented to either ear); third, he was to respond correctly to the signal (i.e., if the signal were presented in the right ear, respond by pressing the "right" button and if presented to the left ear, press the "left" button) and no signals would be presented simultaneously to both ears; fourth, he was to respond correctly to the signal once again except in this condition the signals could be presented simultaneously in both ears as well as the left or right ear singly (See Appendix B for an outline of Moray's paradigms). The signals used were intensity increments in a train of pulses of 3000 Hz to one ear and 2100 Hz to the other ear. His results (Moray, 1970a) showed a dramatic decline in detectability from condition 1 when the task was to detect the signal while monitoring both ears (conditions 3 and 4 cited above). This result, Moray argued, showed attention working on an all-or-nothing basis and that attempts to listen to two channels (ears) simultaneously causes a decrement in performance. He (Moray, 1970b) then performed the same experiment, but varied the signal duration, finding that the longer the signal duration, the more detectable the signal in a two channel monitoring task. This, he argued, was further evidence for an all-or-nothing switching hypothesis (single-band model), because the more time given to sample both channels the easier it would be to detect a signal. In contrast, Sorkin and Pastore (1971) differed with Moray (1970a, 1970b) when they performed a similar experiment using a single frequency (500 Hz) rather than a different tone for each ear. They found that when the signal was of the same frequency for both ears, "no apparent decrement in sensitivity exists when the observer must simultaneously monitor both channels ..." when compared to monitoring signals in one channel (Sorkin & Pastore, 1971). Extending their previous experiment, Pastore and Sorkin found that observers could perform a simultaneous two-channel detection task with no decrement in performance (sensitivity) while the signals were in phase but showed a decrement when the signals were out of phase (Pastore & Sorkin, 1972; Sorkin, Pastore, & Pohlman, 1972). These latter experimenters believed the decrease to be due to cross-channel masking rather than a limitation imposed by processing capacity.

M. Treisman (1972) also differed with Moray as to the time-sharing (or switching) aspects of attention. Treisman used portions of Moray's (1970a, 1970b) data to illustrate, using probability statistics and TSD methods, how the data could be analyzed differently (See Appendix C for a more detailed description of Treisman's analysis). Treisman wished to critically examine whether Moray's data did in fact provide unambiguous evidence for a "slow" (relative to "instantaneous") switching mechanism or whether the results could be more simply explained in terms of established processes (Treisman, 1972). The "established processes" which Treisman mentioned is in reference to acknowledged results of _simultaneous processing_ (analogous to multi-band model) provided by auditory localization and masking-level difference experimentation. More specifically, Treisman inferred that Moray's results could be attributed to the use of an heretofore unrecognized response criterion. Examining the data from Moray's (1970a, 1970b) fourth condition, (i.e., the _S_ knows the signal could be in the left ear, right ear, or both and is instructed to respond accordingly). Treisman (1972) indicated that there was an explanation other than the single channel switching hypothesis (time-sharing). He stated that there was an inferred postulate in Moray's explanation which was not supported. This postulate, Treisman explained, was that the _S_ maintains a single criterion for each ear, regardless of the mode of signal presentation (single criterion model). Furthermore Treisman (1972) hypothesized that it was possible to have another criterion in addition to that assumed by Moray. This combination of two criteria was called the double criterion model. Using TSD concepts, Treisman showed that the double criterion model could predict the outcome of Moray's data (See Appendix C for detailed explanation). However, Treisman could not empirically support his hypothesis because false alarm data were not available from Moray's original studies (Moray, 1970a, 1970b). Nevertheless, Treisman (using a hypothetical situation) showed that the <u>false alarm rates</u> would be practically identical when <u>S</u>s adopted a double criterion rather than a single criterion in the detection task. Moreover, when <u>S</u>s adopt the double criterion the decrease in the detection of "both" signals disappears. That is, the decrease in detectability of two simultaneously presented signals, each from independent channels, is due to the mode of responding rather than to a loss of information due to "slow channel switching." Treisman (1972) has, then, theorized that a decrement in performance may be due to the use of two (double) criteria when both channels are to be monitored and the data from Moray's (1970a, 1970b) experiments are interpretable in more than one manner. Moray's interpretation supports the single-band model and Treisman's suggestion is that a double criterion also explains the data. It should be noted that Treisman explicitly assumes a multi-band signal processing model. The analysis by M. Treisman, thus may prove to be a valuable tactic in discriminating between single-band and multi-band attentional processes or models.

The Problem

Immediate Background

The evidence presented earlier leads to the conclusion that auditory inputs may be under attentional influences. The two models outlined to account for the attentional influences were the single-band and the multi-band models. These models seem to parallel the two theoretical viewpoints of attention theory, viz., the single channel switching theory and the multi-channel theory.

A further concern in the area has recently been elucidated by McFadden (1970). He has shown that there are three ways to calculate the percentage correct (P/C) in a two alternative forced choice (2AFC) paradigm. In his theoretical paper, he illustrated how some of the procedures used to calculate P/C may include a response bias. In his explanation, he also illustrated the effect a response bias would have on the detectability index (P/C). Since many of the earlier studies cited above may have estimated P/C with different calculation procedures, there may have been some slight inaccuracies in the estimates involved in testing between the two auditory selective attention models. McFadden's conclusions, together with Treisman's (1972) view of response bias (the double criterion model), then, may also help explain why predictive formulae have not accurately accounted for the obtained data.

Another important consideration for any experimentation in the area of attentional processes has been previously noted, viz., the duration of the signal. Data relevant to this point have been reported by Doughty and Garner (1947). These investigators have determined that in order for a sinusoid to have a definite "tone," the signal must be at least 10.2 msec in duration. However, their study was not designed to investigate the possibility that the response criterion used for "tonal quality" was the same as the response criterion used when the <u>S</u> is required to differentiate between two different tones. For example, a 1000 Hz tone of 10.2 msec. can easily be differentiated from a 1500 Hz tone of the same duration. Hence, it appears that the temporal duration required to differentiate between two signals having different spectral components is <u>less</u> than 10.2 msec. It is clear that a <u>S</u> need not "dwell" on a signal the full 10.2 msec. in order to obtain enough information to differentiate it from a signal having a different spectral composition. The importance of this point comes into clear focus when one considers the MS paradigm used to test the two models of selective attention (single- and multi-band models). Under the single-band concept, if two signals were separated by more than a CB and presented simultaneously (the MS paradigm) there would be (theoretically) no time available for the <u>S</u> to switch from one CB to the other and thus detect both signals, <u>if the single duration were short enough</u>. Under the single-band model the entire signal duration would be required by the S in order for him to recognize and/or detect just one of the two signals. In summary, if signal duration were too short the S could not detect/recognize both signals because the entire signal duration would be required for the detection of just one tone. If this were the case, the single-band model would predict not an increase in detectability, as suggested by the formula (formula 4, p. 23) but a detection rate equivalent to the detection of a single known signal. In contrast, the multi-band model would predict an increase (formula 5, p. 24) because both signals (critical bands) were monitored. This would cause an increase in the S/N ratio and an increase in the detectability.

In conclusion, if the signal duration were short enough, it is possible that a distinction may be obtained between the predictions of the single-band and multi-band models. The single-band model would predict no increase in detectability over that of the most detectable component; whereas, the multi-band model would predict an increase in detectability over the most detectable component.

Preliminary Investigation

As implied above, it is important that the duration of the signal be carefully controlled. Furthermore, some quantitative data are necessary to substantiate the logical use of short duration signals in selective attention paradigms. In this respect, two experiments were performed to determine the signal duration required to recognize the difference between two equally detectable suprathreshold signals having different frequency composition (Soderquist & Harris, 1973). Since the investigation was germane to the proposed experiments concerning selective attention, a brief summary is included here.

In the first experiment the stimuli were two gated narrow-band (74 Hz) white noise pulses having a center frequency of either 966 Hz (H) or 713 Hz (L). The characteristics of the two filters are illustrated in Figure 5. The five Ss were instructed to respond to that interval of a 2AFC paradigm which contained the high pitched signal (H). The signals were presented monaurally to the S's right ear at a sensation level of 15 dB (determined for a one msec signal). The 75% detection level determined the threshold for each stimulus (H or L). The signals were presented with an instantaneous rise and decay time (fast setting on the Electronic Switch). A constant background of wideband white noise (40 dB SPL) was presented during the stimulus presentation intervals. The H and L signals were randomly presented in either the 1st or 2nd interval of the 2AFC paradigm. Each S completed 400 trials for each stimulus duration (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 msec). The Ss were tested in a sound-attenuated room. Results showed that

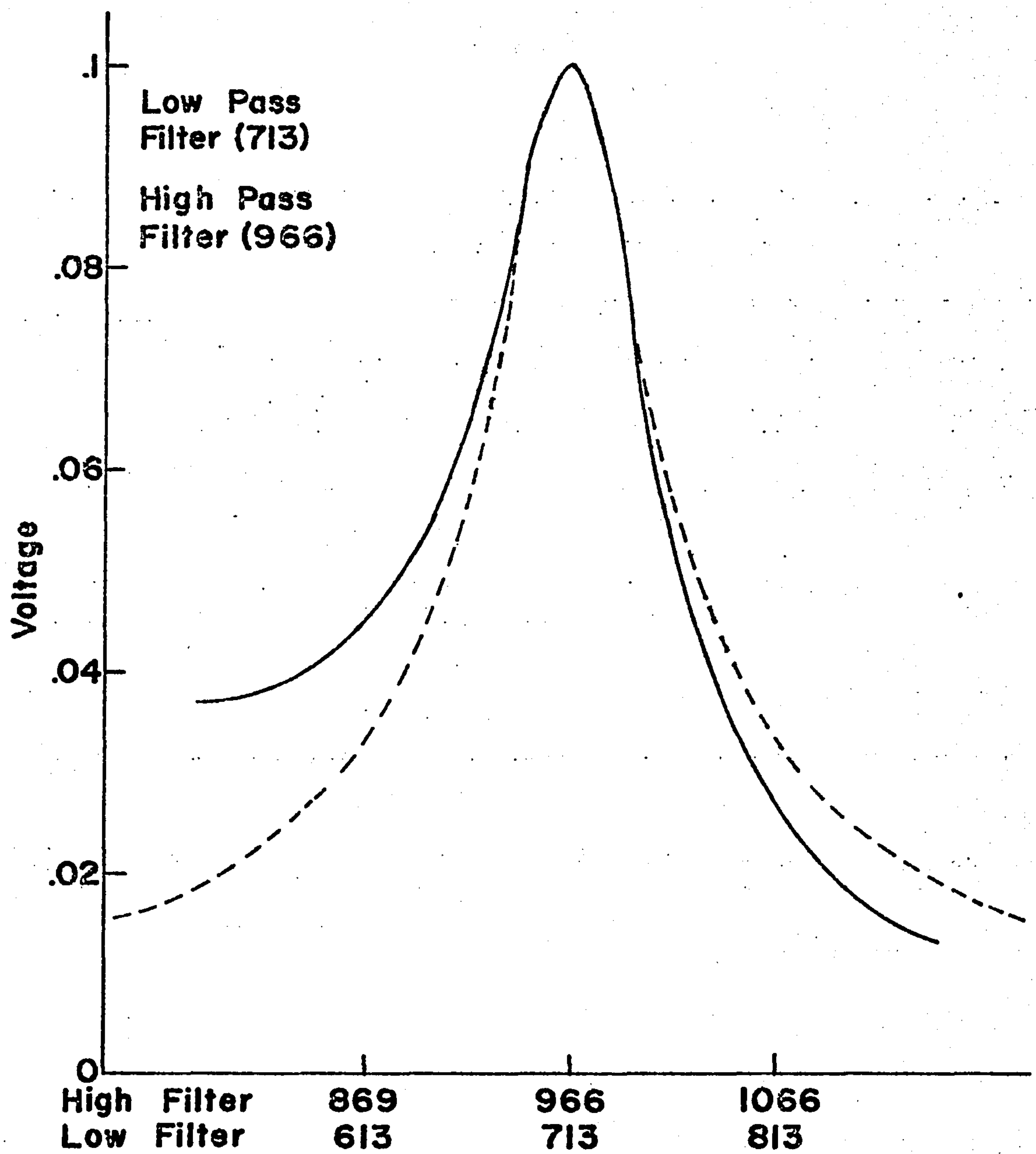

FIGURE 5. Characteristics of the Two Signal Filters

the signal duration to reach a 75% recognition threshold varied slightly from S to S (i.e., from 1.3 to 2.4 msec). A least squares procedure showed the mean recognition threshold to be 1.8 msec (illustrated by the solid line in Figure 6). Since this experiment disregarded the fact that short duration signals have less energy then long duration signals, a second preliminary experiment was performed to control the intensity difference across signal durations.

In this second preliminary experiment stimulus intensity controls were added so that intensity remained the same across all signal durations. In this way, the recognition of the signal could not be ascribed to intensity differences but due purely to the ability to recognize the signal at different durations. Three of the original five Ss participated using the same signals and paradigm as the first experiment. However, in the second preliminary experiment the signal was presented at a sensation level of 15 dB for each stimulus duration (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 msec). In this way, the signal was perceived as equally loud at each duration and the ability to recognize the signal depended on duration alone. Results again showed that the 75% recognition threshold varied slightly from S to S (i.e., from 2.3 to 2.8 msec). A least squares procedure showed the mean recognition threshold to be 2.54 msec (dotted line in Figure 6). The recognition threshold, then, appeared to be a logical place to initiate

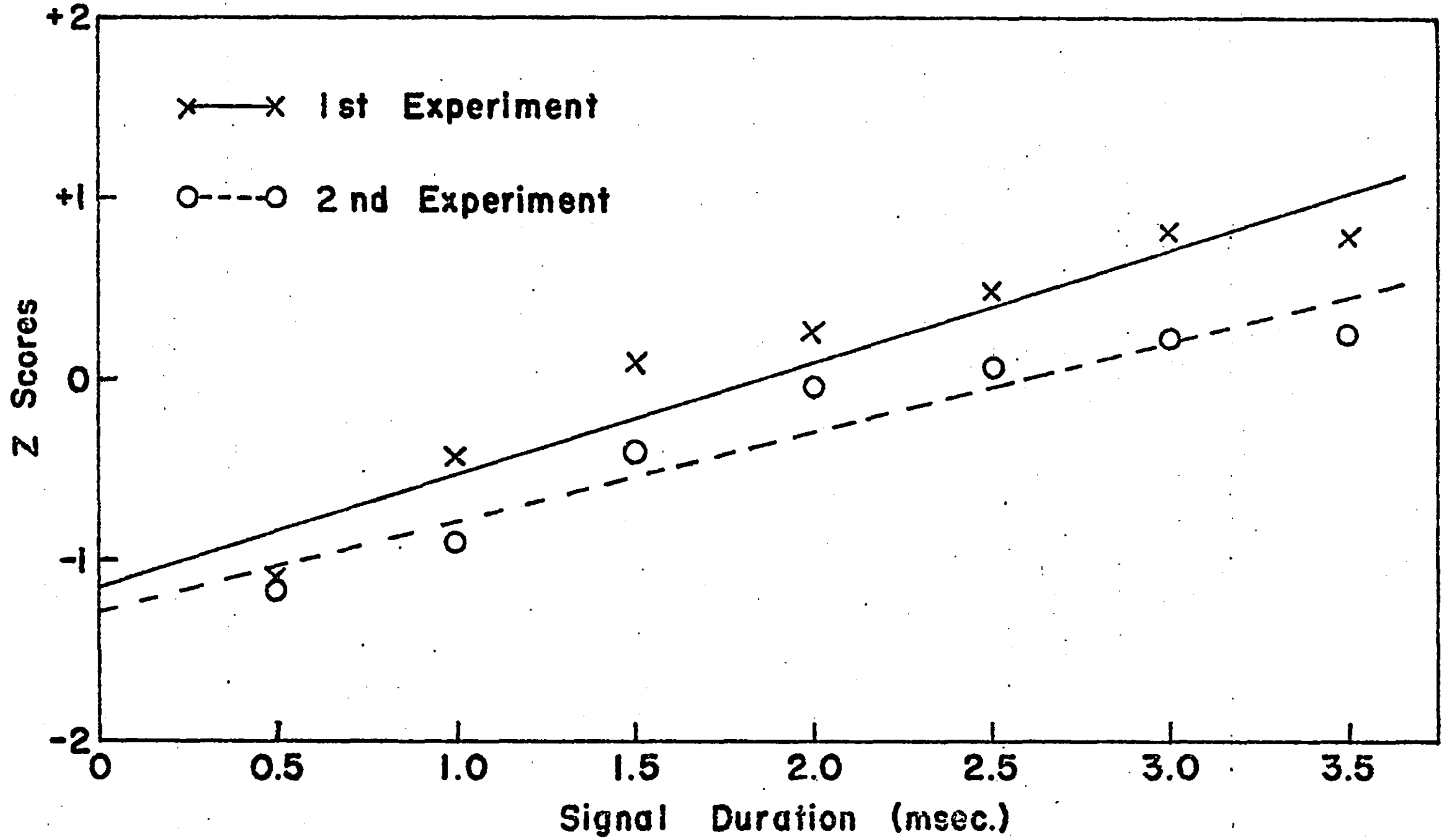

FIGURE 6. A Transformed Best Fit Line Showing the Recognition Threshold Obtained in Preliminary Experiments I and II

further experiments concerning selective attention. That is, for these stimuli, the signals must be presented (on the average) for 2.54 msec before a S can recognize the difference between a "high" and a "low" signal.

Further, these results suggest several implications for the single- and multi-band theories. First, if one assumes that Ss use a multi-band approach to the recognition task, then the S's problem was simply to "pay attention" to both CBs simultaneously (one centered at 713 Hz, the other CB centered at 966 Hz) and contrast the inputs on each trial to determine when the High signal occurred (1st or 2nd interval). Further, since the multi-band model assumes that (a) both CBs are continuously attended and (b) no "switching time" is necessary, it may be postulated that the Temporal Recognition Threshold (TRT) of 2.5 msec reflects the "minimum dwell time" required to differentiate between the two signals 75% of the time. That is, given these data and the multi-band assumptions, it may be inferred that the minimum time required to attend (dwell) on a particular CB, in order to obtain sufficient information to differentiate the two signals, in equal to the TRT. A "dwell time" less than 2.5 msec results is a loss of information and a decrease in performance; whereas, a "dwell time" longer than 2.5 msec increases the amount of information available and increases performance accordingly. In the second instance, if one assumes that the Ss use the single-band model in the recognition task, the TRT represents the <u>maximum</u> dwell time necessary to obtain sufficient information to differentiate the two signals. For example, if during the first interval of the trial, the <u>S</u> is "tuned" to the <u>correct</u> CB (i.e., the 1st interval is, by chance, a High signal <u>and</u> the <u>S</u> is attending to this High CB), then he will obtain the maximum information available from this particular frequency region (CB). Since the <u>S</u> has two CBs to monitor, it is logical to assume that the <u>S</u> will switch to the other CB (the Low frequency region, for example) once sufficient information has been obtained from the initial <u>High</u> CB. Since there are no data which indicate that <u>switching-time</u> (the time needed to switch from one CB to another) requires more than 1.0 sec and several studies which suggest that switching-time is much less than this value (Moray, 1969, 1970a, 1970b; Tulving & Lindsay, 1967), the amount of time required to change from one frequency region (CB) to another is unimportant. The time interval between signal presentations (in the 2AFC task) was greater than 1.0 sec and therefore allowed sufficient time for the <u>S</u> to change CBs and not lose information as a result of a long switching-time. Hence, if the <u>S</u> were <u>always</u> attending to the correct CB at the start of a trial, the TRT would once again represent the minimum "dwell-time" required to recognize one signal from the other. The assumption that the <u>S</u> is <u>always</u> attending to the <u>correct</u> CB at the outset of each trial is, of course, unwarranted since the High and Low signals occurred in either the 1st or 2nd interval on a random schedule and the S had no way of knowing which CB to monitor at the beginning of each trial. Since this was the case, the S would, on the average, be attending to the incorrect CB on half the trials. Further, since the signals are all presented at 15dB SL (second preliminary experiment), it is reasonable to assume that S's attention will be "drawn" to the correct frequency region in those cases when he is initially attending the incorrect CB. Even if switching-time were practically instantaneous, there would be some loss of information before the S could switch and attend to the signal. In this case the 2.5 msec value represents an inflated estimate of dwell-time. Under the single-band model, the reasonable assumption is, then, that the 2.5 msec TRT is an average between the larger estimate of dwell-time (when S is always monitoring the incorrect CB at the start) and the minimum dwell-time (when S is always monitoring the correct CB at trial onset).

In summary, the preliminary experiments allow one to estimate the dwell-time (the minimum period of time that a CB must be attended if one is to obtain sufficient information to differentiate (recognize) these two stimuli 75% of the time) if certain assumptions are made. Under the multiband model the TRT of 2.5 msec represents a minimum dwell-time. The time required to monitor (attend) the CB and still get the necessary information may be less, but very likely is not greater than this estimate. Under the single-band model, the TRT may, once again, be somewhat less than 2.5 msec, but probably is not greater than this value.

CHAPTER II: THE EFFECT OF SIGNAL DURATION ON DETECTABILITY IN A MULTICOMPONENT SIGNAL PARADIGM

Introduction

The following experiment was performed in an attempt to differentiate the single- and multi-band models of auditory selective attention using the earlier determined "dwell-time" as a possible restraining factor. Even though the current experiment is based on recognition relationships, it has been developed from detection paradigms. Furthermore, this experiment, and the previous ones, have defined "dwell-time" in terms of "recognition dwell-time" rather than "detection dwell-time." In short, it is very likely that the time required to recognize a signal (recognition dwell-time) differs from the time required to detect a signal (detection dwell-time). However, even though the "detection" and "recognition" dwell-times very likely are different, the logic underlying the predictions may be derived from the models in the same manner, regardless of whether or not the task is recognition or detection.

The multi-band model predicts that the detectability of a complex or "both" signal (HL) increases as a function of the number of component signals (H or L) at any duration (formula 5). This prediction is made because the multi-band model hypothesizes that all CBs are monitored simultaneously and the total S/N ratio increases with the increased number of signals. However, the single-band model predicts, if the signal duration were equal to or less than the *detection dwell-time*, that only one CB can be monitored at any single period of time and therefore the detectability of the HL signal will equal the most detectable single component signal. Hence, if a *detection dwell-time* is used in a MS paradigm, the two models predict different results. The single-band model predicts a detectability equal to the most detectable component; whereas, the multi-band model predicts an *increase* in detectability of the multicomponent signal. Since, however, switching of bands can occur in the single-band model, there will be a *decrease* in the difference between the single- and multi-band model predictions as the *detection dwell-time* is exceeded by the signal duration. That is, if the signal is long enough, the *S* may monitor several CBs by rapid switching. This will, of course, add signal energy and increase the detectability of the multicomponent signal. In view of these predictions, this initial experiment was done using signal durations which "bracket" the predetermined "recognition dwell-time" of 2.5 msec (0.5, 2.0, and 3.5 msec). The strong possibility that the "recognition dwell-time" and the "detection dwell-time" are not the same, suggests that the results will be the *same under both models*. However, the belief that the times are different is based on logic and extrapolations from related research. Thus, this experiment is necessary to more strongly substantiate this possibility.

Methods

Subjects and Training

Three male Ss, 21 to 39 years, were used in the experiment. All of the Ss had participated in the preliminary experiments. Training was given to the Ss in detection of the signals (H and L) at each duration. During this training the 75% correct detection level for each component signal was determined.

Design

A block diagram of the experimental design is shown in Figure 7. The experiment followed the standard multi-component signal (MS) paradigm with a 2AFC task. The signals were presented at short durations (0.5, 2.0, and 3.5 msec). The component signals were the same signals (H and L) used in the preliminary experimentation on recognition dwell time. These signals were gated narrowband noise pulses each having a 74 Hz bandwidth and a center frequency of 966 Hz (H) and 713 Hz (l). The characteristics of the two signal filters were illustrated in Figure 5. A gated noise background was presented at a spectrum level of 40 dB re: 0.0002 dynes/cm^2 and filtered with a Kron-Hite (model 3100)

Signal Duration	0.5 msec.				2.0 msec.				3.5 msec.			
Signal Condition	H	L	HL_I	HL_D	H	L	HL_I	HL_D	H	L	HL_I	HL_D
S_1												
S_2												
S_3												

FIGURE 7. A Block Diagram of the Experimental Design for Experiment I. H represents a gated narrowband noise pulse having a 74 Hz bandwidth and a center frequency of 966 Hz. L refers to a gated narrow-band noise pulse having a 74 Hz bandwidth and a center frequency of 713 Hz. HL_I represents a combined signal using the above two noise pulses. HL_D is the same combination presented at a lower intensity (equal to the most physically intense single component signal, i.e., H or L).

Bandpass Filter. The settings on the filter were 10 Hz and 6,000 Hz, respectively, at the 3 dB roll-off.

The use of the MS paradigm produced four conditions, the component signal H, the component signal L, and two complex signals (HL_D and HL_I). The normal combination of the two component signals to produce a complex signal yields an increase in signal intensity at the earphone (the HL_I condition). Thus, as a control, another condition was added (the HL_D condition) where the complex signal, HL_D, had an intensity level equal to the most intense single component signal. The independent variables studied in the experiment were the signals (H, L, HL_D, or HL_I) and the duration of the signal presentation (0.5, 2.0, and 3.5 msec). The dependent variable was signal detectability expressed in d' units (cf. Elliot, 1964).

Experimental Sessions and Apparatus

The order of presentation of signal duration was randomly selected for each S. Following the training trials, three experimental sessions were run. A session contained 6 blocks of 100 trials with each block being preceded by about 20 warmup trials. During each daily experimental session, at least one block of each signal was presented. Each block of trials was replicated four times for a total of 400 trials per signal. A rest period of 5 minutes was given between each block of trials. The signal

(H, L, HL_D, or HL_I) that was presented in each individual block of trials was randomly selected.

In each experimental session, the S was seated in a sound-attenuated room before a panel of indicator lights and response keys. A calibrated earphone (Grason-Stadler model TDH49-10Z) mounted in a MX-41/AR muff was placed on the preferred ear. On each trial, the S was instructed to respond by pressing one of the microswitches to indicate his decision regarding in which interval of the 2AFC task the signal occurred. Responses (Hits and Misses) were automatically recorded on electromechanical counters. On each trial, the S was informed by feedback lights whether his response was correct.

The overall timing of the experimental intervals was determined by Lehigh Valley Electronics and Coulbourn Instruments solid state programming equipment. The experimental sequence was as follows: intertrial interval (0 sec.); light for onset of observation interval (0.1 sec.); observation interval A (1.0 sec.); light for midpoint of observation interval (0.1 sec.); observation interval B (1.0 sec.); light for end of observation interval (0.1 sec.); response interval (2.0 sec.); feedback light (0.1 sec.). Each signal was presented at the midpoint of either the first or second observation interval (See Figure 8).

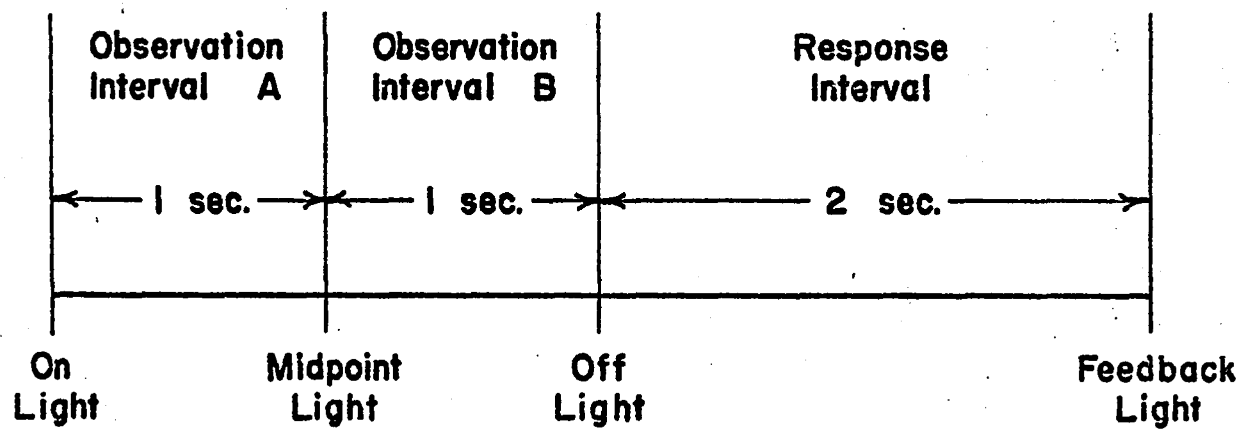

FIGURE 8. A Diagramatic Illustration of a Typical Trial

Each component signal was generated by a Grason-Stadler noise generator and filtered by specially built noise filters with characteristics illustrated earlier. Rise-decay time (fast) was determined by a Grason-Stadler 829-C electronic switch. The signal duration was gated by a Grason-Stadler 471-1 interval timer. The background noise was gated by Lehigh Valley Electronics modular programming equipment. Hewlett-Packard 350-D attentuators controlled the signal and noise intensities. An audio mixer (Calrad model 10-75) was used to mix the component signals to produce the HL_D and HL_I conditions. Measurements of signal and noise level were made at the earphone prior to each experimental session with a Ballantine true RMS voltmeter. Impedance matching was performed antecedent to the earphone with a Grason-Stadler E 10589A impedance matching transformer. The use of Lehigh Valley Electronics modular programming equipment permitted the presentation of the signal in either the 1st or 2nd interval with a probability of 0.50. A figure schematic of the experimental apparatus is presented in Figure 9.

Predictions

The d' units were based on the four replications; consequently, d' values were determined on 400 trials. The d' obtained from each component signal was used in formulae 4 and 5 to predict the d' units for the HL_I signal condition

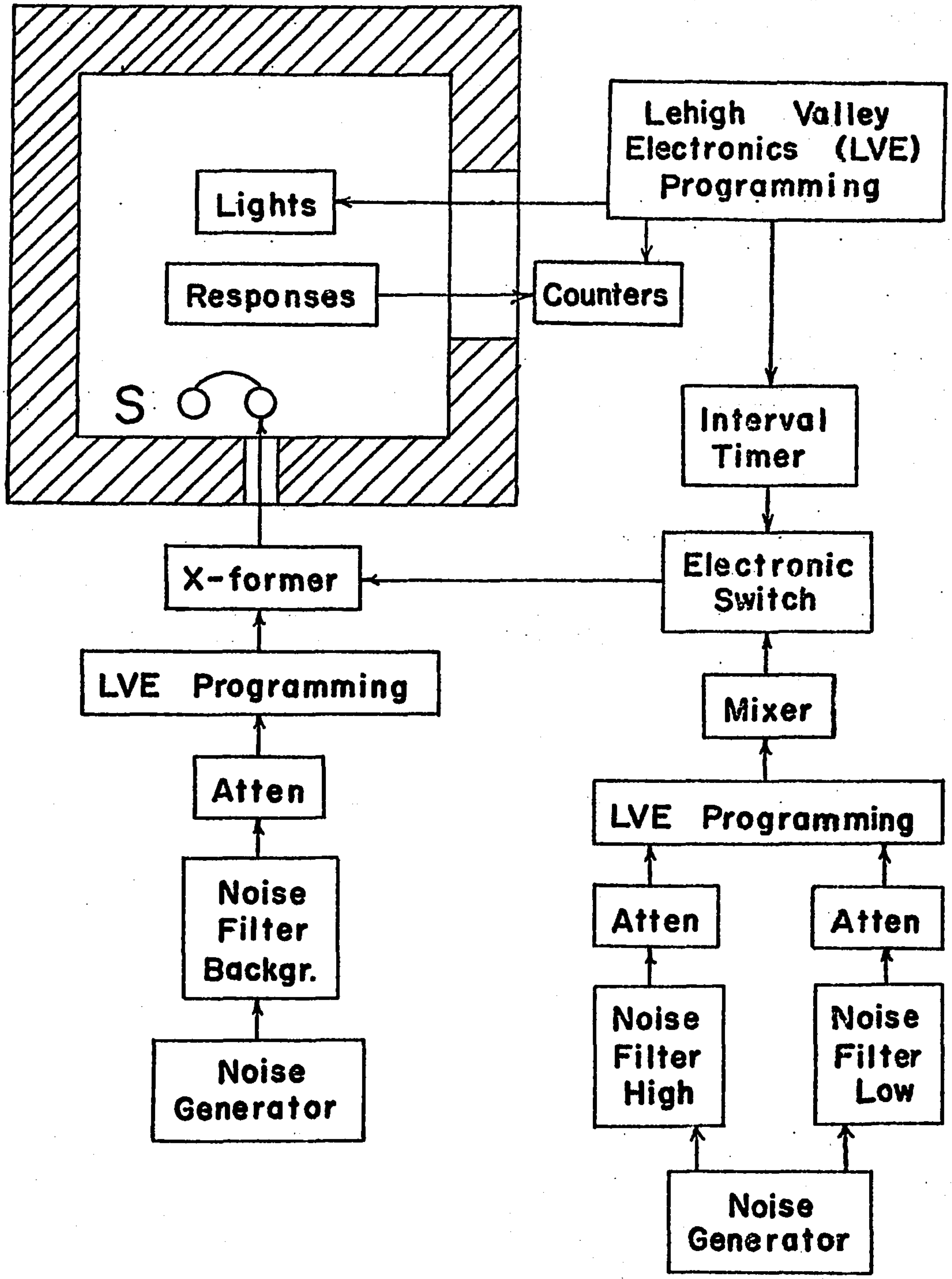

FIGURE 9. Block Diagram of Experimental Apparatus

for each individual S. For the HL_D condition, only a prediction for the Multi-band model could be made.

When the signal is presented at or below the minimum detection dwell-time, there should be a differentiation between the two proposed models: formula 4 predicts that the HL_I signal will be no more detectable than the most detectable component signal (the single-band model); formula 5 predicts that the HL_I signal will be more detectable than the most detectable component signal (the multi-band model). The HL_D condition also should produce a differentiation between the two models when the signal is presented at or below the minimum detection dwell-time: the single-band model would predict a decrease in detectability of the HL_D condition compared to the most detectable single component signal; while the multi-band would predict the HL_D signal would equal the most detectable component signal.

As noted previously, if the "recognition dwell-time" used in this experiment is the same as the "detection dwell-time" the above predictions hold. However, under the logical assumption that the two "dwell-times" are not equivalent; viz., the "detection dwell-time" is less than the "recognition dwell-time," the prediction changes. The single-band model may also yield an increase in performance (d') if the S can switch from one CB to another and obtain an increase in signal energy.

Results and Discussion

The results are outlined in Table I. Table I compares the obtained and predicted d' values for the two MS conditions (the HL_D condition and the HL_I condition). It can be seen that the multi-band model seems to predict the obtained values in the HL_I condition at all signal durations; however, neither of the models, on the average, predicts indices as large as those obtained. The data initially seem to suggest that the multi-band model is the better predictor, for the HL_I condition at all durations, in that the obtained and predicted values are very close. This conclusion, however, may be erroneous in that the increase in detectability may also be explained in terms of the single-band model. For the single-band model to account for the results, all that is necessary is to assume that the Ss switch between the two CB and that the minimum dwell-time for detection was exceeded. That is, the "recognition dwell-time" used in the experiment is not appropriate for detection experiments which attempt to differentiate between the two models.

The data obtained for the HL_D condition was also closely predicted by the multi-band model (based upon the premise that the d' would be approximately equal to that of the most detectable component signal). These results, unfortunately, can also be explained by either model. The multi-band model simply predicts that performance is equal

TABLE I. Predicted Versus Obtained d' Values for Complex Signals at Each Signal Duration

		HL_D Obtained	HL_D MB(Pred)	HL_I Obtained	HL_I MB(Pred)	HL_I SB(Pred)
0.5 msec	S_1	.92	.96	1.45	1.27	.96
	S_2	.72	.91	1.16	1.24	.91
	S_3	.98	.88	1.26	1.15	.88
	Mean	.87	.91	1.29	1.22	.91
2.0 msec	S_1	.80	.89	1.60	1.25	.89
	S_2	1.12	1.04	1.67	1.47	1.04
	S_3	1.01	1.23	1.42	1.48	1.23
	Mean	.97	1.05	1.56	1.40	1.05
3.5 msec	S_1	.84	.90	1.61	1.25	.90
	S_2	1.11	1.04	1.44	1.21	1.04
	S_3	.78	.80	1.30	1.04	.80
	Mean	.91	.91	1.45	1.16	.91

to that of a single component signal. The single-band model, moreover, explains the results by noting, once again, that a S may merely switch channels (CBs) and attends to both signals since the minimum dwell-time for detection has been exceeded.

Therefore, the conclusions drawn from this experiment are not clearly definitive but may be summarized by saying that *if* "recognition dwell-time" is equivalent to the "detection dwell-time," the multi-band model accounts for the obtained results somewhat better than does the single-band model. However, even if "recognition dwell-time" and "detection dwell-time" are the same, a problem exists concerning why there is no consistent decrease in obtained d' values as a function of decreasing signal duration. This may, of course, be due to a poor measure of the TRT previously reported or possibly to some uncontrolled event. In any event, to state categorically that the multi-band model is better at this point in unwarranted. The safest conclusion is to say that "recognition dwell-time" and "detection dwell-time" are *not* equivalent and both models may therefore account for the obtained results. This latter conclusion concerning dwell-time also allows one to accept the lack of change in obtained d' values over different signal durations. The signal durations were simply all too long and the Ss could use the single-band model, switch CBs, and still do very well. The "detection dwell-time," then, is apparently very short.

CHAPTER III: RECOGNITION OF SIGNALS PRESENTED AT SHORT DURATIONS IN A MODIFIED UF PARADIGM

Introduction

Since the experiment described in Chapter II could not adequately differentiate between the two theoretical models of auditory selective attention (single-band and multi-band models), a second experiment was performed. This experiment (Experiment II) used a recognition task with signal duration equal to the "recognition dwell-time" for each S as obtained in the preliminary experiments. This experiment also used a modification of Moray's (1970a, 1970b) fourth condition; viz., the S knew the signal could be either in one CB (H), the other CB (L) or both CBs (HL). The S was instructed to select which case was presented. In this experimental paradigm (a modified single-interval forced choice), the two models predict sharply different results. Whereas previous experiments have provided only limited qualitative differentiations (predictions of the models are in the same direction - either an increase or decrease), this experiment provided both qualitative and quantitative predictions, concerning the recognition of the HL_I signal. If the HL_I signal were presented at a duration equal to the recognition dwell-time, the following predictions can be made: the single-band model predicts a decrease in recognition of the HL_I in relation to a single known component signal (H or L); however, the multi-band model predicts an increase in recognition of the HL_I over a single known component signal. The logic of these predictions is as follows. When the signal duration is equal to the recognition dwell-time, the single-band model states that, since either CB may be monitored, the recognition of the HL_I signal should decrease in respect to a single known component signal (H or L) because the S cannot simultaneously monitor (attend) both CBs and obtain an increased S/N ratio. In contrast, the multi-band model states that both CBs are monitored simultaneously; consequently, an increase in the S/N ratio will occur and produce an increase in the recognition of the HL_I signal in relation to the most recognizable single known component signal. A brief explanation of the theoretical positions concerning this paradigm is discussed in Appendix D.

This second experiment can also aid in determining the amount of influence response bias has in this paradigm. The use of the modified Moray paradigm allows data to be obtained on both Hits (correct detections) and False Alarms (signals reported heard when other signals were presented, FA). Thus, it becomes possible to determine if the single or double criterion model (Treisman, 1972) better describes the data. If the signal duration were equal to the minimum dwell-time for recognition, the double criterion model would predict that the false positive rates (total False Alarm rates for a specific signal) would be maintained at a limiting acceptable level (essentially at an equal rate) in <u>all</u> response categories. However, the single criterion model would predict inequalities in the false positive rates. More complete background and an illustrative example are given in Appendix C.

Subjects and Training

The same <u>S</u>s that participated in Experiment I participated in Experiment II. In order to acquaint the <u>S</u>s with the recognition task, a total of 600 training trials were run prior to the experiment. In the training trials, the stimuli were presented in an uncertain frequency (UF) paradigm (2AFC).

Design

A block diagram of the experimental design is shown in Figure 10. As stated previously, the experiment used Moray's fourth condition (outlined in Appendix B) where on each trial there was either a H signal alone, a L signal alone, or a HL_I signal. The experiment was replicated using an HL_D condition as a control.

The signal parameters were the same as those used previously and the duration and intensity were determined in the preliminary experiment for each individual. Specifically, the signals were gated narrow-band noise pulses each having a 74 Hz bandwidth with a center frequency of 966 Hz (H)

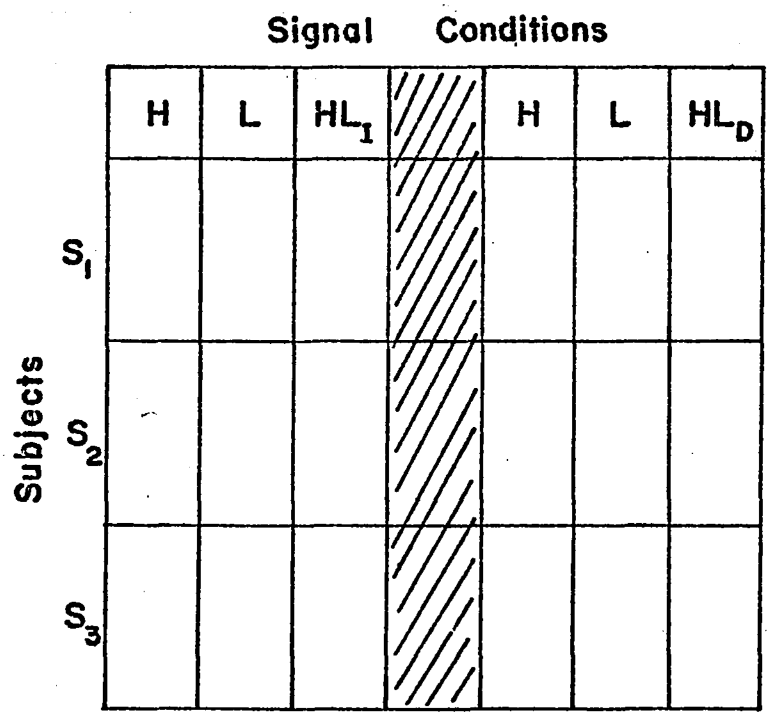

FIGURE 10. A Block Diagram of the Experimental Design for Experiment II. H represents a gated narrowband noise pulse having a 74 Hz bandwidth and a center frequency of 966 Hz. L refers to a gated narrowband noise pulse having a 74 Hz bandwidth and a center frequency of 713 Hz. HL_I represents a combined signal using the above two noise pulses. HL_D is the same combination presented at a lower intensity (equal to the most physically intense single component signal, i.e., H or L).

and 713 Hz (L). The characteristics of the two noise filters are illustrated in Figure 5. A gated noise background was presented at a spectrum level of 40 dB re 0.0002 dynes/cm^2 and filtered with a Kron-Hite (model 3100) Bandpass Filter. The settings on the filter were 10 Hz and 6000 Hz, respectively, at the 3 dB roll-off. The dependent variables were Hit rate, F/A rate, and the recognition variables were the signal presentation conditions (H, L, HL_I or HL_D).

Experimental Sessions and Apparatus

This experiment consisted of the presentation of at least 600 trials for each of the 6 stimulus conditions (H, L, HL_I; or H, L, HL_D). An experimental session consisted of 6 blocks of 100 trials. The signal on any given trial was randomly selected by Lehigh Valley Electronics modular programming equipment. Each stimulus condition had an *a priori* probability of 0.33 on any given trial. The experiment was continued until at least 600 trials for each stimulus condition were accumulated.

In each experimental session, the *S* was seated in a sound-attenuated room before a panel of indicator lights and three response keys (one for each stimulus condition). A calibrated earphone (Grason-Stadler model TDH49-10Z) mounted in a MX-41/AR muff was placed on the preferred ear. The *S* was instructed to respond by pressing one of the microswitches to indicate his decision regarding which signal occurred in the trial. Responses (Hits and F/As) were automatically recorded on electromechanical counters. On each response, the S was informed by feedback lights whether his decision was correct.

The overall timing of the experiment was determined by a Lafayette 8 Bank Timer. The experimental paradigm was a modification of that used in Experiment I. The signal to be recognized always occurred at the midpoint of the second observation interval and a comparison signal (H) was always presented at the midpoint of the first observation interval (a modified 2AFC paradigm).

Analysis and Predictions

In this experiment, one of the S's tasks was to recognize the HL signal condition (either HL_I or HL_D) being presented at minimum recognition dwell-time. If this task were done with an HL_I presentation and the d' increased in relation to the recognition d' of a known component signal (H or L), it would support the multi-band model. If, in contrast, the recognition task (using HL_I) yielded a decrease in d' in relation to a known component signal, the data would support the single-band model. Furthermore, if the task were accomplished under an HL_D presentation, then the recognition d' would equal the most recognizable component signal, thus supporting the multi-band model. Finally, if the HL_D signal showed a <u>decrease</u> in recognition d', when contrasted with the most recognizable component signal, support would be found for the single-band model.

To calculate the d' for comparison of the single-band and multi-band models, and in order to differentiate between the single and double criterion models, a partitioning of responses was necessary. This partitioning was accomplished by recording three response categories for each of the three stimulus conditions (H, L, HL_I; or H, L, HL_D). The response categories for the H condition were Hits, F/A_L (False Alarm L), and F/A_{HL} (False Alarm HL). The other signal conditions had similar response categories which produced two TSD contingency tables illustrated in Figure 11. These contingency tables were further partitioned to obtain individual contingency tables for each signal condition (See Appendix E). The d' units were calculated from the contingency tables and compared separately to the single- and multi-band model predictions.

The false positive rates derived from the contingency tables were compared with expectations of equality as hypothesized by the double criterion model (Treisman, 1972), as illustrated in Appendix C. If Treisman's double

Stimulus Condition

Response	H	L	HL_I
H			
L			
HL			

Response	H	L	HL_D
H			
L			
HL			

FIGURE 11. TSD Contingency Tables for the Results of Experiment II

criterion model fit the responses given by the Ss, there should be an equality in the false positive rates. Thus, the experiment yielded data concerning Treisman's (1972) hypothesis that the changes in detectability found by Moray (1970a, 1970b) were due to shifts in response criterion.

Results and Discussion

The results of the experiment are outlined in Table II and Table III. Table II compares the recognition d' values obtained for each HL condition (HL_I or HL_D) with those of the individual component signals (H and L). It can be seen from this table that the single-band model best predicted the outcome of the experiment. In all cases the HL condition had a clearly lower d' value than either of the single component signals (H or L). Since these data were collected at a time duration equal to the "recognition dwell-time," it appears that there was no time to switch between channels and therefore the detection of the HL signal was essentially a chance occurrence. This statement is verified by the data exhibited in Table II, in that the d' for the HL condition (either HL_I or HL_D) for all Ss was below threshold (d' approximately equal to 1.0). When TRT is defined as the minimum period of time necessary to recognize a signal, it may be criticized that the present experiment adulterated this concept because the time used could be the shortest time period in which

TABLE II. The d' Scores Obtained When the Signals Were Presented at "Recognition Dwell-Time"

Signal Condition

	H	L	HL_I	H	L	HL_D
S_1	.60	1.21	.18	.65	1.12	.16
S_2	.75	1.22	.32	.82	1.11	.12
S_3	.88	1.50	.55	.98	1.26	.48
Mean	.74	1.31	.35	.82	1.16	.25

TABLE III. False Alarm Rates of Signals Presented at a Duration Equal to "Recognition Threshold Dwell-Time"

Signal Condition

	H	L	HL_I	H	L	HL_D
S_1	.45	.33	.23	.43	.35	.23
S_2	.39	.28	.15	.33	.32	.15
S_3	.43	.37	.30	.39	.38	.27
Mean	.42	.33	.23	.38	.35	.22

a single signal could be recognized in addition to the portion of time a second signal may be presented before being recognized. Even though this may negate the actual determination of a "recognition dwell-time," in order for the present experiment to determine the effectiveness of the two theoretical models this enlarged "recognition dwell-time" is adequate. The reasoning behind the previous statement is that if only one signal could be recognized when the TRT was used, the predicted results would still remain diametrically opposed between the two models.

The false alarm rates determined by using Treisman's (1972) method of analysis are shown in Table III. It illustrates the differences in the F/A rates for each HL condition as compared to that of the individual component signals. As can be seen in the table, the F/A rates were not similar, strongly suggesting that the single criterion model fitted the data. A repeated measures analysis of variance (ANOVA) performed on the F/A rates confirmed that the rates were not equal. As shown in Table IV, the ANOVA showed a significant difference ($p < 0.01$) between the F/A rates for the signal conditions (H, L, HL_I, or HL_D). This result indicated that the phenomena observed in earlier experiments (i.e., evidence confirming both the single- and multi-band models) could not possibly be interpreted as the

TABLE IV. ANOVA on F/A Rates of Signals Presented at a Duration Equal to "Recognition Dwell-Time"

SV	df	SS	MS	F
Signal Condition	3	.072336	.024112	34.628 **
Subjects	2	.020010	.010005	
Error	6	.004178	.0006963	
Total	11	.096524		

** $p < .01$

establishment of a double criterion. The data then support a single-band model of auditory processing and a single criterion model for responding.

CHAPTER IV: DISCUSSION AND CONCLUSIONS

The results of the two experiments can now be examined in relation to the concept of single- and multi-band models and whether these models operate separately in detection and recognition tasks. In addition, the two experiments have shown areas where possible flaws in previous experimentation have occurred. Consequently, these experiments have demonstrated how a listener may efficiently process information from any two frequency regions (CBs) to which the human auditory system is sensitive.

All previous experimentation in the area of auditory selective attention was involved in the measurement of the detectability of a signal and has produced a confusing and conflicting literature. The basic premise of Ohm and later theorists was that auditory information is processed in a Fourier manner. This means that a signal is broken into its component parts by the ear and each component part is separately analyzed. The previous studies discussed in the introduction have used detection paradigms in order to test between the single- and multi-band models of auditory selective attention and have failed to produce any conclusive evidence for either model. This earlier work in the area of auditory selective attention is based upon the assumptions of the CB concept and concomitant intensity relationships. These assumptions force the experiments into intensity detection paradigms because the models that were developed by Green and his associates (Tanner, Swets, & Green, 1956; Green, 1958) used S/N ratios to prove intensity differences between the single- and multi-band models as illustrated in Appendix A. However, the basic assumptions of the models were such that the two levels of information processing might be taking place simultaneously (i.e., the single- and multi-band models assume that both detection and recognition of a signal occur concurrently). Thus, again, the theorists who proposed these models were entangled in experimentation using intensity detection paradigms. If the two models developed by Green and his colleagues are interpreted more broadly, the actual test needed to differentiate between them may involve recognizing the different signals when the detection task has been minimized.

The data from the two experiments performed in this study indicate that this concept of simultaneous information processing is incorrect and that there are two distinct levels of information processing. First, there is a detection of the signal to be analyzed and second, there is a recognition of the signal's characteristics. The process of detection seems mainly to be the procedure whereby the intensity aspects of the signal are analyzed. Recognition, however, is a process involving characteristics other than intensity <u>after</u> a signal has been detected. In order to analyze or recognize a signal, it must first be detected and then a decision has to be made concerning its characteristics. This sequential analysis of an auditory signal (detection-recognition) may be one reason for much of the conflict in the earlier data (Creelman, 1960; Gässler, 1954; Green, 1958, 1961; Green, McKey & Licklider, 1959; Marill, 1956; Schafer & Gales, 1949; Swets, 1963; Swets & Sewall, 1961; Swets, Shipley, McKey & Green, 1959; Tanner, Swets, & Green, 1956; Veniar, 1958a, 1958b). A sequential analysis of an auditory signal can explain why the various experiments were equivocal in their support for either a single- or multi-band model of selective attention, because detection must occur before recognition. In addition, this ambiguity can possibly be explained because some experiments may have been primarily detection tasks and others primarily recognition tasks.

The results of Experiment I confirmed the hypothesis that a detection task leads to ambiguous results. Differentiation between the two models may not be established in detection paradigms because the signals were presented at durations which permit the <u>S</u> to monitor more than one CB. It was found that detection of a signal occurs even under extremely short (0.5 msec) signal presentations. It was further shown that an HL signal could be detected under these conditions. This indicated that either the HL signal was being processed under a multi-band model or that the detection "dwell-time" and switching time was so short that both CBs could be monitored (i.e., single-band scanning model). Thus it is hypothesized that a Temporal Detection Threshold (TDT) is less than 0.5 msec, and for all practical purposes, the data reflects essentially a multi-band model of analysis; although both models may theoretically account for the results.

In Experiment II, it was found that recognition of a signal (HL) followed a single-band model of selective attention (i.e., only one CB is monitored at one point in time). It was, also, found in Experiment II that the Ss used a single criterion model for responding. The double criterion model was postulated by Treisman (1972) in order to re-interpret selective attention investigations by using Theory of Signal Detectability (TSD) concepts. Treisman theorized that the single-channel (CB) switching hypothesis (time-sharing) was inadequate and TSD could account for the data by assuming a change in Ss' response criterion. This was not confirmed in Experiment II. The establishment of equal F/A rates under all signal conditions was not found; thereby, eliminating Treisman's argument for a multi-band interpretation.

When both of the present experiments are examined, it seems that both the single- and the multi-band models of selective attention are functioning when a complex signal

(HL) is analyzed. In other words, first, the signal is detected under the multi-band model conditions or the single-band model is operating with so short a TDT that it could not be determined by the present experiments; second, the signal is recognized under the single-band concept at a TRT of 2.5 msec. By the time the components of the signal are being analyzed for frequency content (recognized), the detection information (intensity) has already been analyzed separately for each CB. Therefore, this experimenter proposes that there are two networks for processing information from auditory signals, the Detection Network and the Recognition Network.

The Recognition Network involves a switching mechanism with a maximum "dwell-time" of 2.5 msec for these signals and possibly instantaneous switching-times. This means the Recognition Network uses the single-band model of selective attention and is essentially a stimulus selection process as hypothesized by A. Treisman, Broadbent, and Moray (Broadbent, 1958, 1971; Moray, 1969, 1970a, 1970b; Treisman, 1964, 1969; Treisman & Geffen, 1967). The Recognition Network then focuses attentional processes on a specific CB to determine the signal frequency and then if time remains switches the focus of attention to a second CB to be analyzed. Therefore, in a recognition paradigm when a single-band model of selective attention is used, as was confirmed in Experiment II, the TRT used in the experiment is an average of the larger estimate of "dwell-time" (when the S is monitoring the incorrect CB at the start of the trial and switches to the correct CB) and the minimum "dwell-time" (when the S is monitoring the correct CB at the trial onset) for recognition. The results of Experiment II indicate that the TRT for the present experimental conditions was closer to the minimum "dwell-time" (thus indicating that the majority of the TRT was "dwell-time" spent at one CB) because both the HL (HL_I or HL_D) conditions were recognized at a lower detectability level. This critical "dwell-time" seems to be different for the Detection Network because the signals presented at TRT for these experimental conditions were easily detected for HL signal conditions. This was confirmed in Experiment I when the signals were detected at better than chance levels.

The Detection Network involves analyzing the signal either using a multi- or a single-band model with an extremely fast (less than 0.5 msec) duration TDT. From Experiment I it was not determined which model would apply and detection is still an unknown quality. However, the two present experiments do confirm that detection must first occur prior to recognition.

The integration of the Detection and Recognition Networks is the manner in which auditory information is processed and analyzed. The signal as finally perceived is a composite of this integrated system in which the signal is first detected, then recognized and finally evokes a response.

Therefore, based on the findings of this study, the conclusion is drawn that auditory information processing and selective attention is a two step process:

(1) a detection process, in which this study could not determine whether single- or multi-band models were functioning.

(2) a recognition process, using a single-band model (Stimulus selection) or selective attention.

CHAPTER V: SUMMARY

Two experiments were conducted to compare the single- and multi-band models of selective attention. Previous work cited in the literature had shown conflicting results both confirming and discrediting the models. Some of the data may be accounted for by assuming a change in the subject's (S's) response criterion. Therefore, the present study examined the concepts of time-sharing and Theory of Signal Detectability (TSD) in relation to auditory selective attention.

The stimuli were two narrowband noise pulses 74 Hz wide with low (L) and high (H) center frequencies of 713 and 966 Hz, respectively. These stimuli were presented either separately (H or L) or simultaneously (HL condition). When two signals are presented simultaneously, the intensity of the resulting combined signal is greater than that of either of the component signals (H or L) presented separately. Two different HL presentations were used in the experiments to eliminate this intensity problem. One HL presentation was simple combining of the two component signals (HL_I). The other was when the two component signals were combined again; however, this time the intensity of the resultant HL presentation was lowered to that of the most intense component signal (HL_D). Stimuli were presented at 15 dB SL with a 40 dB SPL white noise background. Responses were recorded automatically and dependent variables (d' and false alarms) were based on at least 600 trials for each stimulua condition.

Three males served as trained Ss. [In a two alternative forced choice (2AFC) paradigm], the Ss were asked in Experiment I to indicate (by pushing one of two microswitches) their decision as to which interval contained the signal. This was studied under four stimulus conditions (H, L, HL_I and HL_D) and three signal durations (0.5, 2.0, and 3.5 msec). Experiment II examined the same stimulus conditions; however, these were presented at the Temporal Recognition Threshold (TR) which reflects the "minimum dwell-time" required to differentiate between the two signals (H and L) 75% of the time. The S's task was to indicate (by pushing one of three microswitches) his decision as to which signal condition had been presented in the second interval of a modified 2AFC paradigm. In this modified 2AFC paradigm, the first interval contained one of the three stimulus conditions (H, L or HL).

In Experiment I, it was found that under the HL conditions the multi-band model predictions closely resembled the obtained data, which showed an increase in detectability for the HL_I condition compared to a single component signal (H or L) and equal detectability for the HL_D

condition compared to the most detectable single component signal.

In Experiment II, it was found that when both noise pulses were presented simultaneously (either HL_I or HL_D conditions), recognition was less than when either the H or L pulses were presented alone. Analysis of the false alarm (F/A) rates showed that the different signal conditions produced significantly different ($p < 0.01$) F/A rates.

The results were discussed in relation to attention theories, selective attention models, and differences between recognition and detection analysis of auditory signals. The experiments indicated that auditory information processing and selective attention is a two step process involving: (1) a detection process, in which this study could not determine whether single- or multi-band models were functioning; and (2) a recognition process, using a single-band model (stimulus selection) of selective attention.

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APPENDIX A

An Example Prediction by the Formula for the Single- and Multi-band Models (formulae 4 and 5 respectively).

(A) Prediction by Single-band Model.

Assuming that the complex signal is composed of four components with two sinusoids in each of two separate CBs (as shown),

the single-band model predicts:

$$d'_c = (\Sigma {d'_{cb}}^2)^{\frac{1}{2}} \; 1/n_{cb} + (n_{cb}-1)/n_{cb} \; ({d'_{cb}}^2)^{\frac{1}{2}}.$$

The detection of each component alone is 1.00 ($d' = 1.00$), thus:

a. $(\Sigma {d'_{cb}}^2)^{\frac{1}{2}} = (1.00^2 + 1.00^2)^{\frac{1}{2}} = (2)^{\frac{1}{2}} = 1.41$

b. $n_{cb} = 2$ (i.e., two CBs in use)

c. thus:

$$(1.41)(\tfrac{1}{2}) + (\tfrac{1}{2})(1.41) = 1.41 = d'_c$$

d. which reduces to:

$$d'_c = (\Sigma {d'_{cb}}^2)^{\frac{1}{2}} = 1.41.$$

(B) Prediction by Multi-band Model.

Assuming the same stimulus configuration as above, the multi-band model predicts:

the detection of each component alone is 1.00 ($d' = 1.00$), thus:

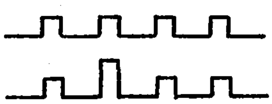
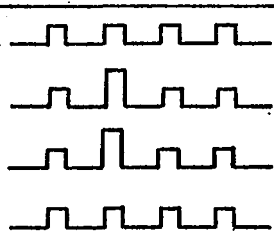
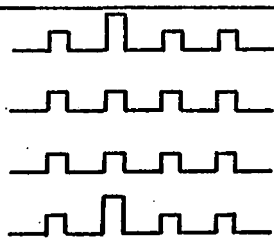
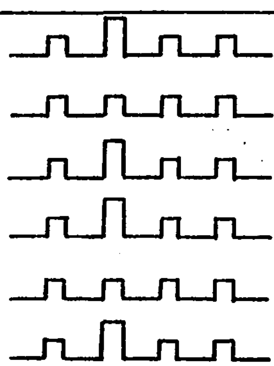
a. $d_c' = (\Sigma d_i{}^2)^{\frac{1}{2}} = (1.00^2 + 1.00^2 + 1.00^2 + 1.00^2)^{\frac{1}{2}}$

b. thus:

$d_c' = (4)^{\frac{1}{2}} = 2.00.$

APPENDIX B

Outline of the Conditions in Moray's Experiments (1970a, 1970b)

Condition	Stimuli	Correct Response	Instructions
1	 L R	Right	S knows the signal will occur in the right ear only (there is a reversal condition for the left ear).
2	 L R L R	Respond signal if a signal is in either ear, but not both.	S knows signal may occur in either ear, but is just required to detect, not specify which ear.
3	 L R L R	Respond Left Respond Right	S knows signal may occur in either ear, and must stipulate the ear in which the signal occurred. (No signals simultaneously presented).
4	 L R L R L R	Respond Left Respond Both Respond Right	S knows the signal could be left, right, or both, and is instructed to respond accordingly.

L = 3000 Hz, R = 2100 Hz

APPENDIX C

Summary of Treisman's Evaluation of Moray's Data

Treisman states that if a statistical decision model (TSD) is applied to the effects of temporal contingencies between stimuli, these effects can be understood as resulting from changes in the decision criteria employed. In assuming the above model, Treisman then states:

> We assume that Moray's subjects analyzed the input to each ear continuously and simply attempted to maintain their over-all false positive rates (FPR) for each response category at or below a limiting acceptable value (the Neyman-Pearson criterion). If the decision criteria applied to each ear were initially such that the probabilities of reporting a signal on the right ear when presented with a signal, or with noise, were respectively, δ_R and ϵ_R, and on the left ear δ_L and ϵ_L; then the over-all false positive rate for the response RIGHT in the binaural condition would be:
>
> $$FPR_R = (17/19)\ \epsilon_R(1-\epsilon_L)+(1/19)\ \epsilon_R(1-\delta_L)+(1/19)\ \delta_R(1-\delta_L) \quad (5)$$
>
> and similarly for FPR_L. For BOTH RESPONSES:
>
> $$FPR_B=(17/19)\ \epsilon_R\ \epsilon_L+(1/19)\ \delta_R\ \epsilon_L+(1/19)\ \epsilon_R\ \delta_L. \quad (6)$$
>
> Since the most important terms in these two equations are $\epsilon_R(1-\epsilon_L)$ and $\epsilon_R\ \epsilon_L$, respectively, and for ϵ reasonably small the former will be much larger than the latter, it is evident that with the same response criteria FPR_B would be much less than FPR_R or FPR_L. If, however, the subject can maintain different

criteria for each response category, so as to attain the same acceptable limiting FPR in each case, then for a BOTH response he can afford to apply criteria which are substantially lower than that for the LEFT or RIGHT responses, a strategy which may produce P(BB) values considerably greater than $P(BB)_{pred}$. This model is illustrated in Figure 12 which shows an example with arbitrary parameters in order to demonstrate the principle. Noise and signal plus noise distributions are shown on the left and right decision axes, which are scaled in standard deviation (SD) units. It is taken that d'=2.5 on the left and 0.5 on the right, and that the criterion for left responses, x_{LL}, is 3.59 SD units above the noise mean on the left and x_{RR}, the criterion for RIGHT responses, is 2.60 units above the noise mean on the right. The corresponding criteria for BOTH responses, on the two axes are 1.45 units to the left of x_{LL} and x_{RR}, respectively. The subject is supposed to apply the following rules to each stimulus pair: Respond LEFT if the input on the left exceeds x_{LL}, and the input on the right is less than x_{RL}; respond RIGHT if the input on the right exceeds x_{RR} and the input on the left is less than x_{LB}; respond BOTH if both x_{LB} and x_{RB} are exceeded. These rules generate the following equations:

$$R(BR)= \delta_{RR}(1- \epsilon_{LB}), \qquad (7)$$

$$P(BB)= \delta_{RB}\ \delta_{LB}, \qquad (8)$$

$$FPR_R=(17/19)\ \epsilon_{RR}(1- \epsilon_{LB})+(1/19)\ \epsilon_{RR}(- \delta_{LB})+ (1/19)\ \delta_{RR}(1- \delta_{LB}), \qquad (9)$$

$$FPR_B=(17/19)\ \epsilon_{RB}\ \epsilon_{LB}+(1/19)\ \delta_{RB}\ \epsilon_{LB}+(1/19)\ \epsilon_{RB}\ \delta_{LB}, \qquad (10)$$

with corresponding formulas for P(BL) and FPR_L.

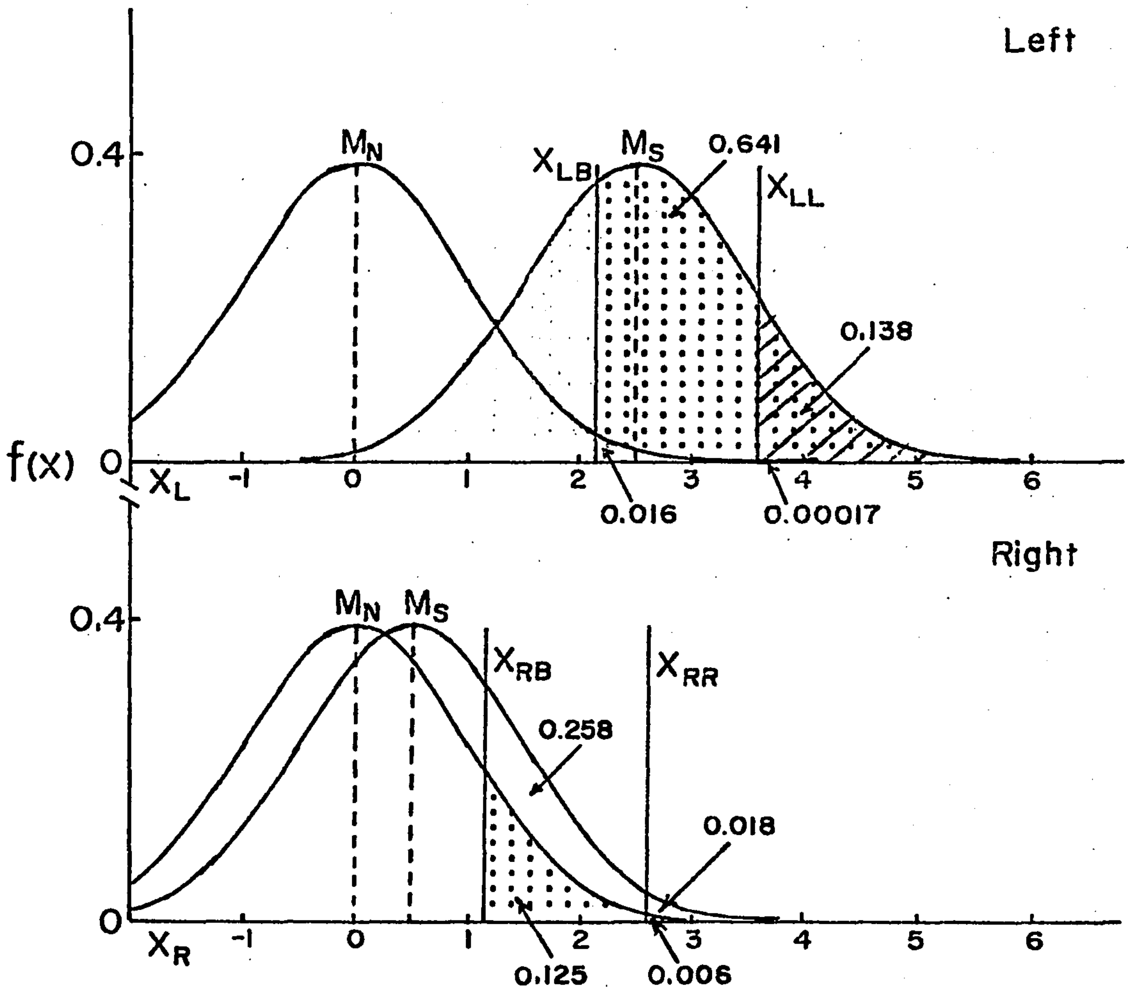


FIGURE 12. An Illustration of the Double-Criterion Model. Signal plus noise and noise distributions are shown for the left and right decision axes. We take it as $\sigma_S = \sigma_N = 1$ on both sides, and the decision axes are scaled in SD units. It is assumed that d'=2.5 on the left ear and 0.5 on the right ear, and x_{LB} is 2.14 and x_{LL} 3.59 SD units above the mean of the noise distribution on the left axis, and that x_{RB} is 1.15 and x_{RR} 2.60 units above M_n on the right. The proportions of the noise and signal plus noise distributions to the right of each criterion are indicated on the figure. On the left, δ_{LB} is shown dotted and δ_{LL} hatched; on the right, ϵ_{RB} is dotted and ϵ_{RR} hatched.

The values of δ_{RR}, the proportion of the signal plus noise distribution to the right of x_{RR}; δ_{RB}, the proportion of this distribution to the right of x_{RB}; ϵ_{RR}, the proportion of the noise distribution to the right of x_{RR}; etc., corresponding to the criterion values assumed above are shown on the figure. If the single-criterion model held (i.e., if the response BOTH is given only for stimulus presentations which exceed both x_{LL} and x_{RR}), these values would generate the following results: P(BR)=0.018; P(BL)-0.137; P(BB)=0.002; FPR_R=0.007; FRP_L=0.007; and FPR_B=0.000046. But if we apply the double-criterion model outlined above, Eqs. 7-10 generate the following results: P(BR)=0.018; P(BL)=0.121; P(BB)=0.165; FPR_R=FPR_L=FPR_B=.006. Thus, when we have the same limiting false positive rate for each response category, there is a very considerable improvement in P(BB). If these results are compared to the binaural data ..., it will be seen that the detection rates given by the double-criterion model are very similar to the mean data at 25 msec. This shows that it is well within the power of the present model to account for excesses of P(BB) over $P(BB)_{pred.}$ as large as those found in Moray's data (Treisman, 1972, pps. 627-629).

Substituting the estimates used in Figure 12, the single criterion model predicts the following:

$$FPR_R = (17/19)(.006)(1-.00017)+(1/19)(.006)(1-.138) +(1/19)(.018)(1-.138)$$

$$= .006456 \text{ or approximately } .006$$

$$FPR_L = (17/19)(.00017)(1-.006)+(1/19)(.00017)(1-.018)$$
$$+(1/19)(.138)(1-.018)$$
$$+ .00729 \text{ or approximately } .007$$

$$FPR_B = (17/19)(.006)(.00017)+(1/19)(.018)(.00017)$$
$$+(1/19)(.006)(.138)$$
$$= .0000444$$

The double criterion model predicts:

$$FPR_R = (17/19)(.006)(1-.016)+(1/19)(.006)(1-.641)$$
$$+(1/19)(.018)(1-.641)$$
$$= .0057 \text{ or approximately } .006$$

$$FPR_L = (17/19)(.00017)(1-.125)+(1/19)(.00017)(1-.258)$$
$$+(1/19)(.138)(1-.258)$$
$$= .0055 \text{ or approximately } .006$$

$$FPR_B = (17/19)(.125)(.016)+(1/19)(.258)(.016)$$
$$+(1/19)(.125)(.641)$$
$$= .0062 \text{ or approximately } .006$$

APPENDIX D

Comparison of Multi-band and Single-band Model Predictions for Experiment II.

A. The first assumption is that all comparisons are contrasted with the presentation of a single (H or L) known component signal.

B. The second assumption is that signal duration is equal to minimum "recognition dwell-time" (as calculated for each _S_).

C. The single-band model states that, when the signal is unknown for any presentation (essentially an UF paradigm), there is a switching operation which occurs between the two monitored CBs. Therefore:

a. If the signal on a given trial were a _single component_ signal (either H or L), the recognition d' would decrease in accordance with formula 2 (p. 20).

b. If the signal on a given trial were the _complex signal_ (HL), it could (because only one CB is monitored) only be recognized as _one_ of the component signals (either H or L) and performance would consequently exhibit a decrease in recognition d'. The decrease would occur because, to be correct, the _S_s must perceive _BOTH_ H and L on the HL trial. If they do not perceive BOTH they will respond incorrectly and d' for HL will decrease.

D. The multi-band model states that when the signal is unknown for any presentation, both the H <u>and</u> the L CBs are monitored simultaneously. Therefore:

a. If the low signal were presented, noise would be monitored from both CBs and a signal monitored in only one (i.e., $S_L/N + -/N = d'$). This would produce a decrease in d' because the S/N ratio contained only one signal and twice the noise.

b. The same reasoning would apply to a single presentation of the high signal. There would be a decrease in d' because the S/N ratio contained only one signal and twice the noise.

c. However, if an HL signal were presented, monitoring of two bands would produce an increase in recognition d' in accordance with formula 5 (a linear summation of the S/N ratios of the two component signals).

APPENDIX E

An Illustration of Partitioning the TSD Contingency Tables in Order to Determine d' and F/A Rates for the Signals in Experiment II.

When three signals (H, L, and HL) are used each having an equal probability of occurrance, the following TSD contingency table is established:

Signal Condition

Response	H	L	HL
H	1	2	3
L	4	5	6
HL	7	8	9

This table can then be partitioned into three separate contingency tables (i.e., one for each signal condition) as follows:

a. Contingency table for the H condition:

Signal Condition

Response	H	$\overline{H}$
H	1, 3, 7, 9	2, 8
$\overline{H}$	4, 6	5

b. Contingency table for the L condition:

Signal Condition

Response		L	$\overline{L}$
	L	5, 6, 8, 9	4, 7
	$\overline{L}$	2, 3	1

c. Contingency table for the HL condition:

Signal Condition

Response		HL	$\overline{HL}$
	HL	9	7, 8
	$\overline{HL}$	3, 6	1, 2 4, 5

The numbers within the cells of the individual contingency tables refer to the data contained in the corresponding numbered cells of the original contingency table as seen below for S 1.

Using data obtained from S 1 in Experiment II, the partitioning method may be illustrated thus:

a. TSD table established from data:

Signal Condition

Response		H	L	HL
	H	408 (1)	100 (2)	205 (3)
	L	97 (4)	338 (5)	350 (6)
	HL	102 (7)	175 (8)	231 (9)

b. The partitioned tables for each signal condition follow:

i. Contingency table for H condition:

Response		Signal Condition: H	Signal Condition: $\bar{H}$
	H	408 (1) 205 (3) 102 (7) 231 (9) 946	100 (2) 175 (8) 275
	$\bar{H}$	97 350 447	338 (5)

ii. Contingency table for L condition:

Response		Signal Condition: L	Signal Condition: $\bar{L}$
	L	338 (5) 350 (6) 175 (8) 231 (9) 1094	97 (4) 102 (7) 199
	$\bar{L}$	100 (2) 205 (3) 305	408 (1)

iii. Contingency table for HL condition:

Response		Signal Condition: HL	Signal Condition: $\overline{HL}$
	HL	231 (9)	102 (7) 175 (8) 277
	$\overline{HL}$	205 (3) 350 (6) 555	408 (1) 100 (2) 97 (4) 338 (5) 943

The F/A rates were obtained from the above tables by calculating the percentage of responses falling within the cell containing F/As (Response - signal present, Signal Condition - no signal present). The F/A rates for the above data were 45%, 33%, and 23% respectively for the signal conditions H, L, and HL.

The percentage of responses falling within the other cells was, also, calculated in order to determine the d' value. Using the percentages of Hits (correct detections) and F/As, the d' values were determined from the tables established by Elliot (Elliot, 1964). In the above example, the d' values were 0.60, 1.21, and 0.18 respectively for the signal conditions H, L, and HL.