RESNICK, Steffi B., 1946-
DISCRIMINABILITY OF TIME-REVERSED CLICK PAIRS: INTENSITY EFFECTS.

The University of Oklahoma, Ph.D., 1973
Audiology

THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

DISCRIMINABILITY OF TIME-REVERSED CLICK PAIRS: INTENSITY EFFECTS

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

DOCTOR OF PHILOSOPHY

BY

STEFFI B. RESNICK

Oklahoma City, Oklahoma

1973

DISCRIMINABILITY OF TIME-REVERSED

CLICK PAIRS: INTENSITY EFFECTS

APPROVED BY

DISSERTATION COMMITTEE

Appreciation is expressed

to

the author's parents

for their encouragement of her academic efforts.

ACKNOWLEDGEMENTS

The author is grateful to Dr. Lawrence L. Feth, University of Oklahoma Health Sciences Center, for his role both in the direction of the dissertation and in the education of its author. His participation in the investigation as a subject was sincerely appreciated.

Appreciation is expressed to Dr. S. Joseph Barry for his guidance of the author's academic program and his invaluable assistance in the initial phases of the investigation. The author is indebted to Dr. Thomas E. Stokinger for the constant encouragement and the constructive criticism which he provided.

A sincere expression of gratitude is extended to Janet Benkosky, Robert Boyd and Margaret Wylde who, by their voluntary participation in a lengthy experimental procedure, made completion of the investigation possible.

And finally, the author is grateful to William W. Washam whose patience and perspective contributed immeasurably to the progress of the dissertation.

Financial support was provided for the author by the Veterans Administration through its Training and Education Funds.

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CHAPTER I

INTRODUCTION

The temporal resolving power of the auditory system, or auditory temporal acuity, is reflected in the minimal temporal interval between successive auditory stimuli which permits appreciation of the sequential nature of those stimuli. The definitions of temporal resolving power offered by various investigators appear to depend, however, upon the particular procedure employed by them in the estimation of that minimal interval. Those procedures, in turn, differ with respect to the stimuli presented and the task with which the subject is confronted.

Investigations conducted to determine the temporal resolving power of the auditory system may be classified into three categories. The first category consists of those investigations which determine the minimal interval between successive stimuli required for the subject to detect that the stimuli are not simultaneous (Gescheider, 1966) or that more than one signal is present (Exner, 1875). In studies of this type, the subject's task is to report whether "one" or "two" signals, generally clicks, were presented. The minimal interval between clicks which produces a change in the responses from "one" to "two" is considered to represent the temporal resolving power of the auditory system.

The second category of investigative procedures includes studies of the minimal interval between successive stimuli which permits detection of the temporal separation (Plomp, 1967; Smiarowski, 1970; Perrott and Williams, 1971) or detection of the temporal discontinuity in periodically-interrupted signals (Miller and Taylor, 1948; Harbert, Young and Wenner, 1968). The subject's ability to discriminate between continuous and discontinuous stimuli, such as noise bursts, as a function of the temporal interval between the noise bursts is assessed in "gap detection" tasks. The perception of a temporal separation between more than two stimuli is evaluated in auditory flutter fusion tasks in which the subject's ability to discriminate between continuous and periodically-interrupted white-noise is determined as a function of the rate of interruption. The minimal interval between successive stimuli at which the temporal discontinuity becomes perceptible in both gap detection and flutter fusion tasks is regarded as a reflection of the temporal resolving power of the auditory system as well.

The third category of investigations of temporal resolving power is composed of studies conducted to determine the minimal duration of transient signals with identical energy density (or power) spectra, but differing in waveform, which permits discrimination of those signals (Patterson and Green, 1970; Ronken, 1970). It has been suggested that the minimal duration which permits discrimination of those signals on the basis of differences in their waveforms also provides an estimate of the temporal resolving power of the auditory system (Green, 1971). The present study is devoted to examination of the validity of that suggestion.

Estimates of the temporal resolving power derived from the three types of experimental procedures are comparable and have been interpreted as an indication that the lower limit of the resolving power of the auditory system is on the order of 2 msec. Inasmuch as similar estimates of the temporal resolving power have been obtained using the three types of experimental procedures, it has been assumed that the temporal processing required for performance of these tasks is mediated by a common peripheral mechanism.

Traditionally, and most frequently, the temporal resolving power of the auditory system has been investigated using procedures in the first two categories. The relatively recent application of forced-choice procedures to the evaluation of temporal resolving power has made the limitations of those investigative procedures apparent (Leshowitz, 1971). The limitations arise from alterations in the power spectra and/or in the total duration which may accompany the introduction of changes in the temporal aspects of the stimuli. The discrimination of those stimuli, in the presence of spectral cues or durational cues, cannot be attributed exclusively to the temporal processing capability of the auditory system.

In an effort to eliminate the effects of spectral confounding on the evaluation of the temporal resolving power, several investigators recently have assessed the discriminability of transient signals which offer identical energy density spectra and are of equal duration but differ with respect to their phase spectra and, consequently, with respect to their waveforms (Green, 1971; Patterson and Green, 1970; Green, 1973). It is the contention of Green and his colleagues that an estimate of the limit of the temporal resolving power can be obtained by a progressive reduction in the total duration of those signals to that point at which the differences in the temporal order of events within the waveform become imperceptible.

The validity of that contention appears to warrant additional evaluation particularly as it pertains to a recent study conducted by Ronken (1970). The stimuli employed in Ronken's study were time-reversed click pairs. The task of the subjects was to discriminate between two pairs of clicks. In one pair, the less intense click preceded the more intense click; in the other pair, the order of the clicks was reversed. Ronken concluded that the basis of the discrimination was "not clear." Green (1971) suggested, more recently, that the discriminability of the click pairs reflected auditory temporal acuity, which he defined as the ability of the auditory system to discriminate the order of events within a time interval. Consideration of the stimulus configurations suggests that a mechanism other than that mediating the resolution of successive stimuli of equal intensity may be associated with discrimination of those click pairs. Their discriminability may be related to differences in the relative detectability of the less intense click in the two types of click pairs.

Information regarding the detectability of a less intense click which is presented following or preceding a more intense click is available from studies of temporal masking. Temporal masking may be defined as the elevation in the threshold for a signal which results when a more intense masking signal precedes (forward masking) or follows (backward masking) the probe (or masked) signal in time. The extent of temporal masking is determined by comparison of the level of the probe click required for its detection in the presence of the masker with that level required for its detection in quiet.

The temporal masking of a probe click has been shown to vary directly with the level of the masking click and inversely with the temporal separation existing between the masking click and the probe (Chistovich and Ivanova, 1959; Raab, 1961). When the interval between the masking click and the probe is less than about 10 msec, the elevation in the threshold for a probe click which follows the masking click generally exceeds that observed when the order of the clicks is reversed. The difference in the relative detectability of the probe click in the two temporal masking paradigms has been termed the "asymmetry of temporal masking."

The extent of that asymmetry has been shown to depend upon intensity relationships. Babkoff and Sutton (1968) used a variant of the temporal masking paradigm to determine the minimal temporal separation between a masking click and a probe click (which was presented at a fixed level) required for detection of the probe click. They altered the definition of the asymmetry of temporal masking to include the difference in the interclick interval necessary for detection of the probe click under those conditions which produce backward and forward masking. It was their conclusion that the asymmetry of temporal masking varied inversely with the level of the masker and directly with the intensity ratio of the clicks within the click pairs.

In order to evaluate the possibility that the asymmetry of temporal masking mediates discrimination of the time-reversed click pairs, it appears reasonable to consider the degree to which the discriminability of those click pairs and the asymmetry of temporal masking are influenced similarly by changes in the level of the more intense click and by variations in the interclick intensity ratio. Information regarding the effects of intensity on the discriminability of the time-reversed click pairs is limited, however. It has been noted, in two investigations which utilized the time-reversed click pairs, that the discriminability of those signals is affected by intensity manipulations.

Ronken's investigation of the discriminability of time-reversed click pairs was devoted to determination of the interclick intensity ratio (ΔI) which yielded 75% correct discrimination of the diotically-presented signals for interclick intervals (Δt) between 1 and 10 msec. The ΔI value was determined using an adaptive two-alternative forced-choice procedure. The adaptive procedure employed was PEST, or Parameter Estimation by Sequential Testing, developed by Taylor and Creelman (1967). The level of the more intense click (I_o) was fixed at about 55 dB SL. Ronken reported that in several instances no value of ΔI could be established which permitted the two trained subjects to discriminate the clicks when the interval between the onset of the clicks within a pair was 1 msec. Both subjects achieved 75% correct discrimination of the click pairs at a Δt value of 2 msec for a ΔI of 6 dB. At an interclick interval of 5 msec, one subject required a ΔI of 10 dB whereas the other subject required a ΔI of only 4 dB. Ronken reported that near perfect performance was obtained at all values of Δt when the difference between the clicks within a pair was greater than 10 dB. In interpreting Ronken's results it is important to note that the PEST procedure provides no information with respect to the shape of the psychometric function and requires that the investigator know whether the slope of the psychometric function is negative or positive.

The observation that intensity relationships alter the discrimination of time-reversed click pairs also was made by Babkoff and Sutton (1971) who used a paradigm comparable to that employed by Ronken for investigation of "interpulse interactions" at various Δt values between 0.5 and 20 msec. The task of their two trained subjects was the discrimination of the time-reversed click pairs in a three-interval forced-choice procedure. Data were collected at I_0 values between 20 and 70 dB SL for values of ΔI equal to 10 dB and greater. The ΔI values employed by Babkoff and Sutton exceed those of Ronken's study. Babkoff and Sutton demonstrated that discrimination of the click pairs was achieved at interclick intervals of 0.5 and 1.0 msec for several values of ΔI and that the Δt values at which optimal performance was obtained were related to the level of the more intense click. Of interest, as well, is their report that the percentage of correct discriminations, P(C), was a nonmonotonic function of Δt. For large ΔI values (ΔI=30 dB), P(C) increased as the interclick interval was increased and remained high for intervals of 5 to 6 msec before decreasing. Smaller ΔI values (ΔI=15 dB) yielded a decrease in P(C) at temporal intervals shorter than 5 msec.

The observations reported by Babkoff and Sutton and by Ronken suggest that estimates of auditory temporal acuity derived from investigations of the discriminability of time-reversed click pairs may be systematically related to the interclick intensity differences and may be altered by the level at which the clicks are presented. A complete description of the relationship between the interclick intensity ratio and discrimination performance is hampered by procedural differences in the two studies. In addition, the demonstrated nonmonotonicity of the psychometric functions suggests that the validity of applying the PEST procedure to the determination of ΔI values required for discrimination of the click pairs at various interclick intervals may be questioned. In summary, the available information does not permit evaluation of the extent to which the asymmetry of temporal masking is associated with discrimination of the time-reversed click pairs.

The demonstration of a relationship between variations in the interclick intensity ratio and changes in the discriminability of the click pairs does provide support, however, for the notion that discrimination of the click pairs is associated, to some degree, with the asymmetry of temporal masking. Furthermore, the nonmonotonicity of the psychometric functions which relate discrimination performance to the interclick interval suggests a correspondence between the reduction in the discriminability of the click pairs and the reduction in the asymmetry of temporal masking which occurs as the duration of the interval between the masking click and the probe click is increased beyond a particular value. It is the purpose of this investigation to document the effects of signal level and interclick intensity ratio on the discriminability of the time-reversed click pairs in order that the relationship between the asymmetry of temporal masking and the discriminability of those click pairs may be evaluated more adequately.

The following chapter is devoted to a review of the literature relevant to the present investigation and to a detailed statement of the experimental hypotheses.

CHAPTER II

REVIEW OF THE LITERATURE

Introduction

The perception of the successiveness of nonsimultaneous auditory stimuli is limited by that characteristic of the auditory system which has been termed its "temporal threshold" (Pieron, 1967). The temporal threshold is considered to represent the limitations imposed on signal processing at a peripheral portion of the auditory system (Miller and Taylor, 1948; Hirsh, 1959; Smiarowski, 1970) and to reflect the temporal resolving power of the auditory system, or auditory temporal acuity. Efforts to evaluate the temporal resolving power of the auditory system have been devoted, therefore, to specification of the minimal temporal interval between successive auditory stimuli which permits appreciation of the sequential nature of those stimuli.

The investigative techniques employed in the determination of that minimal interval have differed, as have the definitions of temporal resolving power offered by various investigators. The rationale underlying the experimental procedures and the common feature of the definitions does appear to be that "failure of temporal resolution results when the interval between successive events is shorter than the resolving power of the neural mechanisms" (Guttman, van Bergeijk and David, 1960).

Estimates of the temporal threshold derived from psychoacoustic investigations have been interpreted as an indication of the resolving power of the neural mechanism at a peripheral level. The results of those investigations generally indicate that an interval of 2 msec between successive stimuli permits appreciation of the successive nature of those stimuli. There is evidence from electrophysiological studies that the resolving power of the auditory system at the level of the eighth nerve is on the order of 2 msec (Finck and Ruben, 1962; Kupperman, 1971).

This chapter is devoted to a review of the psychoacoustic procedures employed in the assessment of the temporal resolving power of the auditory system and the problems associated with their use. The procedures to be discussed may be categorized conveniently into three groups. The first group of studies provides estimates of the temporal resolving power based on the duration of the interval between successive stimuli which results in their perception as two stimuli, rather than as a single stimulus. The second group obtains estimates based on the duration of the interval between successive stimuli which is required for detection of the temporal discontinuity between those stimuli. The third group, to which attention will be directed primarily, derives its estimates of the temporal resolving power from the duration of transient signals which is required for discrimination of those signals on the basis of waveform. The procedures within the third category were developed in an attempt to eliminate the spectral and durational cues which frequently complicate interpretation of measures obtained using procedures within the first and second categories. Interpretation of measures obtained using procedures within the third group, however, may be complicated by cues introduced by the auditory system itself. A description of those cues and the limitations which they may impose on efforts to assess the temporal resolving power of the auditory system, using procedures in the third category, constitutes a major portion of this chapter.

The Perception of Two Successive Stimuli

Early publications indicate a reliance of investigators upon the reports of their subjects to determine the minimal temporal separation between successive stimuli of equal intensity that produced a change in the perception of the number of stimuli occurring from "one" to "two" and thereby to estimate the temporal resolving power of the auditory system. As early as 1875 Exner commented on the "enormous accuracy" of the auditory system which permitted the perception of a "double impact" when successive clicks (generated using a Savart wheel) were separated by an interval of 2 msec.

Buytendijk and Meesters (1942) confirmed Exner's report that clicks are "just noticeable as a double tick when led to the same ear 2 or 3 msec after one another". At 2 msec a "slight roughness" was perceived by some of the listeners while others reported the perception of a "longer duration" and a "smaller degree of 'pointedness' and intensity." At an interclick interval of 3 msec all observers reported a "fluttering" and at 4 to 7 msec the perception was described as "an ever more distinct double click."

Similar observations were made by Wallach, Newman and Rosenzweig (1949) who, in a preliminary portion of a larger investigation, examined the temporal resolution of clicks using the method of limits. They reported that on an ascending series, an interclick interval of at least 6 msec was necessary to produce "a clearly 'double' sound"; on a descending series interclick intervals of 3 msec or less resulted in a "single sound."

Gescheider (1966) investigated resolution of clicks presented monotically and dichotically which were generated by vibrators mounted at a fixed distance from the ear. It is apparent from Gescheider's discussion that the conditions he terms "binaural" actually involved dichotic presentation of the clicks as his subjects were instructed to report the presence of "two" clicks when they perceived a "rough sensation in one ear" or when the "sensations in the two ears were temporally separated". Two clicks of equal intensity presented monaurally at 60 dB SL were perceived as "temporally discrete" when separated in time by 1.6 msec. Gescheider's data are somewhat difficult to interpret in light of his report that the duration of the acoustical waveform produced by the vibrators in response to a 1 msec electrical pulse was at least 10 msec in duration.

Investigation of the temporal resolution of dichotic stimuli has been directed primarily toward examination of the mediation of uniquely binaural phenomena such as lateralization (Wallach, Newman and Rosenzweig, 1949; Babkoff and Sutton, 1966). In a few instances, however, dichotic stimuli have been used to assess the monaural temporal resolving power of the auditory system. In those investigations, a single click presented to one ear has been used to determine the extent of interaction between clicks within a click pair that is presented to the contralateral ear.

An investigation by Guttman, van Bergeijk and David (1960) is representative of the studies employing dichotic stimuli to explore monaural temporal resolution. Guttman and his colleagues applied the characteristics of the binaural time-intensity trading relationship to the study of the monaural temporal resolving power of the auditory system. The dependent variable (termed the "critical monaural temporal interval") was the minimal temporal separation between the onset of the clicks of a click pair presented to one ear that allowed fusion of each of those clicks with a third click presented to the contralateral ear. The click pairs were presented repetitively. The authors reported that an increase in the rate of repetition of the click pairs from 8 to 125 per second produced a decrease in the critical monaural temporal interval from 6 to 3 msec for their three trained observers. Variation in the sensation level of the clicks between 10 and 40 dB SL did not significantly affect the critical monaural temporal interval. Guttman and his co-workers suggested that the reduction in the critical monaural temporal interval associated with an increase in the repetition rate of the click pairs might result from reduction of the magnitude of differences in the neural response evoked by the first click and that evoked by the second click due to a decrease in the recovery time provided the neural elements subsequent to the presentation of the second click of the pair. Comparable results were obtained by Harris, Flanagan and Watson (1963) using a similar experimental procedure.

Clicks have been employed almost exclusively as the stimuli in studies which require a judgment by the subject as to the presence of a single signal or two signals. The results of an investigation of the differential threshold for duration conducted by Abel (1972) indicate that the temporal interval between successive noise bursts which is necessary for their resolution corresponds closely to the interval required for the temporal resolution of clicks.

Abel (1972), in an effort to investigate the mediation of duration judgments in the absence of cues along other psychological dimensions, assessed the ability of her subjects to discriminate the duration of intervals that were bounded by bursts of noise (thus offering no peripheral stimulation during the interval to be judged). The task of the trained observers was the discrimination of a variable "gap" from a reference "gap" in a two-alternative forced-choice procedure. The noise burst markers which bounded the gaps were of various durations and levels. Abel reported that, as the reference gap was increased from 0.63 msec to 2.5 msec, the minimal discriminable gap remained constant at about 2 msec for the 10 msec-85 dB SPL marker. The duration of the minimal discriminable gap for the 10 and 300 msec markers presented at 75 dB SPL decreased slightly from 3.0 msec as the reference duration was increased from 0.63 msec to 2.5 msec. For all the markers, the minimal discriminable interval increased markedly as the duration of the reference increased beyond 5 msec. Abel suggested that for reference intervals shorter than 2 msec, the subject makes a judgment based on the discrimination of two sounds from one sound rather than on the duration of the gap. She noted that the relatively constant 2 msec interval obtained for the more intense marker and the 3 msec interval obtained for the less intense markers was consistent with this idea.

In summary, the temporal threshold, as estimated by the minimal interval between broad-band signals that results in a judgment by the subject that two signals are present, is of the order of 2 to 3 msec. The duration of that interval does appear to be dependent upon the task imposed on the subject and the criterion adopted by him but is not altered significantly by the level of signal presentation.

The Perception of Temporal Discontinuity

Other efforts to assess the temporal resolving power of the auditory system have been devoted to determination of the minimal interval between successive stimuli required for detection of that interval, rather than for appreciation of the successive nature of those stimuli. The stimuli employed in determining the minimal perceptible interval between successive stimuli are of two types: a single stimulus which is periodically interrupted or a pair of temporally-separated stimuli of equal intensity. The observer's ability to detect the presence of the interruption in a periodically-interrupted signal is assessed as a function of the rate of interruption in investigations of auditory flutter fusion. The observer's ability to detect a temporal separation between the members of a stimulus pair is determined as a function of that temporal separation in studies of "gap detection."

It has been suggested that the perception of the temporal discontinuity in the auditory flutter-fusion task (Miller and Taylor, 1948; Harbert, Young and Wenner, 1968) as well as in the gap detection task (Plomp, 1967) occurs only when the residual sensation representing the initial stimulus has decayed to a level such that presentation of a subsequent stimulus represents a just noticeable increment in the magnitude of the sensation. To the extent that performance on the auditory flutter-fusion task and on the gap detection task is mediated by a common mechanism, it may be anticipated that comparable estimates of the auditory system's sensitivity to temporal discontinuity would be derived from the two types of investigations. The brief review of the results of selected investigations in the two areas which constitutes the following portion of this chapter suggests a commonality of mediation and a similarity between the results of those investigations and the previously discussed investigations of temporal resolution.

Auditory Flutter Fusion

Auditory flutter fusion is said to occur at that rate of signal interruption at which a periodically-interrupted auditory signal becomes indistinguishable from a continuous signal; that rate of interruption is termed the auditory flutter-fusion threshold. To avoid confounding of the detection of the interruption by the spectral changes resulting from the rapid interruption of sinusoidal signals, broad-band noise frequently has been employed as the interrupted signal.

In an early investigation of auditory flutter fusion, Miller and Taylor (1948) defined three stimulus parameters which interact to determine the auditory flutter-fusion threshold, and which have since been the subject of several other investigations: interruption rate, duty cycle and signal intensity. They reported that differences in the quality of interrupted and continuous noise were perceptible at interruption rates up to 2000/second although the perception of a "train of bursts with pitch character" was limited to rates of interruption lower than 250/second. The perception of auditory flutter for rates of interruption exceeding 1000/second was considered to be artifactual, reflecting the statistical changes in the characteristics of noise bursts shorter than

1 msec. Miller and Taylor suggested that at rates of interruption from 20 to 250/second, the neural activity from the basal portion of the cochlea is synchronous with the noise bursts. The qualitative differences permitting the subject to detect interruptions at rates above 250/second were thought to result when "the last of the preceding discharge comes from a different group of receptor cells than the first of the following discharge." The highest interruption rate at which the neural responses were considered to correspond to the rate of signal presentation was 250/second; that rate of interruption for a signal with a 50% duty cycle represents a temporal separation between bursts of 2 msec. Changes in signal intensity produced a decrease in the off-time required for detection of the interruptions only when the signal intensity was below about 25 dB SL.

A later investigation by Symmes, Chapman and Halstead (1955) highlighted the interactive effects of the same three stimulus parameters on the auditory flutter-fusion threshold for noise bursts presented binaurally to a single, trained observer. They found that the interruption rate at which fusion occurred varied inversely with the duty cycle. The interruption rate for fusion increased disproportionately as the duty cycle was decreased below about 85% indicating that off-time required for the perception of flutter did not remain constant as the burst duration was reduced below 10 msec. The auditory flutter-fusion thresholds were not changed significantly by changes in the level of the signal for duty cycles less than 70%; for duty cycles greater than 75%, the auditory flutter-fusion threshold varied directly with intensity for signals between 25 and 60 dB SL. Flutter-fusion thresholds were determined for

46 unsophisticated normal-hearing subjects, as well. The signals were tape-reccrded and were presented at about 50 dB SL with a duty cycle of 90%. The mean auditory flutter-fusion threshold was 82.1 ips (interruptions per second) which corresponds to a mean off-time of 1.2 msec.

Besser (1967), employing binaural presentation of interrupted white-noise with a 90% duty cycle, reported that the mean auditory flutter-fusion threshold was 45.5 ips at 55 dB SPL; comparable thresholds were obtained at intensities between 46 and 76 dB SPL. Besser attributed the lower thresholds (i.e., fewer interruptions per second for fusion) obtained in his study relative to the values reported by Symmes _et al._ to the instructional differences in the studies. Symmes _et al._ instructed their subjects to report the detection of any difference between the quality of the continuous comparison signal and the interrupted signal while Besser's subjects were instructed to report the presence of flutter only when the signal was perceived as "obviously chopped." The off-time of a signal interrupted 45 times per second with a duty cycle of 90% is approximately 2.2 msec. Despite the presence of procedural differences, the off-times which produced a report of the presence of auditory flutter in the investigations by Symmes _et al._ and by Besser differed, in absolute value, by only 1 msec.

Harbert, Young and Wenner (1968) noted the effect of rise-decay time on the auditory flutter-fusion threshold for white noise interrupted at rates between 1 and 100 times per second. Duty cycle served as the dependent variable. The interval between the bursts, or the "off-time", required for discrimination of the interrupted signal from a continuous signal was shown to depend upon the rise-time and the duration of the noise bursts. An off-time (measured between the 0.4 dB down points) of 2.5 msec was required under conditions in which the signal was less than 100 msec in duration and its onset was virtually instantaneous. The shortest off-times required for perception of the interruption occurred for bursts less than 10 msec in duration. As either the duration of the noise bursts or the rise-time of the noise bursts was increased, the required off-time was increased. Variation in the intensity of the noise bursts over a 60 dB range did not affect the off-time.

As indicated in the investigation by Harbert et al., the minimum perceptible interval between repetitively-presented noise bursts is altered minimally by changes in the level of the noise bursts. That interval is increased when the duration of the bursts is increased to values beyond those customarily employed in investigations of auditory flutter fusion. Elfner and his co-workers (Elfner and Caskey, 1965; Elfner and Homick, 1966), in their examination of "continuity effects" have been concerned primarily with alterations in that minimal perceptible interval which result when sinusoidal signals occupy the interval between noise bursts of relatively long duration. Of interest, for the purposes of this review, are their determinations of the minimal interval between noise bursts which is required for perception of the discontinuity when the tonal signals are absent. Under those conditions, the mean interval between noise bursts of 70 msec duration (presented at 30 dB SL) which was required for perception of the discontinuity was 6 msec; that interval increased to 8 msec when the duration of the bursts was increased to 950 msec (Elfner and Homick, 1966).

The results of investigations of auditory flutter fusion suggest that the perception of temporal discontinuity for noise bursts of short duration occurs when the temporal separation between the repetitive noise bursts is of the order of 1 to 2 msec. That value is constant over a wide range of intensities but is dependent upon the rise-time and the duration of the noise bursts.

Gap Detection

Investigation of the detectability of a temporal separation existing between two stimuli has been pursued primarily as a method of assessing the residual sensation present at some time following cessation of the first stimulus. As a consequence, studies of gap detection generally have specified the level of the second stimulus required for detection of the gap, as a function of the temporal separation between the members of the stimulus pair. The results have been compared to those obtained in investigations of forward masking and a commonality of the mechanisms mediating forward masking and gap detection has been suggested (Smiarowski, 1970). When the stimuli constituting a stimulus pair are identical in level and the temporal separation required for detection of the gap serves as the dependent variable, however, the similarity of the tasks confronting the observer in studies of auditory flutter fusion and of gap detection becomes apparent.

Plomp (1964) reasoned, as had Miller and Taylor (1948), that the temporal gap between two noise bursts is detectable only when the sensation evoked by the second burst is just noticeably greater than the residual sensation in response to the first noise burst. He, therefore, determined the rate of decay of auditory sensation by recording the minimal perceptible separation between noise bursts as a function of the level of the second noise burst. The level of the first noise burst was varied parametrically. The first noise burst was 200 msec in duration; the duration of the second noise burst was varied to assure that it was terminated 200 msec after the termination of the first noise burst. The task of the two trained observers was the discrimination of a pair of noise bursts separated by a temporal gap from a pair of noise bursts that were temporally contiguous. The observers responded within the constraints of a two-interval forced-choice procedure and received immediate feedback. Plomp reported that the minimal detectable separation decreased exponentially, or linearly in log time, as the level of the second burst was reduced. When the noise bursts within a pair were of equal intensity, the minimal detectable gap decreased (as the intensity of the noise bursts increased) from an average of 19.5 msec for noise bursts presented at 10 dB SL to 3.6 msec for noise bursts presented at 30 dB SL. The temporal values remained relatively constant for additional increases in the level of the noise bursts to 75 dB SL. The temporal values were at a minimum when the intensities at which the noise bursts were presented were in the range of 50 dB SL; the smallest temporal separation required was 2.6 msec.

As part of a larger investigation, Smiarowski (1970) also determined the minimal interval between two successive noise bursts of equal intensity required for detection of the temporal gap. The noise bursts were 500 msec in duration. The minimal detectable interval was determined for six listeners using a double-random staircase method. The duration of the interval required for perception of the interruption was 2.8 msec for bursts presented at 60 dB SPL and 2.7 msec for bursts presented at 80 dB SPL.

Perrott and Williams (1971) investigated the "interevent disparity" required for detection of a temporal gap between sinusoidal signals, rather than noise bursts. A two-interval forced-choice procedure, comparable to that employed by Plomp, was used to determine the minimal detectable interval between the sinusoidal signals, which were 100 msec in duration and were presented at 35 dB SPL. The frequencies of the two signals constituting a signal pair were varied symmetrically about 1000 Hz. Perrott and Williams observed that the minimum detectable gap increased as a function of the frequency difference between the signals from a value of 6.08 msec for pulses of equal frequency to 26.05 msec for pulses differing in frequency by 600 Hz. The authors stated that their results indicated a lack of correspondence between temporal masking and gap detection; temporal masking would be anticipated to decrease as a function of the frequency difference between the pulses.

In a later investigation by the same authors (Williams and Perrott, 1972), a reduction of pulse duration from 300 to 3 msec was shown to be accompanied by a reduction in the effect of the frequency difference between the members of a pulse pair on gap detection. For a pulse duration of 3 msec, the minimal detectable gap remained relatively constant at 1.6 msec despite variation in the frequency differences between the members of the pulse pair. For the 300 msec pulses, the temporal gap of 8.8 msec required when the pulses were equal in frequency, was increased to 42.7 msec when the frequency difference was 240 Hz. Williams and Perrott suggested that their results may be explained by invoking the concept of a critical band which narrows as the stimulus duration is increased. The implication of the two studies by these authors is that performance on a gap detection task is optimized by the presentation of brief, broad-band stimuli which produce comparable excitation patterns.

The results of investigations reviewed to this point indicate that the perception of a temporal discontinuity between repetitive stimuli or within a single pair of stimuli requires that the interstimulus interval be at least 1 to 2 msec in duration. Variations in the duration or spectral characteristics of the stimuli frequently result in prolongation of the minimum perceptible interval. Sensitivity to the presence of a temporal discontinuity appears to be optimized when the stimuli are broad-band signals of brief duration and moderate intensity. It is apparent that the temporal interval required for the listener to perceive that two signals, rather than a single signal, are present is comparable to that required for perception of the presence of a temporal discontinuity. That interval is generally considered to represent the time necessary for recovery of some undetermined, but presumably peripheral, sensory or neural function.

Another group of procedures employed to assess that same minimal interval is described in the following portion of this chapter. The stimuli employed in the investigations to be considered represent a significant departure from those employed in the previously cited studies of temporal resolution. The implications of the use of a particular stimulus configuration for the estimation of the temporal threshold are discussed at length, and the validity of the estimate of the temporal threshold obtained using that stimulus configuration is examined.

The Discrimination of Transient Signals with Identical Power Spectra

In an effort to define the limit of the temporal resolving power of the auditory system, several investigators have rejected the classical psychophysical procedures characteristic of studies devoted to determination of the auditory flutter-fusion threshold or to specification of the minimal interstimulus interval required for recognition of the successive nature of two stimuli. They have tended to favor the adoption of forced-choice procedures with highly-trained subjects. This transition has made apparent the ability of subjects to discriminate between signals which differ temporally on the basis of spectral changes which may accompany alterations in the temporal aspects of the signals.

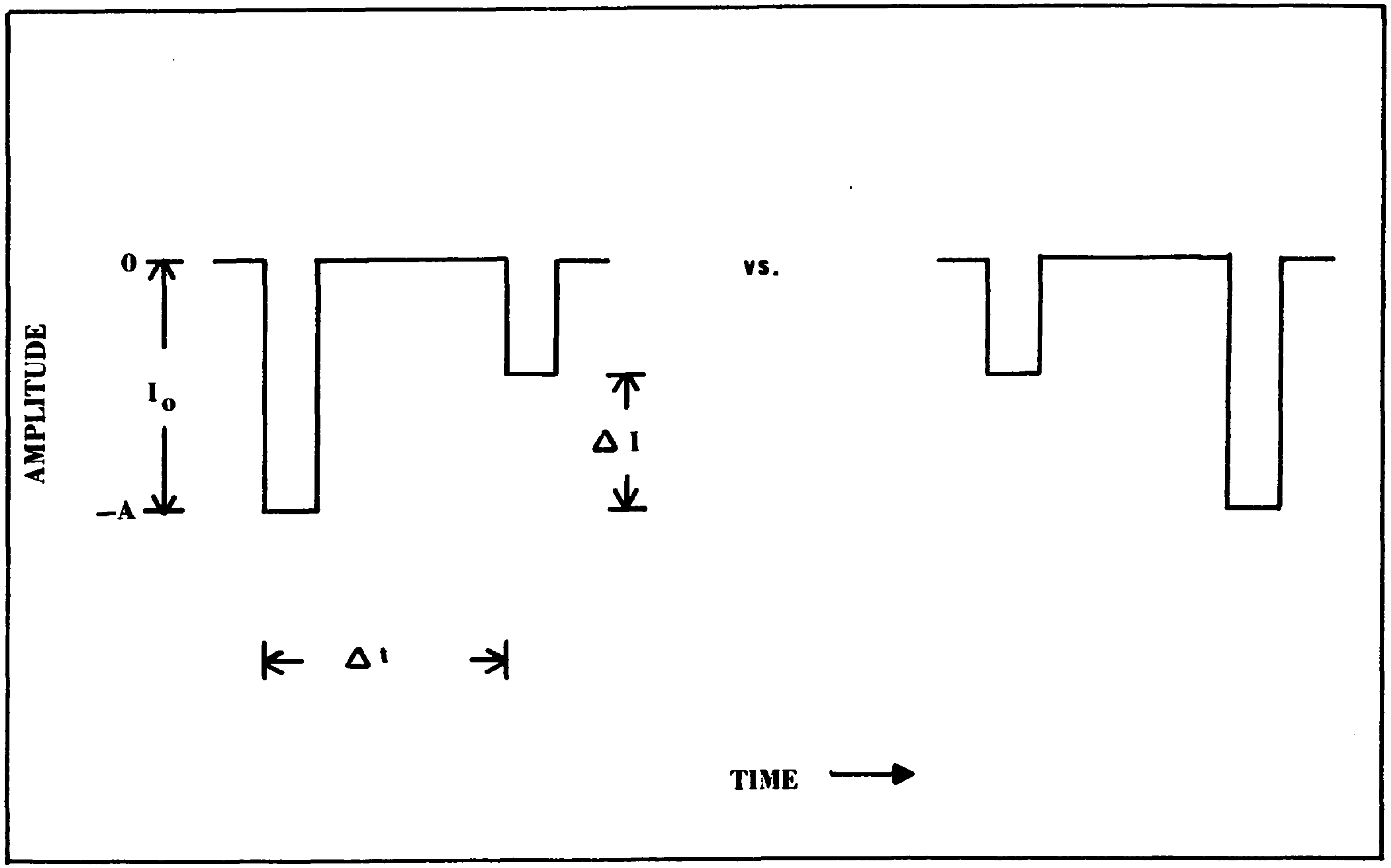
The discrimination of stimuli with temporal differences in the microsecond range has been demonstrated in several investigations employing transient, and characteristically (although not exclusively) repetitive stimuli, presented to highly-trained listeners responding with the constraints imposed by a forced-choice procedure. Pollack (1967, 1969) has demonstrated the auditory system's sensitivity to the introduction of temporal irregularities in a periodic pulse train ("jitter discrimination") or to the change in the temporal spacing of a single pulse pair within a periodic pulse pattern ("gap discrimination") for temporal intervals shorter than 20 μsec. Pollack (1968) concluded that the inherent variability of the neural response patterns within the central auditory system precluded discrimination of those signals on a temporal basis and attributed the discrimination to spectral analyses performed by the auditory system. Leshowitz (1971) has reported that the minimal interval between a pair of 10 μsec pulses at which his listeners were able to discriminate the 10 μsec pulses from a single 20 μsec pulse (of equal total energy) deteriorated from a value of 10 μsec subsequent to low-pass filtering or to attenuation of the clicks. The deterioration in performance subsequent to those manipulations, in combination with consideration of the theoretical distribution of the spectral energy of the stimuli, led Leshowitz to conclude that the basis for the discrimination was the energy difference between the stimuli in the frequency region above 10,000 Hz.

In order to cirvumvent the problems associated with spectral confounding, Green and his colleagues have pursued the investigation of auditory temporal acuity using forced-choice procedures in which the stimuli to be discriminated offer identical power spectra but differ with respect to their phase spectra and, therefore, with respect to their waveforms. The ability of listeners to discriminate among continuous signals which are identical in their power spectra but differ with respect to their phase spectra (and waveform) has been amply demonstrated in investigations of monaural phase perception, although the basis of the discrimination has not been established (Mathes and Miller, 1947; Craig and Jeffress, 1962; Raiford and Schubert, 1971). Green and his colleagues have employed transient signals with those same characteristics in order to document the minimal signal duration at which those differences in waveform are detectable. Green (1971) recently reviewed several investigations of "temporal acuity" in which the stimuli to be discriminated offered identical power spectra but differed with respect to their phase spectra (and waveforms). He described the basic procedure in those studies as the establishment of some difference in the temporal order of events within the waveform and the progressive reduction of the total duration of the stimuli to a point at which the differences in temporal order are no longer perceptible. It is assumed that in the absence of any spectral or durational cues, the discriminability of the stimuli reflects the auditory system's sensitivity to temporal cues and provides a measure of "temporal acuity" unconfounded by differences in power spectra. Green reported that the limits of temporal acuity found in these investigations were of the order of 1 to 2 msec.

Stimuli which are identical with respect to their energy density (or power) spectra but differ in their waveforms are typified by time-reversed click pairs. An example of the pulse pairs which may be used for generation of those click pairs is represented in Figure 1. Ronken (1970), in a study to be discussed later in this chapter, studied the detectability of the reversal of the order of presentation of the more intense and less intense clicks within a pair at various interclick intervals. In discussing the characteristics of the click pairs, Ronken noted that each pair may be considered to be a single transient and that the reversal in the order of the clicks within that transient is reflected in the phase spectra of the Fourier transforms of those click pairs but not in the power spectra of those transforms.

Patterson and Green (1970) employed Huffman sequences to assess the discriminability of transient signals which offer identical power spectra but different phase spectra. For a detailed description of the characteristics of Huffman sequences, the reader is referred to those authors' publication. Briefly, Huffman sequences are broad-band signals,

Figure 1.--Schematic representation of the pulses used for generation of the time-reversed click pairs. The level of the more intense click, the interclick intensity ratio and the interval between the onsets of the clicks within the click pairs (generated by those pulses) are designated I_0, ΔI and Δt, respectively.



AMPLITUDE
0
I_o
-A
ΔI
Δt
vs.
TIME

the frequency components of which are constant in phase except within a narrow band of frequencies within which the phase changes rapidly by 2π radians; that phase change produces a "selective delay in the frequency bands where the rapid change in the phase characteristic occurs". These stimuli permit the introduction of phase differences in limited frequency regions, whereas the time-reversed click pairs are characterized by differences in phase throughout the frequency range. Patterson and Green noted that a period of "considerable training" was required before their subjects were able to make the "subtle discriminations" necessary for identification of the Huffman sequences in a two-alternative forced-choice procedure. Of particular relevance to this review are the effects of duration on the discrimination of a Huffman sequence with its first singularity (or region of rapid phase change) at 800 Hz from a Huffman sequence with its first singularity at 1600 Hz. Reduction in signal duration for those stimuli is associated with a reduction in the relative delay of energy in the different frequency regions; therefore, the minimal duration at which the signals are discriminable may be considered to reflect the limit of the auditory system's sensitivity to differences in the waveform. The percentage of correct discriminations, P(C), was shown to increase from 50% for stimuli that were 1.25 msec in duration to 70% and 100% as the stimuli were increased in duration to 2.5 msec and 10 msec, respectively.

Green (1973) modified the time-reversed click paradigm earlier employed by Ronken (1970) and varied certain parameters of the Huffman sequences employed by Patterson and Green (1970) in an attempt to ascertain the extent to which temporal acuity is dependent upon the frequency components of the signals. In one experiment, the ability of subjects to discriminate a comparison Huffman sequence with a variable energy delay from a standard sequence with an energy delay equal to one-half the duration of the sequence was evaluated using a two-alternative forced-choice procedure. The standard sequences had center frequencies equal to those of the sequences with the variable energy delay; those center frequencies were 625 Hz, 1875 Hz, and 4062 Hz. The standard sequences were 3.2 msec, 6.4 msec and 12.8 msec in duration and had energy delays of 1.6 msec, 3.2 msec and 6.4 msec, respectively. The just noticeable change in delay required for discrimination of the stimulus (the discriminable delay) was of the order of 2 msec for Green's well-practiced subjects. That value was not altered systematically as a function of the frequency region in which the energy delay occurred, but the sequences which were 12.8 msec in duration consistently resulted in discriminable delays which were larger in value than those obtained with shorter stimuli. In addition, the effect of signal level on discrimination performance was evaluated for a sequence which was 12.8 msec in duration and was centered at 1800 Hz. An increase in the signal level from 25 dB to 35 dB SL was accompanied by a reduction in the discriminable delay but additional increases in the level to 65 dB SL had a minimal effect.

In the second experiment discussed in the same publication, Green altered the stimulus configuration employed by Ronken, in the following manner. Sinusoidal signals (1000, 2000 and 4000 Hz) were presented for a total duration of T msec; for T/2 msec of that period, the signal level was 10 dB higher than for the other T/2 msec. The subjects' task was to discriminate between stimuli which differed only in the order of presentation of the more intense portion of the signal. The effect of signal frequency on the discrimination of those transient signals was considered to be insignificant. Green, however, observed that a duration of 2 msec produced optimal discrimination of the time-reversed sinusoidal signals; performance peaked in the region of 2 to 4 msec, declined in the 4 to 32 msec region, and improved again at longer durations of the stimuli. He also reported that when signal duration was fixed at 2 msec, manipulation of the intensity relationship existing between the two halves of the signal did alter the discriminability of the signals. Performance was found to be optimal when the intensity differences between the two halves of the signal were on the order of 5 to 10 dB and deteriorated when those differences were either increased or decreased.

In an earlier publication, Ronken (1970) explored the effects of the same intensity manipulations on the discriminability of time-reversed click pairs at various interclick intervals (Δt). The clicks were presented binaurally. The relative amplitude of the clicks (ΔI) constituting a click pair served as the dependent variable. The value of ΔI was determined using an adaptive two-alternative forced-choice procedure. The adaptive procedure employed was PEST (Parameter Estimation by Sequential Testing), developed by Taylor and Creelman (1967). Taylor and Creelman characterized PEST as an efficient method for determination of a signal parameter which provides no information regarding the shape of the psychometric function and assumes knowledge by the experimenter of the sign of that psychometric function. The level of the more intense click (I_0) was fixed at about 55 dB SL. The interaction of the relative amplitude of the clicks within the click pairs with the temporal separation required for correct discrimination of the signals makes interpretation of the data with respect to the temporal resolving ability of the auditory system difficult.

Ronken did report that when the interval between the onset of the clicks within a click pair was 1 msec, the two trained subjects obtained less than 75% correct on a "disproportionate" number of trials. The implication of this with respect to the PEST procedure was that no value of ΔI could be established for a Δt of 1 msec. Inspection of the data presented graphically indicates that both observers achieved 75% correct discrimination of the time-reversed click pairs at Δt values of 2 msec with a ΔI of 6 dB. At an interclick interval of 5 msec, however, one subject required a ΔI value of 10 dB whereas the other subject required a ΔI value of only 4 dB to make the discrimination. Performance near chance occurred when the interclick intensity ratio was less than 1 dB, while ratios greater than 10 dB resulted in errorless performance at an interclick interval of 5 msec. Ronken considered the basis on which the signals were discriminated as "not clear" but discounted as "implausible" the notion that discrimination of the click pairs was based on the "asymmetry between forward and backward masking". This is an issue to be discussed in considerable detail later in this chapter.

Babkoff and Sutton (1971), using time-reversed click pairs comparable to those employed by Ronken, offered additional documentation of the effects of intensity on the discrimination of the click pairs and demonstrated that discrimination of those click pairs is a nonmonotonic function of the interclick interval. Their interest was not in examining the temporal resolving power of the auditory system but, rather, in evaluating the presence of "interpulse interactions" existing at interclick intervals at which pairs of clicks are discriminable from single clicks. They attempted to assess that interaction at interclick intervals at which the less intense clicks of both click pairs were above their masked threshold, as determined from previous studies of temporal masking. A three-interval forced-choice procedure was used to determine the ability of their two trained subjects to discriminate a pair of clicks of unequal level in which the less intense click preceded the more intense click from click pairs in which the order of presentation of the clicks was reversed.

Babkoff and Sutton investigated the effect of three variables on the discriminability of the click pairs: the level of the more intense click; the interclick intensity ratio; and the interclick interval. The more intense click was presented at levels between 20 and 70 dB SL. The values of the interclick intensity ratio which were employed exceeded those of Ronken's study, being greater than 10 dB. Psychometric functions representing the percentage of correct discriminations, P(C), as a function of the interclick interval were presented for intervals between 0.5 and 20.0 msec. Those psychometric functions were nonmonotonic. The shape of the psychometric functions was altered, however, by manipulation of the interclick intensity ratio. P(C) increased as the interclick interval increased, remaining high at temporal values of 5 to 6 msec for large values of the interclick intensity ratio (ΔI=30 dB) and then decreased. Smaller values of the interclick intensity ratio (ΔI=15 dB) resulted in a decrease in performance at values of Δt shorter than 5 msec. Interpretation of the data which were presented graphically suggests that the steepness of those psychometric functions was inversely related to the overall signal level and, furthermore, that discrimination of the click pairs was achieved at interclick intervals of 0.5 msec and 1.0 msec for several values of the interclick intensity ratio.

Green (1973), in commenting on the nonmonotonicity of the psychometric functions which represented P(C) as a function of the total duration of the time-reversed sinusoidal signals, proposed that the optimum discrimination performance occurs in the region of 2 msec and deteriorates at longer temporal intervals because "with a brief sound it is easier to listen for the slight qualitative differences between the two bursts," while at longer durations, the "qualitative differences become more difficult to hear because the tonal quality of each burst becomes more prominent." This explanation sheds no light on the nature of the "qualitative differences" which permit discrimination of the signals. It may be argued that if the qualitative differences are obscured at the longer durations due to the relative prominence of the tonal quality of the bursts, then no reduction in discrimination performance should accompany the use of time-reversed click pairs when the interclick interval is extended beyond 2 msec. Babkoff and Sutton (1971) have demonstrated this same deterioration in discrimination performance when click pairs are employed as the stimuli.

The implication of the results reported by Babkoff and Sutton (1971) for the estimates of the temporal threshold derived from the investigations of Ronken (1970) and Green (1973) merit consideration. The results reported by Babkoff and Sutton indicate a relationship between the discriminability of time-reversed stimulus pairs, such as those employed by Ronken and by Green, and interstimulus intensity differences, as well as the overall level of stimulus presentation. The observation that intensity relationships alter the discrimination of the time-reversed click pairs has implications for the mechanism that has been assumed to mediate that discrimination. Intensity manipulations have been demonstrated to affect systematically the detectability of a less intense click which precedes or follows a more intense click in investigations of temporal masking. Should the discriminability of time-reversed click pairs be shown to reflect interactions between the clicks that are predictable on the basis of temporal masking data, the assumption that the mechanism mediating discrimination of the click pairs reflects only the temporal resolving capabilities of the auditory system may be considered questionable. It appears essential to determine whether the relationships between the intensity manipulations and the discriminability of the click pairs which were reported by Babkoff and Sutton (1971) extend to the range of interclick intensity ratios employed by Ronken. That is the aim of the proposed investigation. To the extent that the discrimination of the time-reversed signals is related to temporal masking, the effects of level manipulations on discrimination of those signals would be predictable on the basis of previous investigations of temporal masking. In order that the reader may appreciate the nature of those predictions, a brief review of temporal masking data, as it relates to click stimuli, is presented in the following section of this chapter.

Temporal Masking

Temporal masking may be defined as the elevation in threshold for a signal which results when a more intense masking signal precedes (forward masking) or follows (backward masking) that signal in time (Studebaker, 1973). In studies of temporal masking the masking signals typically have been restricted to levels below about 90 dB SPL and to relatively short durations so as to minimize the possibility of long-term fatigue effects.

Forward Masking

Forward masking, observed as an increase in the threshold of a signal (the probe or masked signal) presented following the offset of the masking signal, relative to the threshold for the test signal in quiet, has been regarded as a method of assessing the residual sensation in response to the masking signal. The demonstration of forward masking, (also termed "short-duration fatigue" and "residual masking") has been employed as a vehicle for exploration of the frequency selectivity of the auditory system (Harris, Rawnsley and Kelsey, 1951; Harris and Rawnsley, 1953; Glattke and Small, 1967) as well as a method for assessing the effects of stimulus intensity on the duration of residual sensation (Lüscher and Zwislocki, 1947, 1949; Rawnsley and Harris, 1952; Samoilova, 1959). More recently, the extent to which forward masking represents a peripheral phenomenon has been questioned by several investigators who have cited the demonstration of forward masking under conditions in which the masked signal is presented to one ear and the masking signal is presented to the contralateral ear as evidence of the contribution of a central mediator (Elliot, 1962b; Deatherage and Evans, 1969). In addition, the demonstration of masking level differences under conditions of forward masking (Deatherage and Evans, 1969; Small, Boggess, Klich, Kuehn, Thelin and Wiley, 1972) has been interpreted as supporting the concept of central mediation of forward masking.

Backward Masking

Backward masking is observed as an increase in the threshold for the probe signal presented prior to the onset of the masking signal as compared with the threshold for that probe signal in quiet. Traditionally, backward masking has been attributed to a decrease in the delay of synaptic transmission of the neural response elicited by the more intense masking signal, which causes the impulse evoked by that signal to reach a central neural site prior to the arrival of the impulse evoked by the first stimulus. The view that backward masking is mediated centrally is shared by several investigators (Guttman, van Bergeijk and David, 1960; Raab, 1961; Elliot, 1962a,b; Wright, 1964; Deatherage and Evans, 1969). The presence of masking level differences under conditions of backward masking (Deatherage and Evans, 1969; Dolan and Trahiotis, 1972; Small *et al.*, 1972) and forward masking (Deatherage and Evans, 1969; Small *et al.*, 1972) for tonal signals, led Small and his co-workers to suggest a commonality of the mechanisms mediating backward and forward masking at a central neural site.

There is an extensive body of literature devoted to specification of the significant variables affecting the backward masking and forward masking of tonal signals. In general, it may be said that temporal masking is directly related to the level of the masking signal and inversely related to the interval between the masking signal and the probe. Backward masking decreases more rapidly as a function of the interstimulus interval than does forward masking, and the time course of the functions appears to be different as well. These differences have given rise to the term, the "asymmetry" of backward and forward masking. For a brief review of the literature pertaining to the temporal masking of tonal signals, the reader is referred to recent publications by Elliot (1971) and Wilson and Carhart (1971). The review included in this chapter is confined largely to discussion of the temporal masking of clicks by clicks.

Temporal Masking of Clicks

Assessment of the temporal masking of one click by a preceding or subsequent click is complicated by the spectral changes attendant upon the introduction of the probe click (Robinson and Pollack, 1971). Possibly as a consequence, the criteria employed by the subject in making a judgment regarding the presence of the masked click has been shown to influence substantially the amount of masking recorded (Chistovich and Ivanova, 1959).

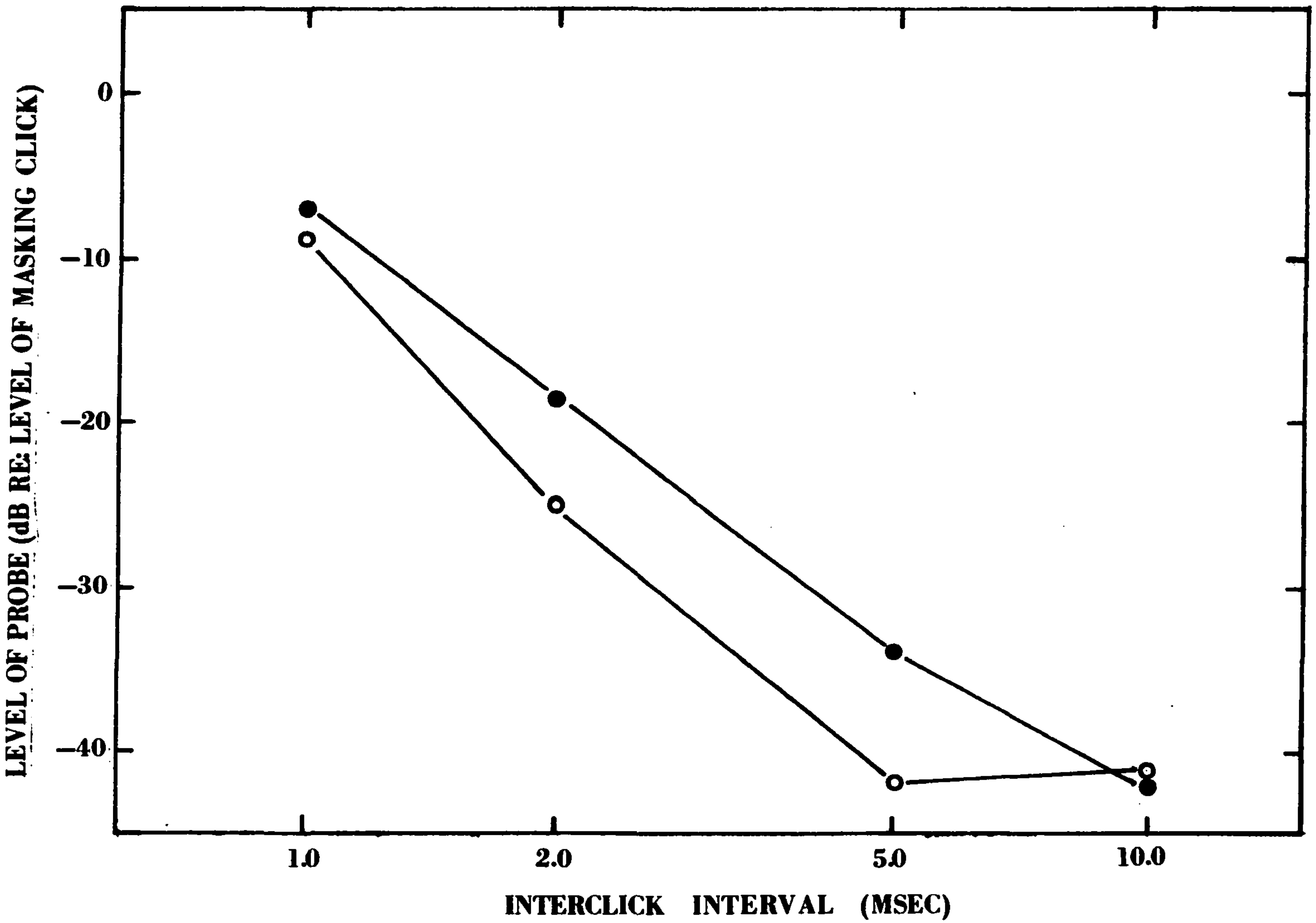
Chistovich and Ivanova (1959), investigating the masking of one click by a preceding or following click presented at 63 dB SL, noted that when the clicks were separated by a sufficiently brief interval, the subjects did not perceive the individual clicks but responded to a change "in the character of sensation including increased loudness, increased duration or 'cracking'." The decrease in masking as a function of time was found to be more rapid than that reported for tonal stimuli but the steepness of those functions was reduced when the subjects were instructed to report the detection of two clicks rather than detection of an alteration in the quality of a single click. When the subjects were faced with the task of discriminating between a single masking click and a click pair, the masking was reported to be independent of the interval between and the sequence of the clicks within the temporal range extending from 1.5 msec preceding the onset of the masker to 1.5 msec following its offset. Increasing the interval between the masking click and the probe to values in excess of 1.5 msec produced a rapid decrease in masking; backward masking had ceased for temporal intervals greater than 5 msec while forward masking continued for approximately 30 msec following the offset of the masker. The asymmetry between forward and backward masking reported by Chistovich and Ivanova is apparent from the graphic presentation of their data. Evaluation of the extent of that asymmetry is hampered, however, by the combination of the rapid change in masking with time and the compressed time scale of their graph.

The backward and forward masking of one click by another click was also investigated by Raab (1961). Unfortunately, interpretation of his data for the temporal masking produced by masking clicks presented at 70 dB SL and 85 dB SL is subject to the same limitations previously cited for the investigation conducted by Chistovich and Ivanova (1959). Inspection of the graphs presented by Raab does reveal that increasing the level of the masking click produces a greater increase in the magnitude and duration of forward masking than of backward masking and, therefore, suggests that the asymmetry of the forward-masking and backward-masking functions is enhanced when the intensity of the masking click is increased.

A detailed description of the temporal masking of one click by another click for interclick intervals between 1 and 10 msec was provided by Ronken (1970). The level of the masked click required for its detection (or more correctly, the level required for discrimination of the combination of the masking signal and probe from the masking signal alone) was determined as a function of the interclick interval for a single subject in a two-alternative forced-choice procedure. The masking click was presented at approximately 56 dB SL. The data presented by Ronken have been replotted in Figure 2 to facilitate comparison of the time course of forward and backward masking. In Figure 2, the mean level of the probe (relative to the level of the masking click) required for its detection is plotted as a function of the interclick interval. Ronken stated that backward and forward masking are "approximately symmetrical" for interclick intervals of 1 msec and 10 msec. Forward masking was found to exceed backward masking by about 5 dB at 2 msec and about 8 dB at 5 msec. Thus the asymmetry increased as the temporal separation was increased from 1 to 5 msec; that asymmetry was absent at an interclick interval of 10 msec.

Additional information regarding the asymmetry of backward and forward masking is available from the data of Babkoff and Sutton (1968). Using a variant of the temporal-masking paradigm, they sought to determine the minimal temporal separation between clicks of unequal intensity required for detection of the less intense click. The interclick interval, rather than the click level, served as the dependent variable. The one "well-trained" subject was presented with a pair of clicks which he was to discriminate from a single click (equal in level to the more intense click of the click pair) in a three-interval forced-choice

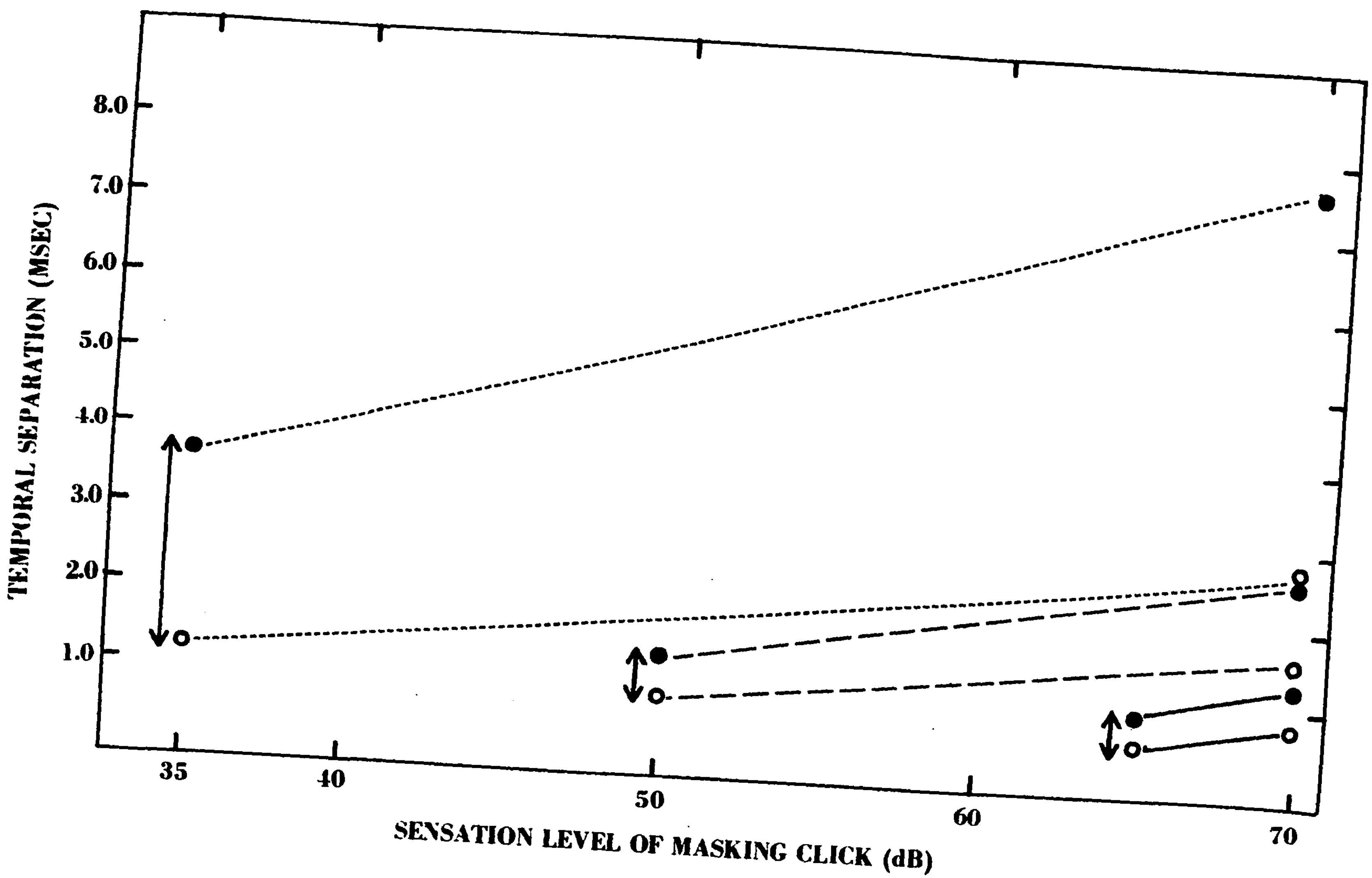
Figure 2.--Masked threshold of a probe click as a function of the interval between the probe click and the masking click. The level of the masking click was 55 dB SL. Masked threshold was determined under conditions of backward masking (○) and forward masking (●). Modification of Figure 8-2, Ronken (1970).


0
−10
−20
−30
−40
LEVEL OF PROBE (dB RE: LEVEL OF MASKING CLICK)
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

procedure. The more intense (or masking) click was presented at levels between 40 and 70 dB SL; the less intense click was presented at 15, 30 and 45 dB SL. The level of the more intense click within a click pair always exceeded the level of the less intense click by at least 20 dB. As anticipated from the results of other investigations of temporal masking, the authors found that the temporal separation required for detection of the less intense click was greater when the more intense click preceded the less intense click (forward masking) than when the order of the clicks was reversed (backward masking). The temporal separation required for detection of the less intense click increased as the interclick intensity ratio increased (i.e., the less intense click was reduced in level) and as the level of the more intense click increased. The greatest temporal separation (7.0 msec) was required when the 70 dB SL click was followed by a 15 dB SL click; the smallest temporal separation (0.75 msec) was required when the 45 dB SL click preceded the 70 dB SL click.

A compilation of the data reported by Babkoff and Sutton is presented in Figure 3. Their data have been replotted with time on a linear scale, rather than on the logarithmic scale which they employed. In Figure 3, the temporal separation required for detection of the less intense click in the backward-masking and forward-masking conditions is plotted as a function of the sensation level of the less intense click. Inspection of Figure 3 reveals that for a given level of the masking signal, the asymmetry is least at the lowest interclick intensity ratio (i.e., when the level of the two clicks within a pair are most nearly comparable, the difference in the interclick intervals required for

Figure 3.--Temporal separation required for detection of a probe click, as a function of the level of the masking click, under conditions of backward masking (O) and forward masking (●). The level of the probe click was 15 dB SL (---------), 30 dB SL (— — —) or 45 dB SL (———). Modification of Figure 2, Babkoff and Sutton (1968).



TEMPORAL SEPARATION (MSEC)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
35
40
50
60
70
SENSATION LEVEL OF MASKING CLICK (dB)

detection of the less intense click in the forward-and backward-masking conditions is smallest). It is also apparent from Figure 3 that the asymmetry at a given interclick intensity ratio (such as that for ΔI of 20 dB, indicated by the arrow) is reduced as the intensity of the more intense click is increased.

The studies of the temporal masking of clicks have been reviewed to provide the reader with information regarding the effects of intensity manipulations on the asymmetry of temporal masking. If the discriminability of the time-reversed click pairs is related to the asymmetry of temporal masking, then manipulation of the overall signal level and of the interclick intensity ratio should affect the discriminability of the time-reversed click pairs in a manner predictable from the temporal masking data which has been reviewed. The predicted effects of those level manipulations are presented in the following section of this chapter.

The Predicted Effects of Intensity on the Discriminability of the Time-Reversed Click Pairs

If one assumes that the asymmetry of forward and backward masking is reflected at suprathreshold levels, it follows that clicks which are presented at the same suprathreshold intensity level (and same Δt) but which differ in order of presentation relative to the more intense click, are at different levels above masked threshold. The following example is intended to clarify the above statement. Refer to the left-hand portion of Figure 3 for the results obtained by Babkoff and Sutton for a masking click at 35 dB SL and a probe click at 15 dB SL. Under conditions of forward masking, a temporal separation of 3.4 msec is required for detection of the probe click; only a 1.4-msec separation is required for detection of the probe click under conditions of backward masking. If the level of the probe click is increased, then the degree to which the probe exceeds masked threshold will be greater in the backward masking condition than in the corresponding forward masking condition.

In addition, the data obtained from Ronken's (1970) investigation of temporal masking indicate that the degree of the asymmetry increases as the temporal separation between the masker and the probe is increased for temporal separation less than 5 msec.

If the assumption that the asymmetry of temporal masking is reflected at suprathreshold levels is valid and if discrimination of the time-reversed click pairs is related to the asymmetry of temporal masking, then discrimination of those click pairs should be altered by manipulation of click level in the manner described below:

1. Increasing the level of the more intense click decreases the asymmetry in detection of the less intense click and, thereby, decreases the asymmetry at suprathreshold levels. The temporal separation between the clicks required to produce a given asymmetry in the level of the less intense clicks (above masked threshold) must increase as the level of the click pairs is increased. Thus, an increase in the level of presentation should result in an increase in the interclick interval necessary for discrimination of the time-reversed click pairs.

2. Decreasing the interclick intensity ratio (while maintaining I_0 constant) also decreases the asymmetry in detection of the less intense click. Clicks which are closer in level to that of the more intense click are at more nearly equivalent levels above the masked threshold at a given interclick interval than are clicks which are much lower in level than the more intense click. Thus, the temporal separation between the clicks within a pair must be increased, as the interclick intensity ratio is decreased, in order to reach a given degree of asymmetry. Therefore, a decrease in the interclick intensity ratio should result in an increase in the interclick interval necessary for discrimination of the time-reversed click pairs.

In summary, an increase in the level of the click pairs or a reduction in the interclick intensity ratio would be expected to produce an increase in the interclick interval required for the time-reversed click pairs to become discriminable _if_ the discriminability of those stimuli is related to the asymmetry of temporal masking. The demonstration of a relationship between the asymmetry of temporal masking and the discriminability of the time-reversed click pairs must cast doubt on the assertion that the use of those click pairs permits assessment of the temporal resolving power of the auditory system. The temporal resolving power presumably reflects the functioning of a more peripheral portion of the auditory system than is generally considered to be responsible for the mediation of temporal masking.

The following chapter presents a description of the experimental procedures employed to determine the relationship between the discriminability of the time-reversed click pairs and the level of presentation and interclick intensity ratio of those click pairs.

CHAPTER III

SUBJECTS, STIMULI, PROCEDURES

Introduction

The present investigation was conducted to determine the effects of the level of signal presentation and the interclick intensity ratio on the discriminability of time-reversed click pairs. The ability of individuals with normal hearing to discriminate a click pair in which the more intense click precedes the less intense click from a click pair in which the order of the clicks is reversed was determined using a two-interval forced-choice procedure. The influence of the level of signal presentation and the effect of the intensity ratio of clicks within the click pairs on the discriminability of those time-reversed click pairs were evaluated for interclick intervals between 0.5 and 10.0 msec.

The experimental task, the characteristics of the test signals and the methods employed in the generation, presentation and calibration of those signals are described in sections of this chapter. Also included in this chapter are a discussion of the criteria employed in subject selection and a description of the training and testing procedures.

Subjects

The five adults (two males and three females) who served as subjects in the present investigation were selected from a group of eight volunteers on the basis of their availability and their demonstrated ability to perform the experimental task with consistency. The participants, one of whom was the investigator, ranged in age from 22 to 31 years. All subjects demonstrated hearing sensitivity for pure-tones which was no poorer than 15 dB re: the ANSI 1969 standards for the frequencies at octave intervals from 250 Hz to 8000 Hz. Three of the subjects had participated in other psychoacoustic investigations; the other two subjects had no prior experience as listeners in investigations of this sort. Two of the subjects (one of whom was the investigator) were familiar with the phenomenon under investigation as well as with the hypothesized effects of the experimental manipulations; the other three subjects were acquainted only with the nature of the experimental manipulations.

Acoustic Environment

The experiment was conducted in a two-room acoustically-treated audiometric test suite which was located at the Speech and Hearing Center of the University of Oklahoma Health Sciences Center. The subject was seated in one room; the experimental apparatus, with the exception of the earphones and subjects' response box, was located in the adjoining room. A "talk-back" system permitted verbal communication between the subject and the experimenter.

The ambient noise level in the room was measured using a sound level meter (General Radio, Type 1551-C) in conjunction with an octave-band analyzer (General Radio, Type 1558-AP). The noise levels in the octave bands between 125 Hz and 8000 Hz were lower than those which would be anticipated to produce masking for pure-tone signals presented via earphones at 0 dB HTL re: ANSI 1969.

Experimental Conditions

The manipulations which constituted the various experimental conditions were applied to the three parameters defining the time-reversed click pairs as represented in Figure 1 (page 27): the level of the more intense click (I_0); the interclick intensity ratio (ΔI) and; the interval between the onsets of the clicks within a pair (Δt). The interclick intensity ratio (ΔI) is defined as the difference in the amplitudes of the clicks within a click pair, expressed in dB. The level of signal presentation is specified with reference to the level of presentation of the more intense click (I_0).

The more intense click was presented at one of two fixed levels (I_0); one corresponded to a level of approximately 75 dB SL for a single click, and the other corresponded to a level of approximately 45 dB SL for a single click. Four values of the interclick intensity ratio (ΔI) were employed such that within a click pair, the level of the more intense click exceeded that of the less intense click by 3, 6, 12 or 24 dB. The discriminability of each of the eight conditions representing the combinations of I_0 and ΔI was assessed as a function of the temporal interval between the onset of the clicks within a pair for temporal intervals between 0.5 msec and 10.0 msec. The eight values of Δt selected were 0.5, 0.75, 1.0, 1.5, 2.0, 2.5, 5.0 and 10.0 msec. Thus, there was a total of 64 experimental conditions. The click pairs were presented monaurally to the right ear of each subject.

The discriminability of the click pairs was determined using a two-interval forced-choice procedure (2IFC). That is, each of the click pairs was presented in one of the two observation intervals constituting a trial. The subjects' task was to identify which of the two observation intervals contained the click pair in which the less intense click preceded the more intense click (McFadden, 1970). Immediate feedback was provided.

Training and Testing Procedure

In view of the nature of the discriminations required of the subjects, it was necessary to expose them to a lengthy period of practice prior to the collection of data. A discussion of that training procedure as well as of the testing procedure is presented in the following sections of this chapter.

Instructions

The extensive practice in which the subjects participated eliminated the necessity for detailed instructions. Instead, the subjects were acquainted with the general features of the procedure and were cautioned regarding response tendencies that might have a deleterious effect on performance.

The subjects were familiarized first with the nature of the signals to be presented and with the types of stimulus manipulations which constituted the various experimental conditions. The orientation was followed by a description of the conduct of the training and test sessions. The sequence of events within a single trial was discussed and demonstrated. The subjects were informed that discrimination of the click pairs was dependent on features of the signal that would become apparent with practice and that the purpose of the feedback lights was to assist them in learning to identify the appropriate click pair by utilizing any cues which they judged to optimize their performance.

The subjects were advised that the click pair whose interval of occurrence they were to identify (i.e., the pair in which the less intense click preceded the more intense click) had an equal probability of occurring in either the first or second observation interval on any given trial; they were cautioned against attempting to predict the interval of occurrence of the signal pair based on its occurrence in previous trials. In addition, the subjects were told that, under various conditions, discrimination of the signals might depend upon the level of the signals but that the level at which the signals were most easily discriminated might vary with changes in other signal parameters. This information was communicated to the subject in an effort to reduce any biases developed by the subject regarding the relative discriminability of the signals as a function of the level of signal presentation, independent of other stimulus manipulations.

Training Sessions

A total of at least 10,000 training trials was administered to each of the subjects prior to the initiation of the experimental testing. Each of the 64 experimental conditions was administered in at least one block of trials. A block consisted of 100 trials. Only 50 trials were administered for those conditions under which the subject demonstrated 100% correct discriminations. Those experimental conditions selected for administration more than one time were generally those for which the subject achieved less than 85% correct discriminations on the first presentation.

Generally, 7 to 10 blocks of 100 trials were administered in a single training session. Completion of a block of trials required about 8 minutes. Consequently, 12 to 15 one-hour training sessions were required to complete the 10,000 training trials.

Experimental Sessions

The order of presentation of the 64 experimental conditions was predetermined in the following manner. Administration of the four interclick intensity ratios (ΔI) was counterbalanced across four of the subjects in accord with a Latin squares design. The order of presentation of the conditions to the fifth subject was identical to that of one of the other four subjects. Within a single experimental session the value of ΔI was kept constant; that ΔI was maintained for two consecutive experimental sessions in order to allow completion of the 16 conditions involving that ΔI. The order of presentation of the eight values of Δt (within the two experimental sessions at a given ΔI) was randomized independently for each ΔI and for each subject. The two blocks of trials which were presented successively at a specified combination of Δt and ΔI differed with respect to the level of signal presentation (I_0). The order of presentation of the two I_0 conditions was counterbalanced across the Δt values.

Thus, the eight blocks of trials in each experimental session provided data on the discriminability of click pairs presented at one interclick intensity ratio for four values of Δt and both levels of I_0. Eight experimental sessions were required to complete administration of the 64 experimental conditions. The experimental procedure was completely replicated for each subject; in the second group of eight experimental sessions, the order in which the conditions were presented was completely reversed.

Each experimental session occupied approximately a 70-minute period during which brief rest periods were provided between blocks of trials. The blocks of trials usually consisted of 100 trials, presented in two consecutive sets of 50 trials. Only a brief interruption, sufficient for recording the tabulated responses, followed the first 50 trials. Under those circumstances in which the two sets of 50 trials yielded differences greater than 5 in the number correct, a third set of 50 trials was administered for that same experimental condition. The computation of the percentage of correct discriminations, P(C), was based on those two sets of 50 trials which yielded the best performance, provided those two sets of trials differed by no more than 5 in the number of correct discriminations.

The P(C) scores obtained by each subject for the two blocks of trials, administered under the same experimental condition, were compared. If the P(C) scores for a given experimental condition differed by more than 15%, and if one P(C) score was greater than 75% but the other was less than 75%, then that experimental condition was administered in a third block of 100 trials. The computation of P(C), in those cases, was based on the two blocks of trials for which the P(C) values were most comparable.

Experimental Apparatus

Automation of the two-interval forced-choice procedure, including the presentation of the test signals, the tabulation of responses and the presentation of feedback was achieved through the use of the

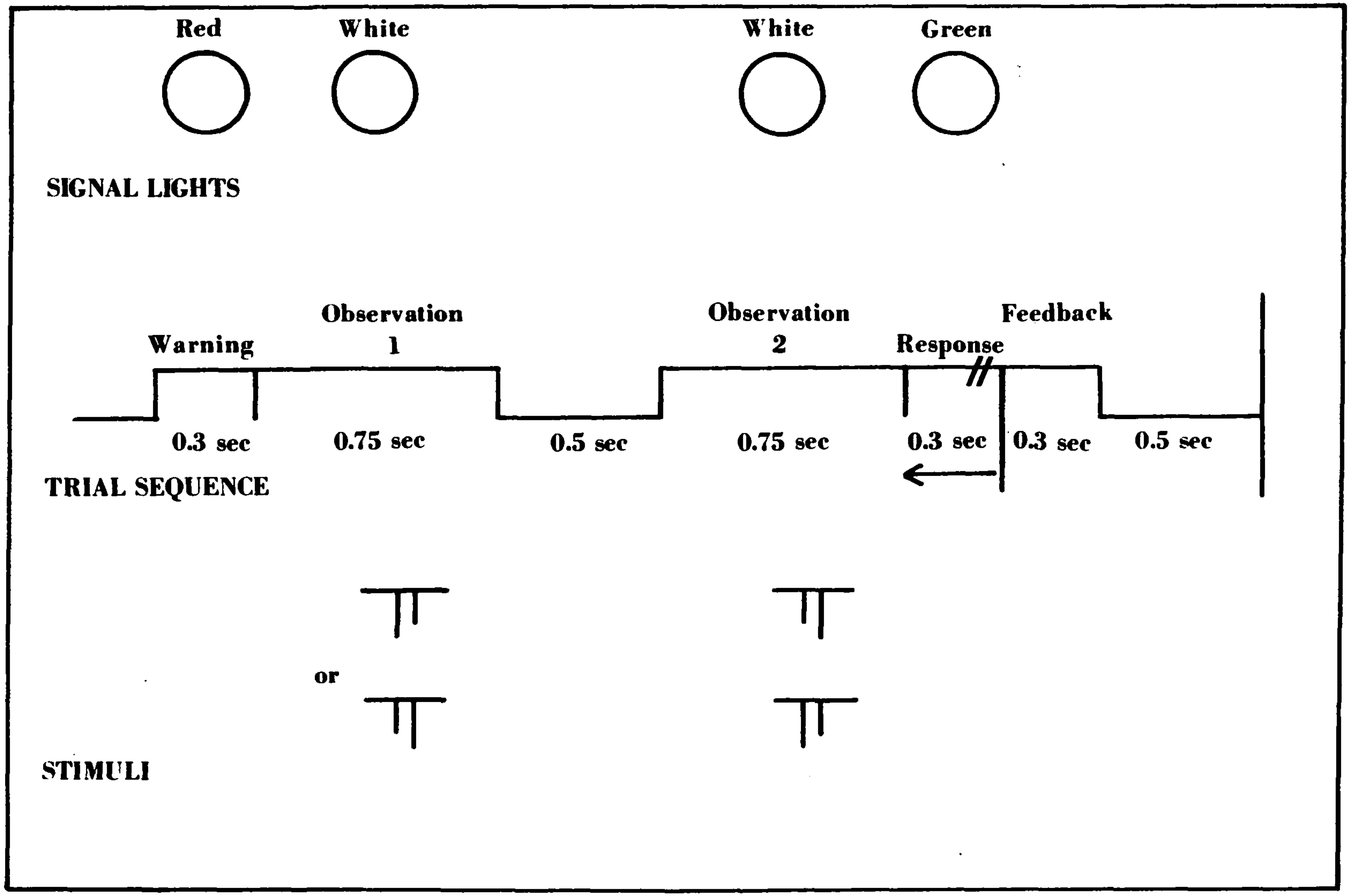
Grason-Stadler 1200 modular programming system. A detailed schematic of the program is available in Appendix A.

Trial Sequence

The sequence of events within a single trial is illustrated in Figure 4. The order and the duration of the various intervals comprising a trial sequence were controlled by 10-second and 100-second TIMERS of the modular programming system. Those same TIMERS controlled the periods during which each of the four lights mounted on the subjects' response box was lighted to mark the intervals and to provide feedback.

The beginning of a trial was marked by the onset of the red light which signalled the 0.3-second warning interval. The warning interval was followed by two successive observation intervals each of which was 0.75 seconds in duration and was marked by one of two white lights. The presentation of each signal pair was delayed 0.45 seconds from the beginning of each observation interval. The observation intervals were separated by a 0.5-second silent interval. The second observation interval was followed by a 0.3-second response interval which was marked by a green light. A response by the subject, occurring subsequent to the onset of the green light, was recorded and initiated a 0.3-second feedback interval. The beginning of the subsequent trial was delayed by 0.5 seconds from the termination of the feedback interval. Thus, there was always a period of 0.8 seconds between the recording of a response and the beginning of the next trial. Feedback was provided by lighting the white light corresponding to the observation interval in which the designated click pair (i.e., that pair in which the less intense click preceded the more intense click) had occurred. The procedural recom-

Figure 4.--Sequence of events within a single trial for the two-alternative forced-choice procedure.


Red
White
White
Green
SIGNAL LIGHTS
Observation 1
Observation 2
Feedback
Warning
Response
0.3 sec
0.75 sec
0.5 sec
0.75 sec
0.3 sec
0.3 sec
0.5 sec
TRIAL SEQUENCE
or
STIMULI

mendations made by Robinson and Watson (1972) were followed in the determination of the duration of the intervals constituting a trial. Those same authors recommended that feedback be presented to indicate the interval during which the designated stimulus had occurred rather than the correctness of the subject's response.

Response Tabulation

The subject responded by pushing one of the white buttons located below each of the two white lights on his response box. The recording of responses was programmed using FLIP-FLOP modules in conjunction with AND GATES to insure that, on any given trial, the first response made by the subject subsequent to the initiation of the response interval was the only response recorded. Four sums, representing all possible combinations of the interval of occurrence of the designated click pair and of the subject's responses were displayed on four cumulative counters. The combination of the interval in which the designated click pair occurred and the response which was associated with the presentation of that click pair in each of the intervals is presented in Table 1. The figures in those four COUNTERS at the end of a block of trials are designated Sum_1, Sum_2, Sum_3 and Sum_4, respectively.

The tabulation scheme permitted rapid determination of the total number of correct responses in a block of trials ($Sum_1 + Sum_2$), as well as the per cent correct, P(C). The computational formula employed for determination of P(C) was adopted from McFadden (1970) and is indicated below:

$$P(C) = \left\{\tfrac{1}{2}\left[Sum_1/(Sum_1 + Sum_3) + Sum_2/(Sum_2 + Sum_4)\right]\right\} \times 100\%$$

This computational formula is based on the *a priori* probabilities of the

TABLE 1

RESPONSE TABULATION

Counter	Interval of Occurrence	Response	Sum
1	1	1	Sum_1
2	2	2	Sum_2
3	1	2	Sum_3
4	2	1	Sum_4

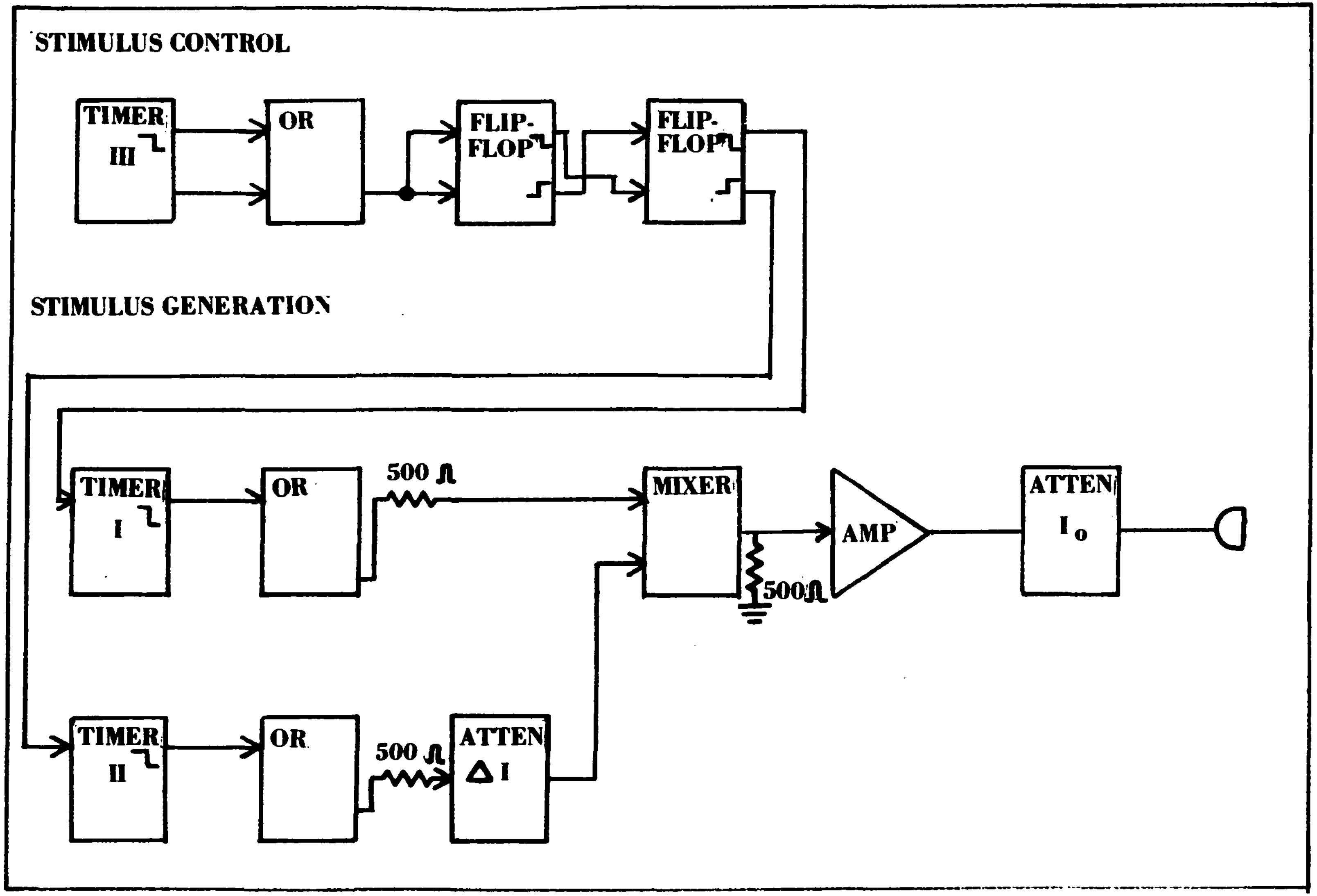
designated stimulus pair occurring in each of the observation intervals rather than on the actual proportion of times it occurred in each of the intervals within a block of trials.

Generation of the Test Signals

The electrical pulses used for generation of the time-reversed click pairs which were employed as the test signals are represented in Figure 1. The time between the onset of successive pulses within a pulse pair is designated Δt. The difference in the amplitudes of the pulses is specified in dB relative to the amplitude of the less intense pulse and is termed ΔI. The amplitude of the more intense click is expressed in dB SL and is designated I_0.

Control of pulse level. The simplified block diagram in Figure 5 represents the equipment used for generation of the click pairs. Independent 100-second TIMERS, TIMER I and TIMER II, produced the 0.1-msec negative pulses which were presented (following transduction by the earphone) as the more intense and less intense clicks, respectively. The

Figure 5.--Simplified block diagram of the equipment used for generation of the time-reversed click pairs.


STIMULUS CONTROL
TIMER III
OR
FLIP-FLOP
FLIP-FLOP
STIMULUS GENERATION
TIMER I
OR
500 Ω
MIXER
AMP
500 Ω
ATTEN I₀
TIMER II
OR
500 Ω
ATTEN ΔI

output of each of the TIMERS was led to a separate dc OR GATE. The dc OR GATES reproduced the pulses generated by the TIMERS and simultaneously reduced the background noise which characterized the output of the TIMERS. The output pulses from the OR GATES were summed using a resistive mixing network. The introduction of the continuously variable attenuator (labelled ATTENUATOR - ΔI), in the branch of the circuit originating at TIMER II and preceding the mixing network, allowed reduction of the level of one pulse relative to the level of the other pulse within the pulse pair. The output of the resistive mixing network was loaded with a 500-ohm resistor and was paralleled by the high-impedance input of the 1-watt AMPLIFIER (Grason-Stadler Model 1288). The AMPLIFIER served to amplify the pulses and to reduce the impedance of the circuit to 10 ohms. A 10-ohm attenuator (labelled ATTENUATOR - I_0) immediately preceded the earphone and was used to control the level of signal presentation. A TDH-39 (10Ω) earphone served as the transducer of the electrical pulses. The earphone was mounted in an MX-41/AR cushion and was held in place by a standard headband; the non-test ear was occluded by a dummy earphone and cushion.

Control of the interpulse temporal interval. In order to insure equality of the temporal intervals between successive pulses for the two types of pulse pairs, the system was programmed according to the basic scheme indicated in the upper portion of Figure 5. The duration of the interval between successive pulses in both pulse pairs was controlled by a single 100-second TIMER, TIMER III. The complementary outputs of TIMER III served as the inputs to a pulse OR GATE, causing a negative logic pulse to be generated at the initiation and termination of the timing interval. The output of the OR GATE constituted the input to both the SET and RESET modes of a FLIP-FLOP module; a change in state of the FLIP-FLOP was produced by each logic pulse delivered. The complementary outputs of that first FLIP-FLOP were crossed and served as the complementary inputs to a second FLIP-FLOP. The crossing of the outputs of the first FLIP-FLOP and the introduction of the second FLIP-FLOP served to circumvent possible differential delays associated with reversal of the order of the change of state of the FLIP-FLOP module. Each of the two complementary outputs of the second FLIP-FLOP, in turn, constituted the input to one of the TIMERS used for pulse generation. Each change of state of the ganged FLIP-FLOP modules triggered one of the TIMERS. The FLIP-FLOPS changed state twice within each observation interval, at the initiation and termination of the timing interval which, as indicated above, was controlled by TIMER III.

The following description of the sequence of events within one of the two observation intervals occurring on each trial may clarify the programming scheme. As described earlier, in the two-interval forced-choice procedure each of the click pairs is presented in one of the two observation intervals constituting a trial. Establishment of the SET mode of the first FLIP-FLOP, in the 0.45-second period between the beginning of an observation interval and the triggering of TIMER III, caused the first logic pulse (generated at the initiation of the timing interval) to produce a change to the RESET mode for the first FLIP-FLOP and to the SET mode for the second FLIP-FLOP; this change in state of the second FLIP-FLOP triggered TIMER I. The second logic pulse (generated at the termination of the timing interval) then produced a change in the state of the first FLIP-FLOP to the SET mode and of the second FLIP-FLOP to the RESET mode; this second change of state triggered TIMER II. Establishment of the RESET mode of the first FLIP-FLOP at the beginning of an observation interval produced a reversal of the order in which TIMERS I and II were triggered. In summary, the order in which TIMERS I and II were triggered was controlled by the state of the first FLIP-FLOP prior to receipt of the first logic pulse. The interval between the onset of successive pulses within a pair was determined by TIMER III and was independent of the order in which TIMERS I and II were triggered.

The state of the first FLIP-FLOP, prior to receipt of the first logic pulse was predetermined and was maintained by collector triggering (Malmstadt and Enke, 1969, p. 183). The state of the FLIP-FLOP in the first observation interval of any trial was determined on a random basis; the complementary state was imposed for the second observation interval. A NOISE GENERATOR (Grason-Stadler Model 1285), used in combination with an INPUT CONVERTER, served as the 50% probability generator, controlling random assignment of the click pairs to the two observation intervals.

Signal Calibration

Precautions were taken to insure that the duration of the electrical pulses remained constant throughout the experiment and that the amplitude of the pulses corresponded to those specified for each experimental condition. Analysis of the acoustical waveform of the clicks was undertaken to determine whether changes in the signal level or variations in the interpulse amplitude ratio resulted in spectral differences between click pairs which might enhance the discriminability of those stimuli.

Calibration of the Electrical Signals

The electrical signals were calibrated at the input to ATTENUATOR-I_0. Pulse amplitude and pulse duration were set prior to each experimental session. The interpulse interval was set each time the value of Δt was changed within the experimental sessions. The electrical signals were monitored throughout the experimental sessions by observation of the visual display on an oscilloscope (Tektronix Model 564).

Pulse duration. TIMERS I and II were set to generate pulses of 0.1-msec duration, initially, by referring to the visual display of an oscilloscope (Tektronix Model 564) which offered a calibrated time base and a storage capability. Measurements of pulse duration at those TIMER settings subsequently were confirmed using a digital electronic counter-timer (TSI Model 361). Thereafter, pulse duration was adjusted and monitored using the counter-timer. Monitoring of pulse duration indicated that daily changes were on the order of less than 1% of the nominal duration. Pulse duration was checked and adjusted prior to each experimental session.

Pulse amplitude. Subsequent to the determination of the duration of the pulses, pulse amplitude was set in the following manner. The experimental apparatus was programmed for periodic presentation of a single pulse from TIMER I at the rate of one every 5 msec. The gain of the AMPLIFIER was adjusted to produce a waveform with a given peak voltage when the amplifier was loaded with the 10-ohm attenuator controlling the signal level (ATTENUATOR-I_0). That peak voltage was determined from observation of the visual display of the oscilloscope described above; setting the pulse level to that peak voltage was shown to produce a repeatable reading on a true RMS vacuum-tube voltmeter (Ballantine Model 321).

The experimental apparatus was then programmed for periodic presentation of a single pulse from TIMER II at the same rate. The electrical input to ATTENUATOR-I_0 was then adjusted, using the continuously variable attenuator (ATTENUATOR-ΔI), to a value 3, 6, 12 or 24 dB less than the level of the pulse generated by TIMER I. Precautions were taken to minimize the effect of the crest factor of the pulse train on the measurements by using only the lower one-half of the voltmeter scale for the adjustment of the relative level of the pulses. The appropriateness of the attenuator settings was confirmed by comparison of the peak voltages of the waveforms displayed on the oscilloscope with the peak voltages computed to correspond to the desired attenuation values. Voltage measurements confirmed the linearity of operation of the attenuator used to control the level of signal presentation (ATTENUATOR-I_0), as well.

The true-RMS voltmeter was employed for daily adjustment and monitoring of the pulse levels. Day-to-day variation in the level of the unattenuated pulse (i.e., the pulse generated by TIMER I) was found to be less than 0.2 dB.

Interpulse interval. The interval between the onset of successive pulses of the pulse pairs (Δt) was set, using the counter-timer, prior to each block of 100 trials administered at a given interpulse interval. Adjustment of the duration of the interval to within 0.5% of the nominal duration was achieved.

Calibration of the Acoustical Signals

The temporal and spectral characteristics of the clicks were determined through spectral analysis and oscilloscopic observation of the acoustical waveform of those clicks. For the purposes of those measurements, the earphone was mounted on an NBS-9A coupler which was used in conjunction with a Western Electric 640 AA microphone and Western Electro-Acoustic Laboratory condensor microphone complement (Type 100 D/E).

The waveform of the click was characterized by an initial rarefaction followed by a condensation and a smaller second rarefaction phase. This major activity ceased in about 0.5 msec and was followed by smaller pressure variations. The logarithmic decrement of the waveform, that is, the natural logarithm of the ratio of the first rarefaction to the second rarefaction was 1.07. The peak equivalent sound pressure level of a click presented at a sensation level of about 75 dB was determined by noting the sound pressure level generated in the 6 cc coupler by a 1000 Hz tone whose negative peak amplitude was equal to the first negative peak of the click. The level of that 1000 Hz tone was 114 dB SPL.

Spectral analyses of the acoustical waveforms of the time-reversed click pairs were performed by repeating the click pairs at the rate of one every 10 msec. The spectra for both orders of click presentation and all combinations of ΔI and I_0 were measured at Δt of 0.5 msec. Spectral analyses at Δt values of 0.75 and 1.0 msec were obtained only for ΔI's of 3 dB and 24 dB at the high level of signal presentation. The spectral analyses confirmed that those time-reversed click pairs were, in fact, identical with respect to their energy density spectra. These measurements were considered to provide sufficient evidence that discrimination of the click pairs at small values of Δt could not be attributed to differences in the energy density spectra of those click pairs.

In order to determine whether the resonant characteristics of the earphone differentially altered the waveform of the less intense click for the two orders of click presentation, the oscilloscope traces of those waveforms were photographed and compared. Particular attention was directed to the waveforms generated at the high level of signal presentation when the interval between the onset of the pulses was of the order of 0.5 and 0.75 msec. In all cases, the temporal characteristics of the less intense click remained essentially unchanged, reflecting simple superposition. In no case was the presence of the less intense click obscured by the presentation of the more intense click.

In this chapter, the experimental conditions employed in assessment of the effects of intensity manipulations on the discriminability of time-reversed click pairs have been discussed. The effects of those manipulations are described in the following chapter.

CHAPTER IV

RESULTS AND DISCUSSION

Introduction

Assessment of the discriminability of time-reversed click pairs, as a function of the interclick interval, has been proposed as a method for evaluating the temporal resolving power of the auditory system (Green, 1971; Green, 1973). There is some evidence, however, that the discriminability of those click pairs is altered by variations in either the interclick intensity ratio (Ronken, 1970) or the level of signal presentation (Babkoff and Sutton, 1971). Documentation of the effect of the interclick intensity ratio on the discriminability of the click pairs at different levels of signal presentation is limited to a single study (Babkoff and Sutton, 1971); furthermore, the interclick intensity ratios employed in that study exceed those employed in investigations in which the time-reversed signals have been used to evaluate the temporal resolving power of the auditory system. The nature of the changes in the discriminability of the click pairs which accompany changes in both the interclick intensity ratio and the level of presentation suggests that the discriminability of the time-reversed click pairs may be maximized by the same intensity manipulations that maximize the asymmetry of temporal masking.

The present investigation was designed to determine the changes in the discriminability of the time-reversed click pairs resulting from variations in the interclick intensity ratio for two levels of signal presentation. To this end, the discriminability of the click pairs was determined for five normal-hearing listeners using a two-interval forced-choice procedure. The discrimination performance of the subjects was measured at eight interclick intervals between 0.5 and 10.0 msec. The level of the more intense click was either 75 dB SL or 45 dB SL; the interclick intensity ratio was 3 dB, 6 dB, 12 dB, or 24 dB.

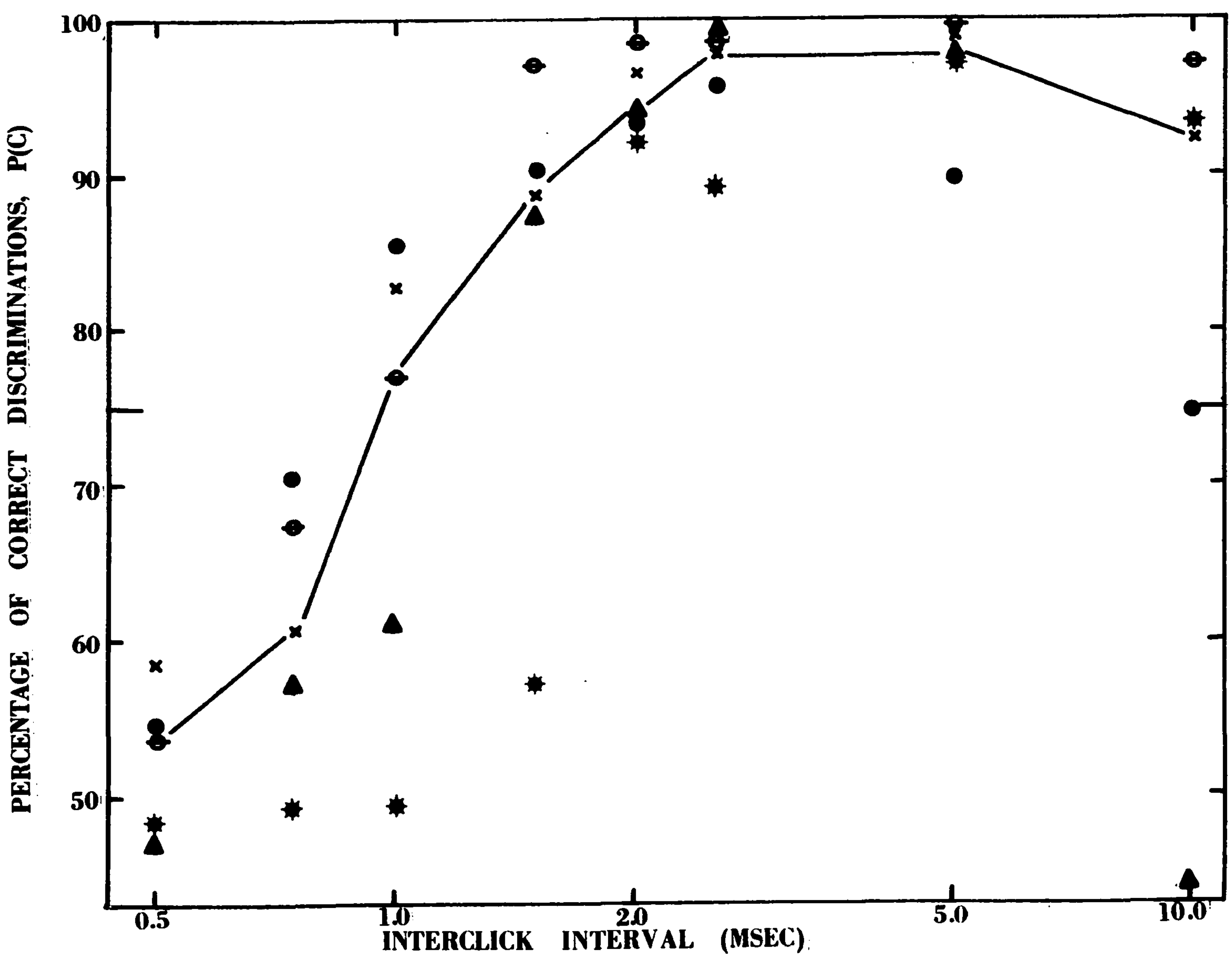
For purposes of brevity and simplicity, the following terminology has been adopted in the description of the experimental results. Psychometric functions which represent the percentage of correct discriminations, P(C), as a function of the interclick interval are termed "temporal psychometric functions." The term "intensive psychometric functions" designates those psychometric functions which represent P(C) as a function of the interclick intensity ratio. The three experimental variables, which were the level of the more intense click, the interclick intensity ratio and the interclick temporal interval are designated I_o, ΔI and Δt, respectively. The particular value of the variable under consideration is specified by a subscript. For example, the experimental condition in which the level of the more intense click was 75 dB SL, the interclick intensity ratio was 3 dB and the interclick interval was 5 msec, is designated I_{75}-ΔI_3-$\Delta t_{5.0}$. The interclick interval at which the click pairs became just discriminable (i.e., the percentage of correct discriminations reached 75%) is designated by <u>T</u>. The designation <u>T</u> is reserved for interclick intervals briefer than those at which optimal performance was demonstrated. In order to simplify description of the click pairs, those click pairs in which the less intense click preceded the more intense click are termed "L-M" click pairs; the designation "M-L" is applied to those click pairs in which the more intense click preceded the less intense click.

Description of the Experimental Results

To evaluate the effects of the experimental manipulations, P(C) scores first were calculated for each of the five subjects in each of the 64 experimental conditions. The P(C) scores for each of the subjects in the various conditions were based on 200 trials; those P(C) scores were equal to the average of the P(C) scores obtained by the subject on two blocks of trials administered under the same condition. This average score then was used to represent the performance of the subject. The scores for each subject under each condition are presented in tabular form in Appendix B.

The marked differences in the performance of the individual subjects at any particular Δt become apparent upon even the most cursory examination of Appendix B. Frequently the performance of a single subject deviated substantially from that of the other subjects. The reader is provided with examples of such deviations in Figure 6 in which the individual scores for the I_{75}-ΔI_{24} conditions are presented. The differences in the performance of the subjects at $\Delta t_{1.5}$ and $\Delta t_{10.0}$ are on the order of 30% to 40%. Although the subjects tend to be ordered similarly with respect to their general level of performance at most values of Δt for a particular combination of I_0 and ΔI, that order is not maintained across all combinations of I_0 and ΔI.

Figure 6.--Percentage of correct discriminations by each of the subjects, as a function of the interclick interval, for those click pairs in which the level of the more intense click was 75 dB SL and the interclick intensity ratio was 24 dB (I_{75}-ΔI_{24}). The P(C) scores for each of the subjects are represented by a different symbol: Subject 1 (●); Subject 2 (✱); Subject 3 (▲); Subject 4 (✖); and Subject 5 (⊖). A solid line connects the median P(C) scores at each interclick interval.


PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
100
90
80
70
60
50
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

Fortunately, for the purposes of description and interpretation of the data, examination of the trends in the individual data suggested that the performance of the subjects was more similar than is apparent upon initial inspection of the data. Evaluation of the individual data revealed that the variability of performance at the shorter interclick intervals generally reflected a displacement in time of the temporal psychometric functions. The differences in the individual results at $\Delta t_{5.0}$ and $\Delta t_{10.0}$ did not appear to be interpretable in a similar fashion.

In view of the small number of subjects, the magnitude of the differences in individual performance at any given Δt complicated the selection of a descriptive statistic appropriate for comparison of the group data across experimental conditions. The descriptive statistic selected was the median of the individual scores, rather than the mean of those scores. The selection was based, in part, on consideration of the asymmetrical distribution of the individual scores at a number of Δt's (p. 41, Sokal and Rohlf, 1969). Furthermore, use of the mean might have implied a degree of consistency in the data that was unwarranted. Both the median P(C) values and the mean P(C) values have been made available to the reader in Table 2, however. The differences between those two statistics are generally on the order of less than 5%.

The same factors which led to selection of the median as the descriptive statistic emphasized the necessity for determining whether the trends apparent in the group data were applicable to the individual data. Therefore, in the description of the results, discussion of the effects of each experimental manipulation on group performance is followed by a discussion of its effects on individual performance.

TABLE 2

MEAN AND MEDIAN P(C) VALUES FOR EACH EXPERIMENTAL CONDITION

Interclick Temporal Interval (in msec)	Statistic	Interclick Intensity Ratio (in dB)							
		ΔI = 3 dB		ΔI = 6 dB		ΔI = 12 dB		ΔI = 24 dB	
		I_{75}	I_{45}	I_{75}	I_{45}	I_{75}	I_{45}	I_{75}	I_{45}
0.5	Median	54.8	80.8	60.9	66.9	59.5	51.5	53.9	53.0
	Mean	55.3	79.7	57.3	70.7	62.1	52.3	52.6	52.7
0.75	Median	56.4	87.7	60.8	91.3	78.1	61.6	60.2	48.4
	Mean	57.4	85.7	63.7	88.9	77.3	68.9	61.0	48.6
1.0	Median	58.9	87.5	66.5	95.0	77.9	81.6	77.1	54.1
	Mean	57.7	90.4	67.2	95.7	75.5	83.4	71.2	52.6
1.5	Median	70.1	80.9	81.9	97.0	95.4	97.0	88.6	60.8
	Mean	69.4	77.0	84.2	94.1	92.9	96.3	84.2	66.1
2.0	Median	78.6	68.1	89.7	91.3	95.9	99.0	94.7	81.8
	Mean	80.3	73.1	88.4	80.1	93.6	97.8	94.9	80.5
2.5	Median	84.5	53.6	93.8	63.2	94.1	99.2	99.0	89.9
	Mean	79.4	63.6	90.3	74.0	94.9	96.3	96.6	91.3
5.0	Median	62.2	63.6	82.3	77.7	92.9	92.6	98.5	94.4
	Mean	69.1	63.4	80.2	73.3	85.6	90.2	97.0	88.0
10.0	Median	67.1	60.3	89.7	67.7	95.7	73.1	93.0	90.4
	Mean	65.3	56.6	76.2	64.6	80.7	71.0	80.5	89.7

Effect of the Level of Signal Presentation

In Chapter II, the existence of a relationship between the asymmetry of temporal masking and the discriminability of the time-reversed click pairs was proposed. The prediction was made that such a relationship would be reflected in an increase in *I* as the level of signal presentation was increased. In evaluating the effect of I_0 on the discriminability of the click pairs, the temporal psychometric functions generated at I_{75} and I_{45} were compared for each of the four values of ΔI. The temporal psychometric functions for ΔI of 3 dB, 6 dB, 12 dB and 24 dB are presented in Figures 7, 8, 9 and 10, respectively. In each of those figures, the temporal psychometric functions are based on the median P(C) values at each Δt; the parameter is I_0. The comparable individual data are presented in Figures 11, 12, 13, 14 and 15. Each of those figures is devoted to presentation of the data for one subject and is divided into four sections to permit evaluation of the effect of I_0 at each ΔI. In the presentation of the temporal psychometric functions, Δt is represented on a logarithmic scale.

Group data. For ΔI_3 (Figure 7), an increase in I_0 was accompanied by an increase in *I*. At the low signal level, discrimination had reached 80% at the shortest Δt, 0.5 msec. The interclick interval required to produce comparable performance at the high signal level was in excess of 2.0 msec. Note that discrimination performance at both signal levels was a nonmonotonic function of Δt. The implications of the nonmonotic relationship between discrimination performance and Δt will be considered later in this chapter.

The effect of I_0 on the discriminability of the ΔI_6 click pairs

Figure 7.--Median percentage of correct discriminations, as a function of the interclick interval, for click pairs in which the interclick intensity ratio was 3 dB. The level of signal presentation was either 75 dB SL (————) or 45 dB SL (---------).

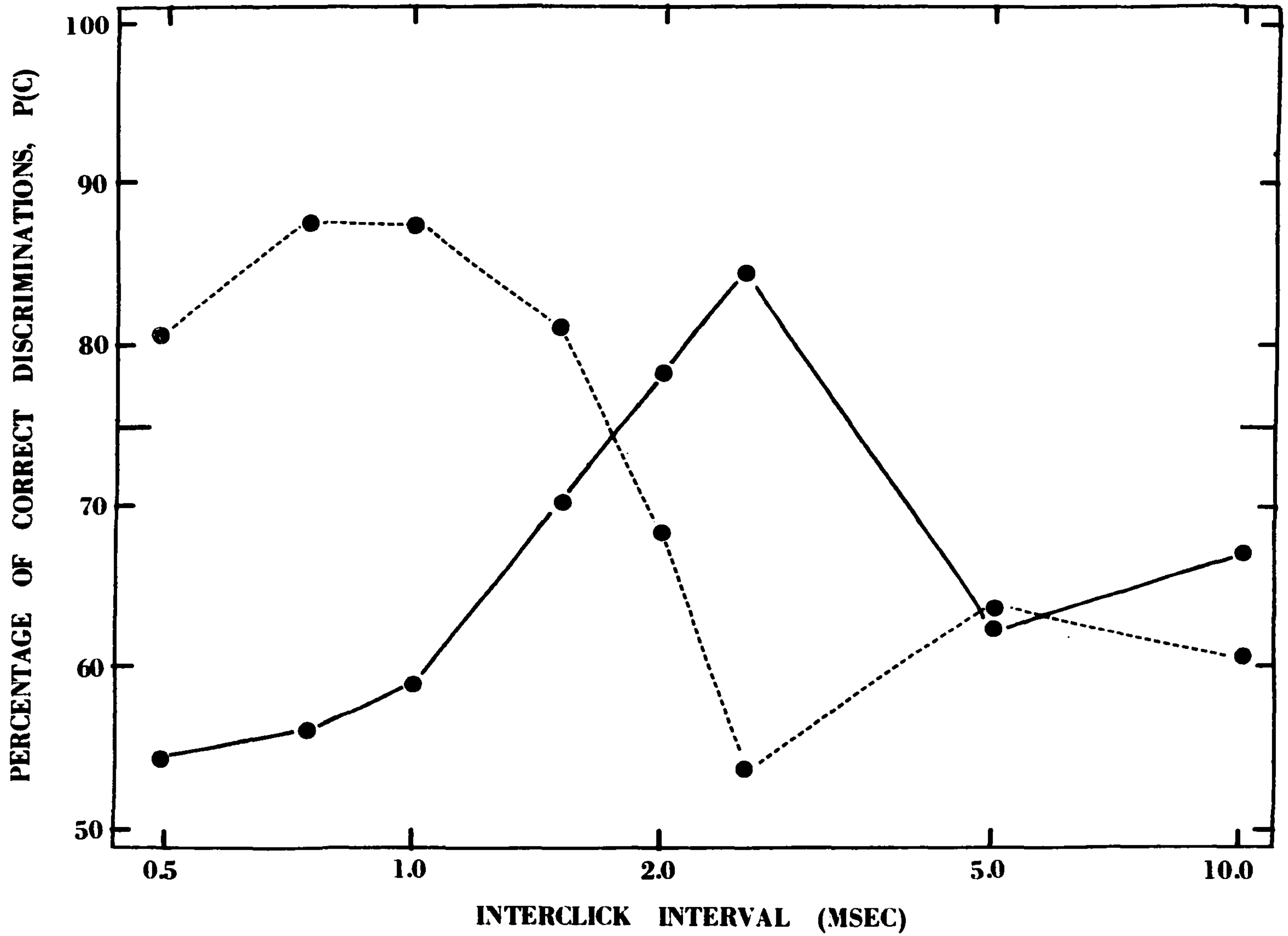

100
90
80
70
60
50
PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

Figure 8.--Median percentage of correct discriminations, as a function of the interclick interval, for click pairs in which the interclick intensity ratio was 6 dB. The level of signal presentation was either 75 dB SL (———) or 45 dB SL (---------).

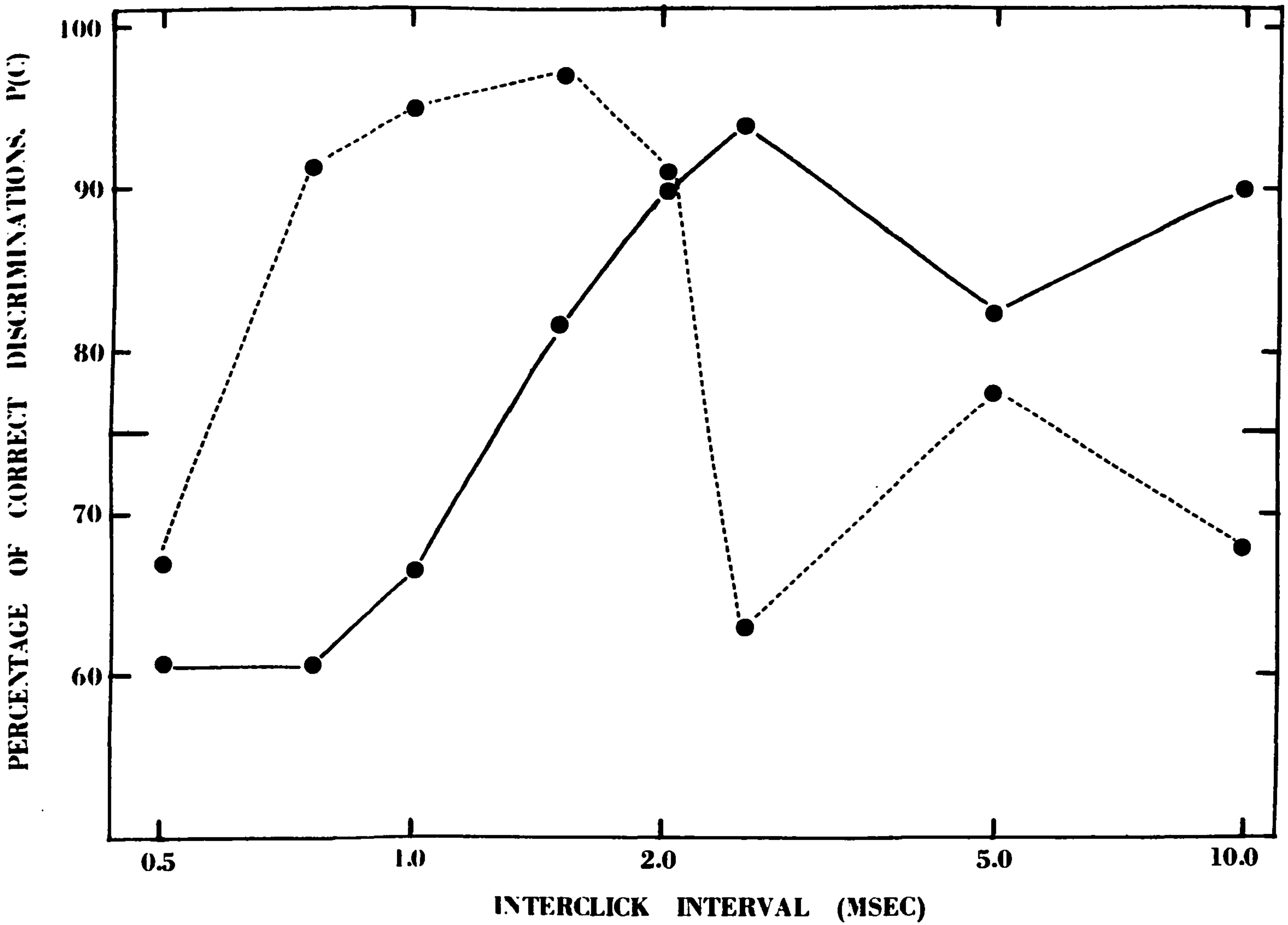

100
90
80
70
60
PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

Figure 9.--Median percentage of correct discriminations, as a function of the interclick interval, for click pairs in which the interclick intensity ratio was 12 dB. The level of signal presentation was either 75 dB SL (————) or 45 dB SL (---------). Data from Babkoff and Sutton (1971) and from Green (1973) are represented by crosses (✖) and open circles (○), respectively (discussed on page 109).

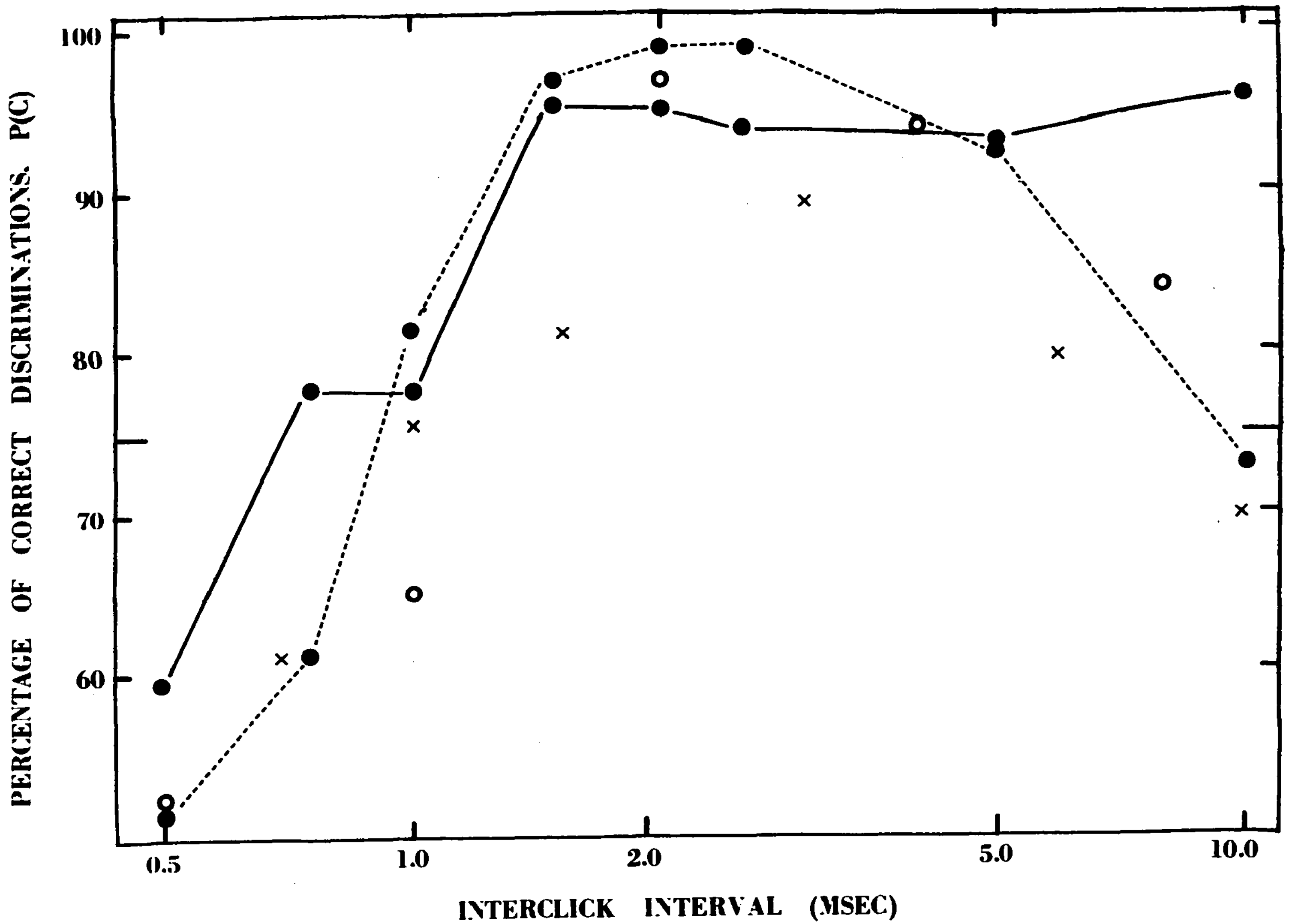
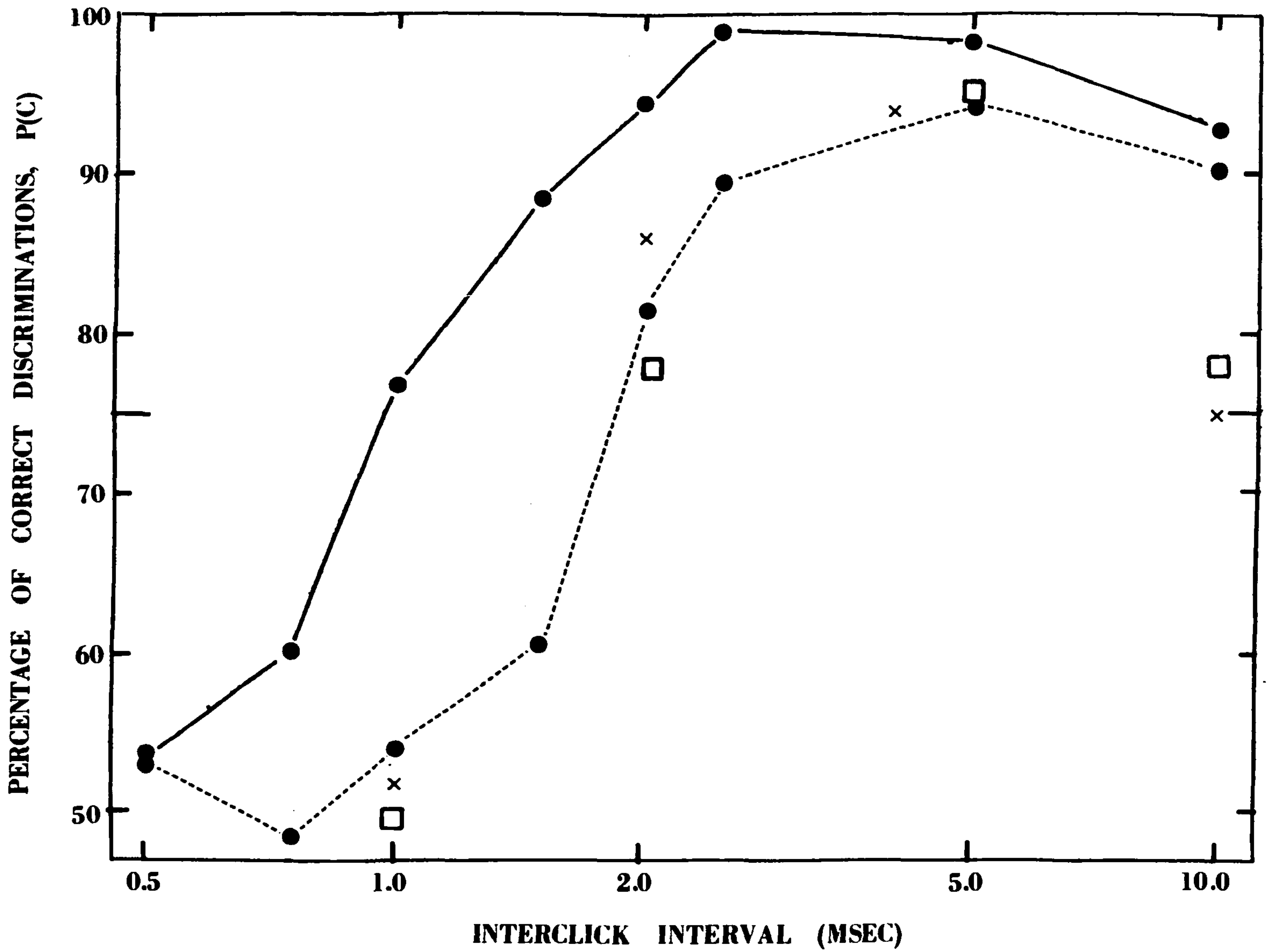

PERCENTAGE OF CORRECT DISCRIMINATIONS. P(C)
100
90
80
70
60
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

Figure 10.--Median percentage of correct discriminations, as a function of the interclick interval, for click pairs in which the interclick intensity ratio was 24 dB. The level of signal presentation was either 75 dB SL (———) or 45 dB SL (---------). Data from Babkoff and Sutton (1971) are represented by crosses (x) and open squares (□) (discussed on page 111).


PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
100
90
80
70
60
50
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

(Figure 8) is similar to that observed for ΔI_3 in that an increase in I_0 produced an increase in <u>I</u>. The temporal psychometric functions representing performance at I_{75} and I_{45} overlap to a greater degree than was apparent for those functions at ΔI_3.

For ΔI_{12} (Figure 9), the overlap of the temporal psychometric functions for the low and high signal levels is virtually complete. In fact, for Δt shorter than 1.0 msec, the discriminability of the high-level signals exceeded that of the low-level signals.

The effect of I_0 on discriminability for ΔI_{24} (Figure 10) is the opposite of that observed for ΔI_3 and ΔI_6. That is, for ΔI_{24} an increase in the signal level was accompanied by a <u>reduction</u> in <u>I</u>. Discrimination performance reached 75% for the high-level click pairs at Δt of approximately 0.95 msec; comparable performance was attained at 1.7 msec for the low-level click pairs.

<u>Individual data</u>. Although the shapes of the temporal psychometric functions differ among subjects, inspection of the individual data (Figures 11 through 15) indicates that the trends noted in the group data are evident in the individual data. The psychometric functions for Subject 1 (Figure 11) and Subject 4 (Figure 14) show the anticipated direct relationship between I_0 and <u>I</u> for ΔI_3 and ΔI_6, as well as the unanticipated reversal in that relationship for ΔI_{24}.

Minor differences between the group data and the individual data are revealed upon examination of the psychometric functions for the other three subjects. Subject 2 (Figure 12) did not attain the high P(C) scores under the I_{75}-ΔI_3 and I_{75}-ΔI_6 conditions for Δt between 0.5 and 5.0 msec attained by the other subjects. Comparison of the interclick

Figure 11.--Percentage of correct discriminations by Subject 1, as a function of the interclick interval, for four values of the interclick intensity ratio. Each section of the figure represents performance for a single value of the interclick intensity ratio: a) 3 dB; b) 6 dB; c) 12 dB; and d) 24 dB. The level of signal presentation was either 75 dB SL (————) or 45 dB SL (----------).

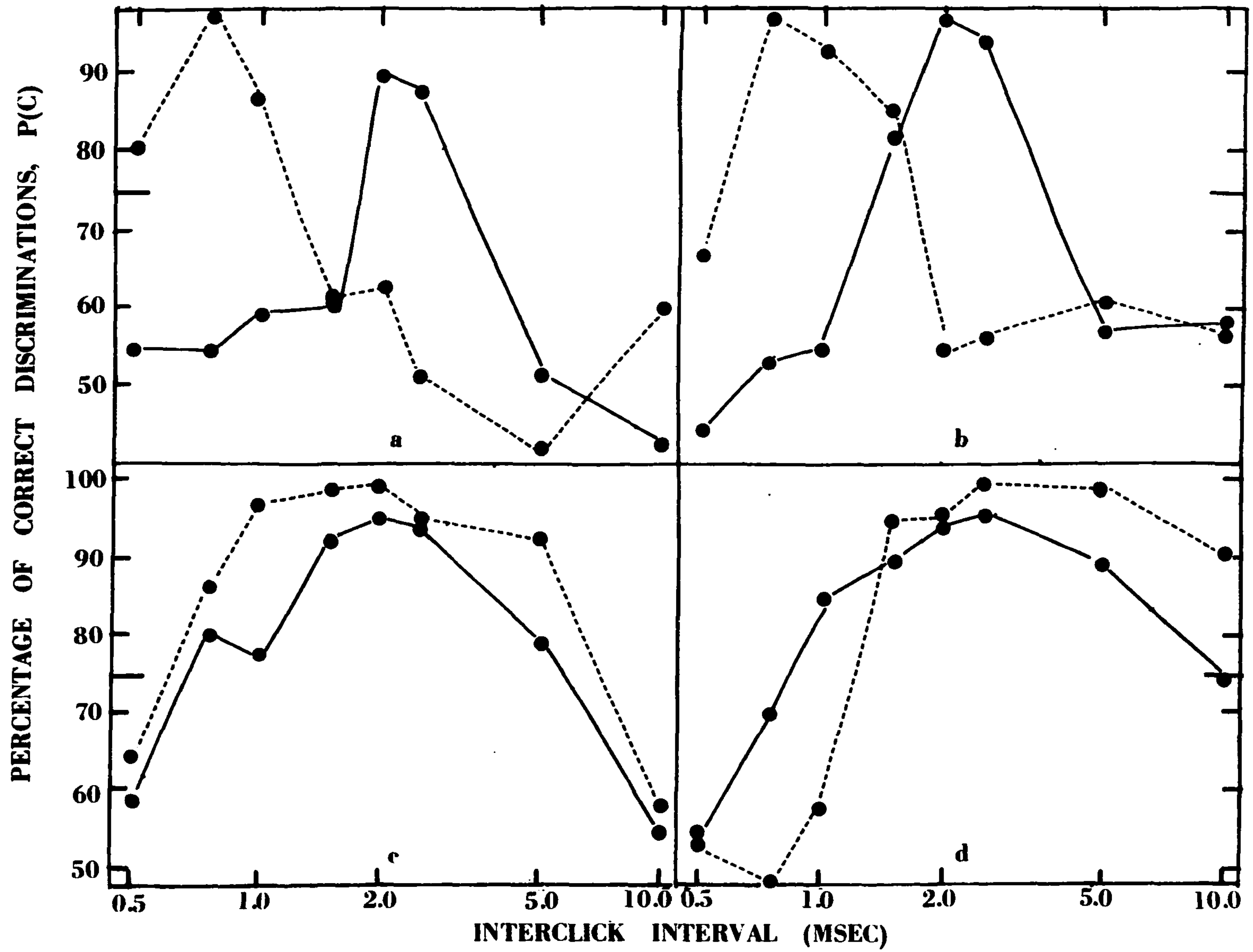

PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
90
80
70
60
50
100
a
b
c
d
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

Figure 12.--Percentage of correct discriminations by Subject 2, as a function of the interclick interval, for four values of the interclick intensity ratio. Each section of the figure represents performance for a single value of the interclick intensity ratio: a) 3 dB; b) 6 dB; c) 12 dB; and d) 24 dB. The level of signal presentation was either 75 dB SL (———) or 45 dB SL (----------).

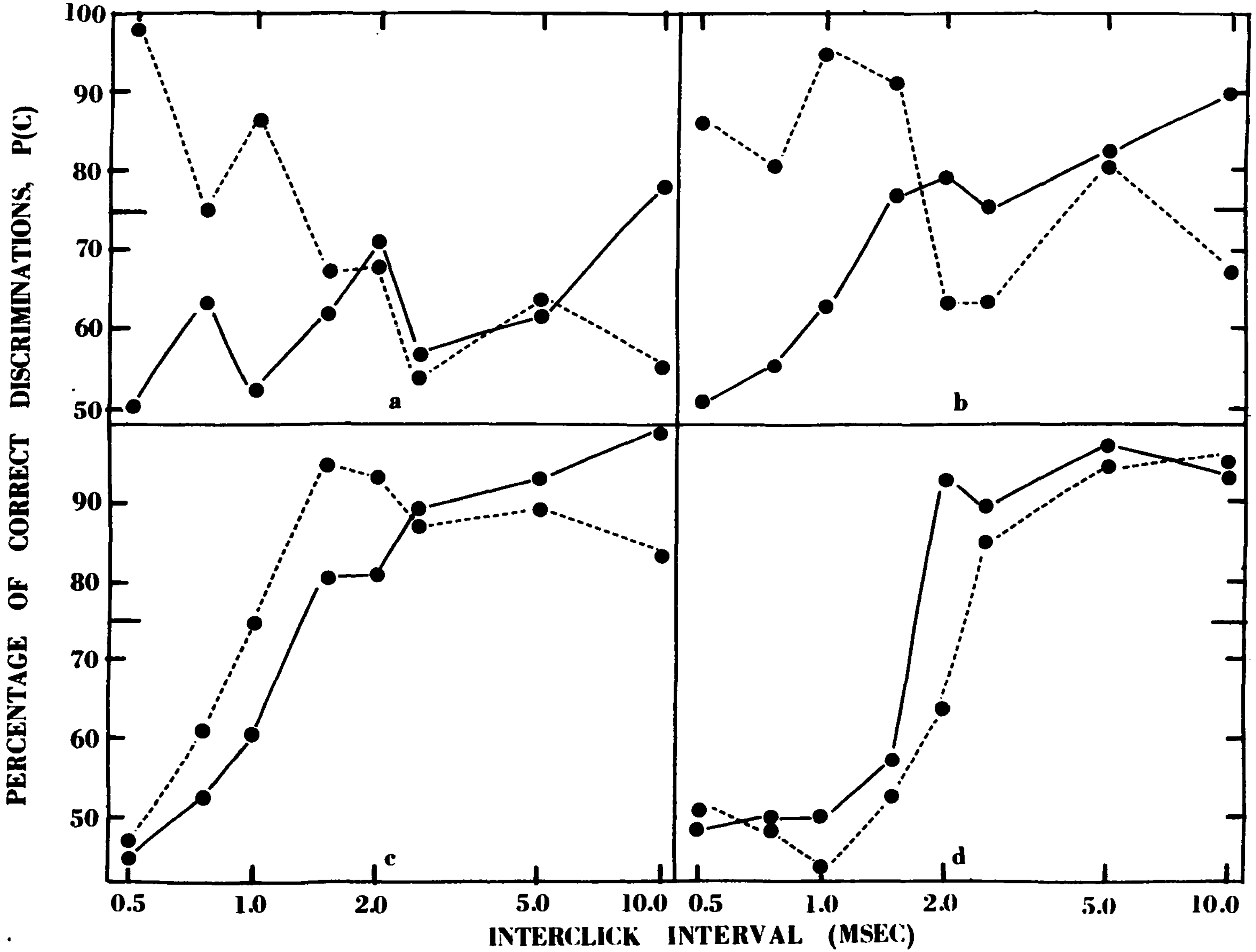

PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
100
90
80
70
60
50
a
b
c
d
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

Figure 13.--Percentage of correct discriminations by Subject 3, as a function of the interclick interval, for four values of the interclick intensity ratio. Each section of the figure represents performance for a single value of the interclick intensity ratio: a) 3 dB; b) 6 dB; c) 12 dB; and d) 24 dB. The level of signal presentation was either 75 dB SL (————) or 45 dB SL (----------).

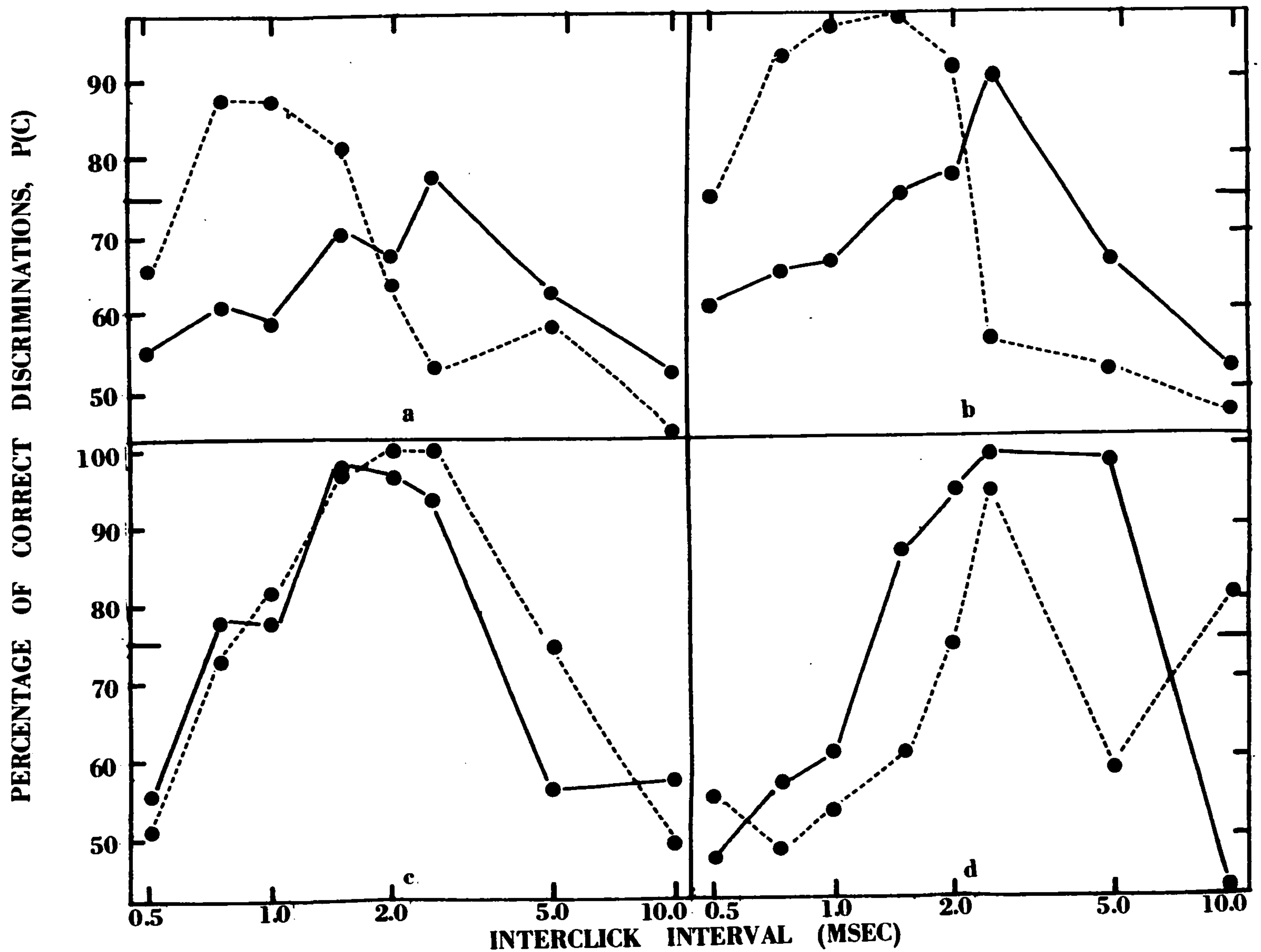

PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
90
80
70
60
50
100
90
80
70
60
50
a
b
c
d
0.5
1.0
2.0
5.0
10.0
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

Figure 14.--Percentage of correct discriminations by Subject 4, as a function of the interclick interval, for four values of the interclick intensity ratio. Each section of the figure represents performance for a single value of the interclick intensity ratio: a) 3 dB; b) 6 dB; c) 12 dB; and d) 24 dB. The level of signal presentation was either 75 dB SL (————) or 45 dB SL (---------).

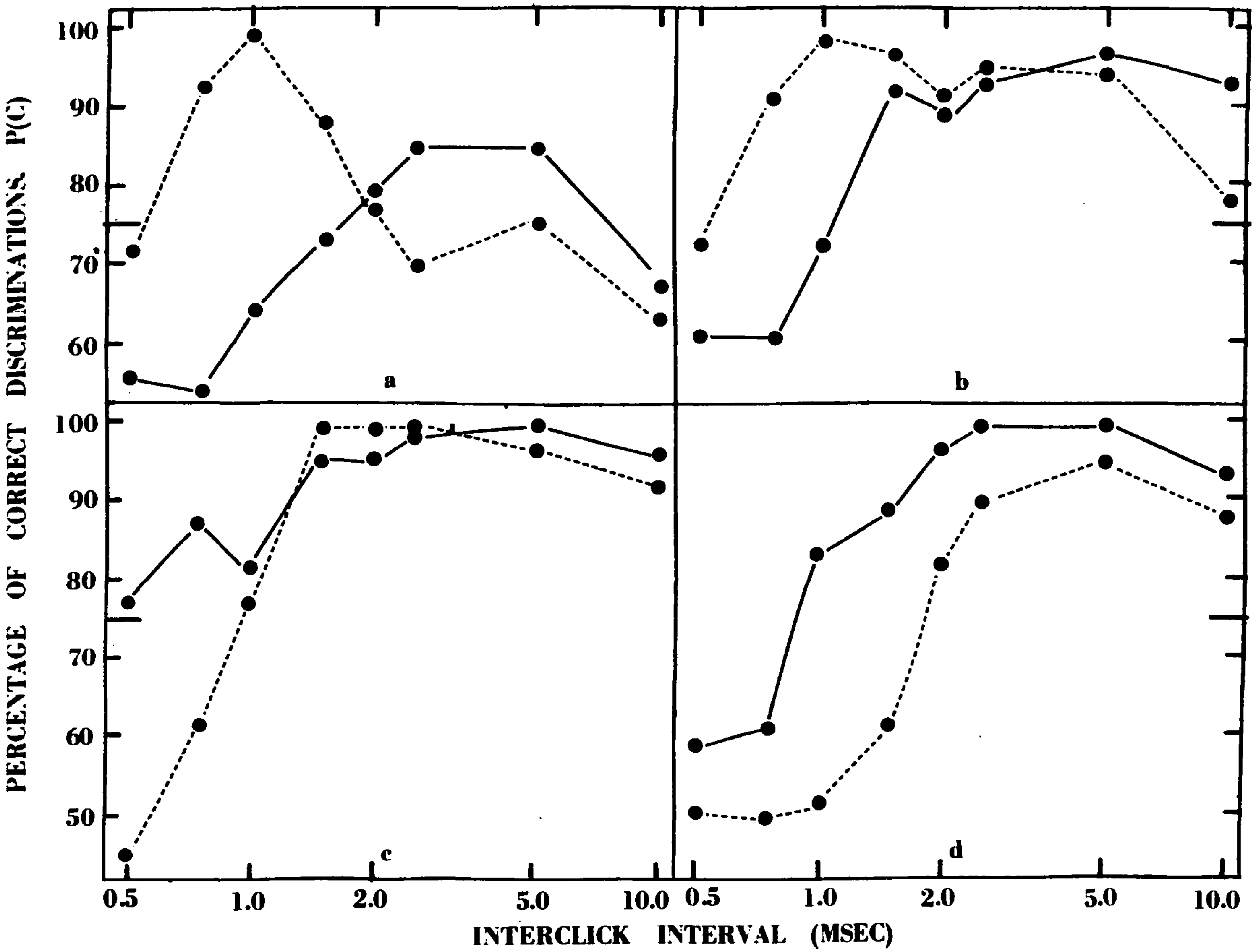
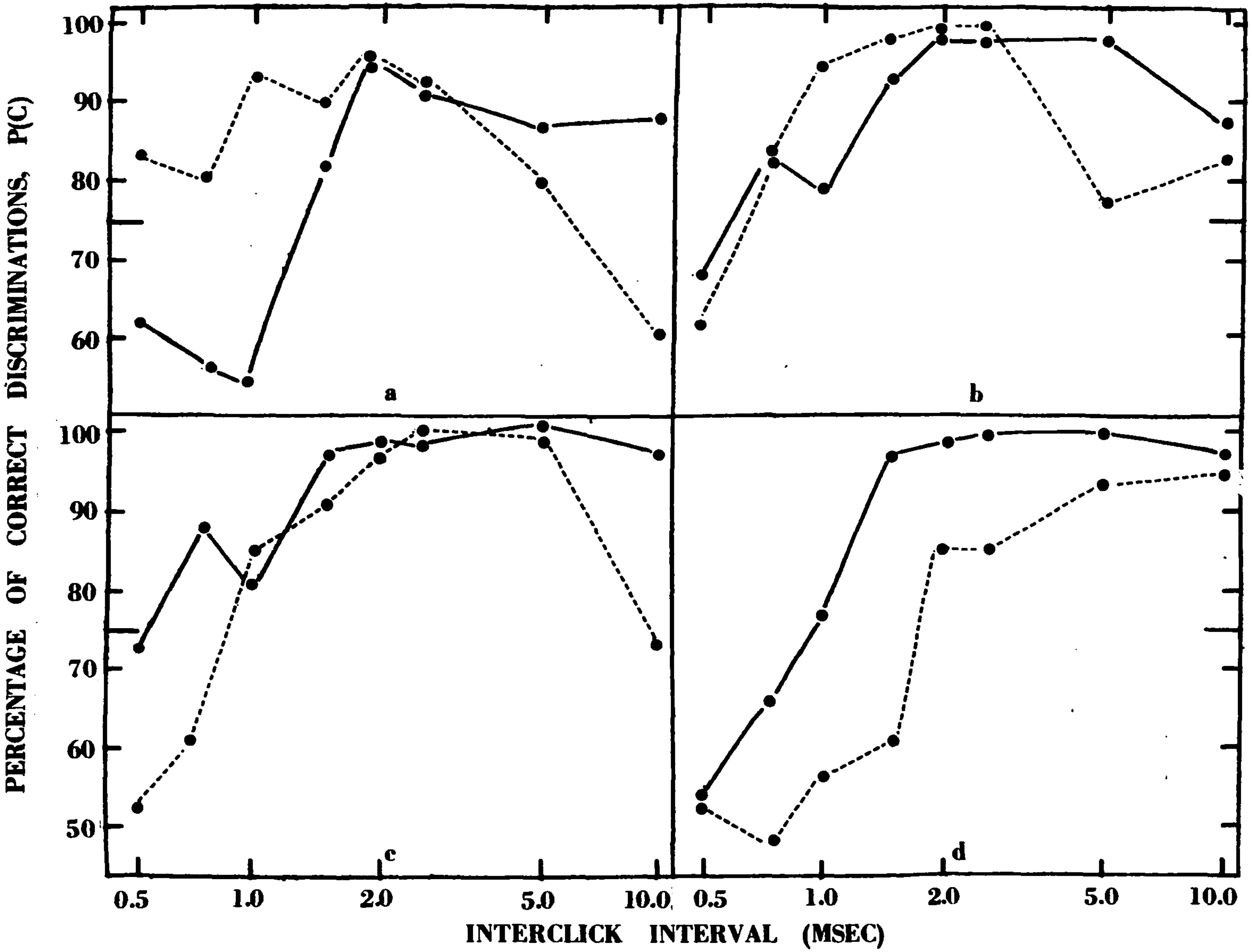

PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
100
90
80
70
60
50
a
b
c
d
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

Figure 15.--Percentage of correct discriminations by Subject 5, as a function of the interclick interval, for four values of the interclick intensity ratio. Each section of the figure represents performance for a single value of the interclick intensity ratio: a) 3 dB; b) 6 dB; c) 12 dB; and d) 24 dB. The level of signal presentation was either 75 dB SL (————) or 45 dB SL (---------).


PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
100
90
80
70
60
50
a
b
c
d
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

intervals at which major peaks in performance did occur indicates the effect of I_0 to be comparable to that reported for the group. Subject 3 (Figure 13) demonstrated a decrease in discrimination performance for I_{45}-ΔI_{24} as Δt was increased beyond 2.5 msec. This decrease was not apparent in the data of the other subjects. For Subject 5 (Figure 15), I_0 had less of an effect on the discriminability of the ΔI_6 click pairs than it did for the other subjects although it did affect discriminability for ΔI_3, ΔI_{12} and ΔI_{24} in a manner comparable to that discussed for the group data. For all subjects, an increase in I_0 produced an increase in I at ΔI_3 and a decrease in I at ΔI_{24}. An increase in I_0 failed to produce an increase in I at ΔI_6 for only one subject.

Effect of the Interclick Intensity Ratio

In Chapter II, the proposed relationship between the asymmetry of temporal masking and the discriminability of the click pairs led to the prediction that ΔI would affect discriminability of the click pairs. The prediction was made that a decrease in ΔI would result in an increase in I. That is, as the levels of the clicks within a pair became more similar, I would be increased.

For evaluation of the effect of ΔI on discriminability, the temporal psychometric functions generated at each ΔI were compared, first at the high signal level (I_{75}) and then at the low signal level (I_{45}). The temporal psychometric functions based on the medians of the group data at I_{75} and I_{45} are presented in Figures 16 and 17, respectively. In each figure, the parameter is ΔI. The comparable individual psychometric functions are presented in Figures 18, 19, 20, 21 and 22. The results for one subject are represented in each those figures. The figures are divided into two sections to permit examination of the effect of ΔI at both signal levels.

Group data. The systematic changes in the discriminability of the time-reversed click pairs which are associated with changes in ΔI at I_{75} become apparent upon inspection of Figure 16. As anticipated, a decrease in ΔI was accompanied by an increase in *T*. The relationship applied with one exception. A decrease in ΔI from 24 dB to 12 dB resulted in a decrease in *T*.

The reduction in *T* as ΔI was increased appears to reflect an overall improvement in discrimination performance attendant upon an increase in ΔI (except in the case of ΔI_{24}). This improvement is manifest in an increase in the height of the psychometric functions and in a broadening of the temporal region over which the P(C) values exceed 75%. The psychometric functions for ΔI_3 and ΔI_6 are characterized by a reduction in P(C) at $\Delta t_{5.0}$ which is not apparent for ΔI_{12} and ΔI_{24}.

The changes in discriminability which accompanied changes in ΔI are as systematic at the low level of signal presentation as they are at the high level. The relationship between ΔI and *T*, however, is (as illustrated in Figure 17) the opposite of that observed at the high signal level. That is, *T* increased as ΔI increased. The effect of the change in ΔI was to displace the psychometric functions in time. The temporal displacement was such that the discrimination performance for ΔI_3 and ΔI_6 began to deteriorate at those values of Δt at which the discrimination performance for ΔI_{12} and ΔI_{24} was increasing. These results were clearly unanticipated. The implications of the differences in the effect of ΔI at I_{75} and I_{45} will be discussed later in this chapter.

Figure 16.--Median percentage of correct discrimination at the high level of signal presentation (I_{75}), as a function of the interclick interval. The interclick intensity ratio was 3 dB (————), 6 dB (— — —), 12 dB (- — - —) or 24 dB (.........).

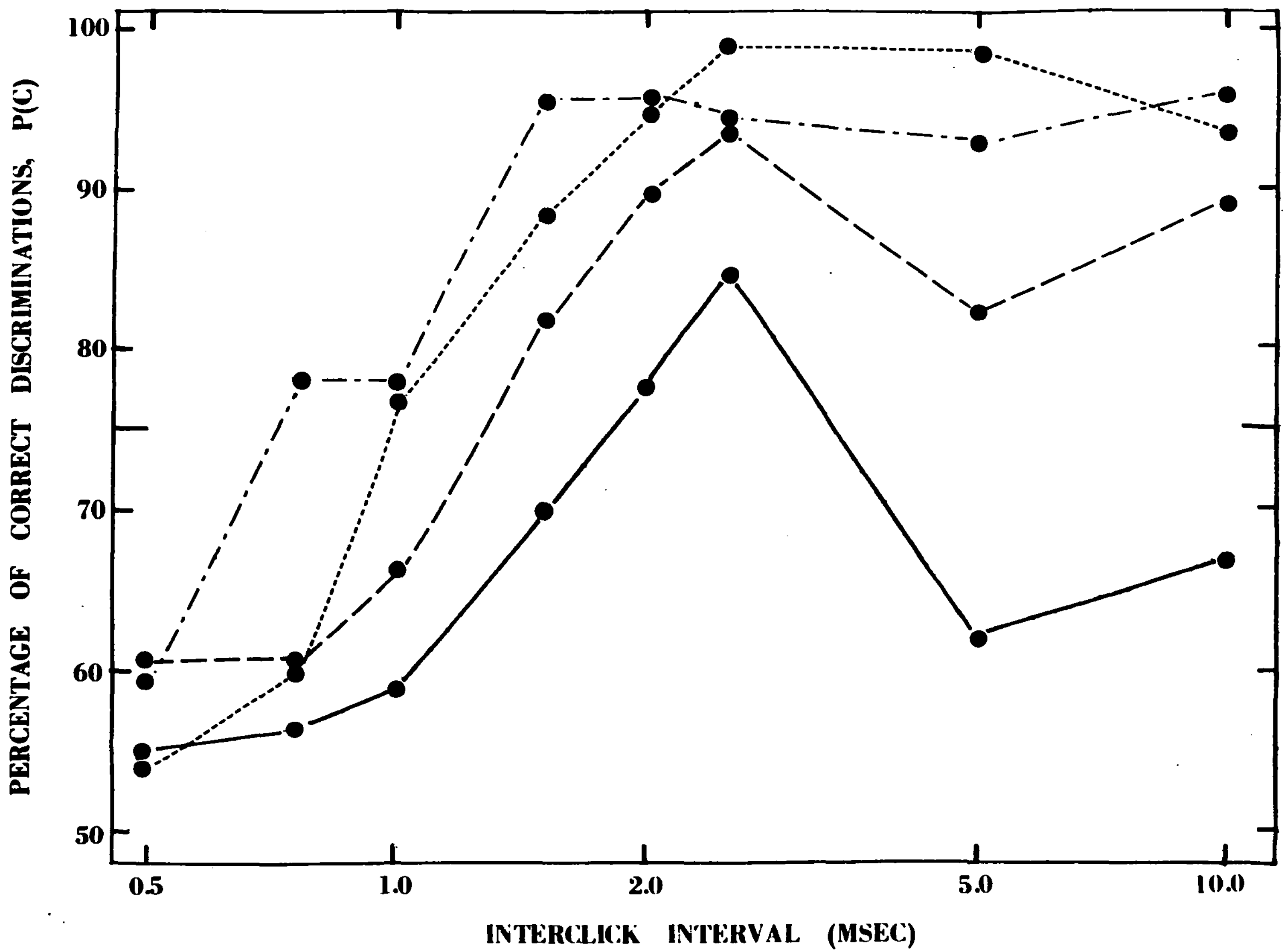
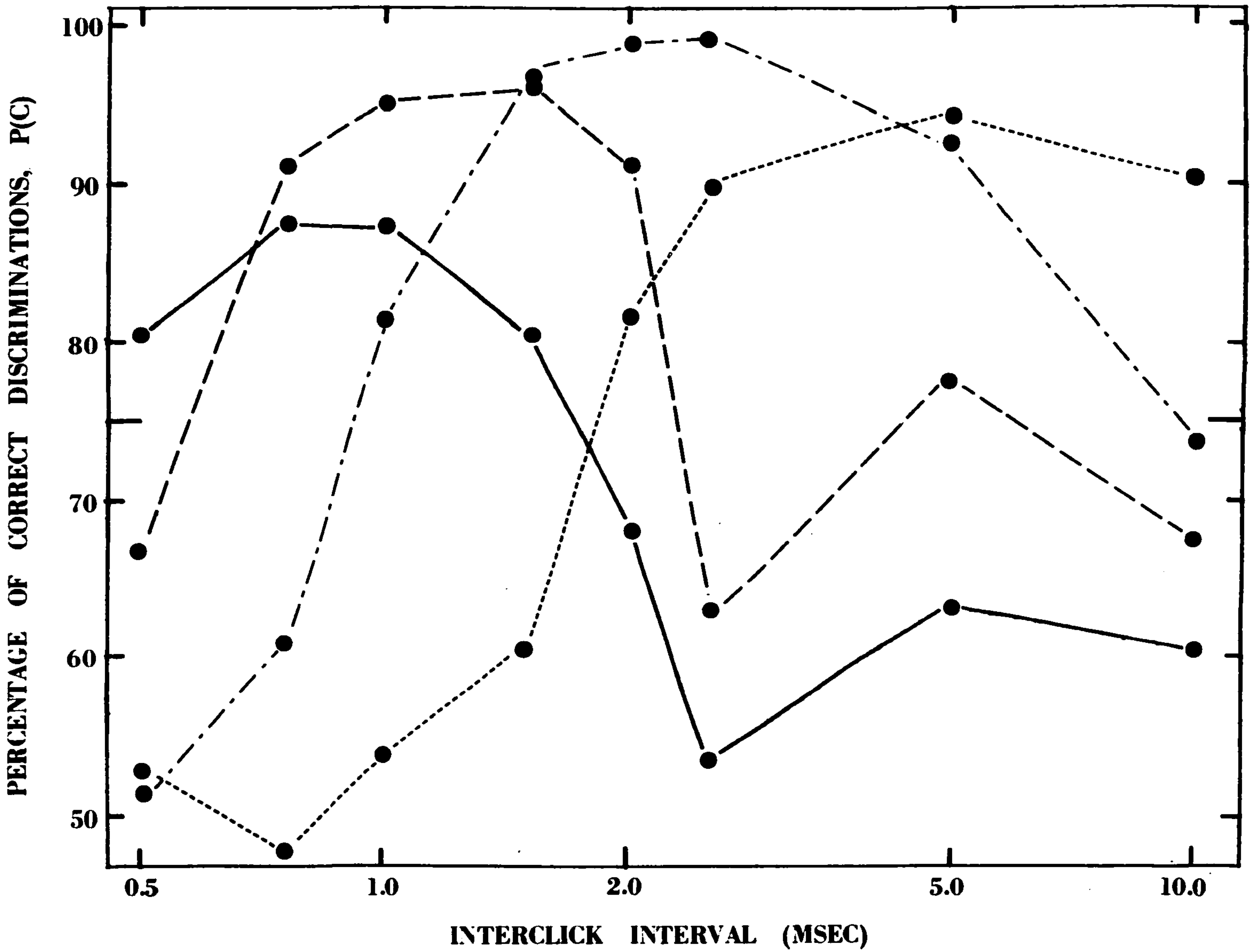

PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
100
90
80
70
60
50
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

Figure 17.--Median percentage of correct discriminations at the low level of signal presentation (I_{45}), as a function of the interclick interval. The interclick intensity ratio was 3 dB (————), 6 dB (— — —), 12 dB (- — - —) or 24 dB (..........).


PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
100
90
80
70
60
50
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

Individual data. The statements which were made, based on the group data, regarding the effect of ΔI on discriminability at the high signal level are equally applicable to the individual data. To review, as ΔI increased, *T* decreased, with one exception. The exception pertained to the relative discriminability of the ΔI_{12} and ΔI_{24} click pairs; P(C) for ΔI_{12} exceeded that for ΔI_{24} at the shorter interclick intervals. The trends observed in the group data are evident in the data of Subject 1 (Figure 18), Subject 3 (Figure 20) and Subject 4 (Figure 21).

Interpretation of the data of Subject 2 (Figure 19) is complicated by the appearance of multiple peaks in the psychometric function for ΔI_3 and by the more gradual improvement in discrimination performance, as a function of Δt, than was demonstrated by the other subjects. The P(C) scores for Subject 2 increased as Δt was increased from 1.0 to 2.0 msec, but (unlike the scores for the other subjects) failed to reach 75%. The psychometric function for ΔI_6 closely approximates the function for ΔI_{12} at Δt equal to and shorter than 2.0 msec; at longer intervals, discrimination performance for ΔI_{12} was superior to that for ΔI_6. For Subject 2, *T* for ΔI_{24} exceeded that for both ΔI_{12} and ΔI_6.

The temporal psychometric functions for Subject 5 (Figure 22), although indicating a level of performance generally superior to that demonstrated by Subject 2, are ordered similarly in time. The functions for ΔI_6, ΔI_{12} and ΔI_{24} are comparable at Δt's greater than 1.0 msec. At interclick intervals of 0.5 msec and 0.75 msec the discrimination performance for ΔI_6 and ΔI_{12} exceeded that of ΔI_{24}. Discrimination performance for ΔI_3 was generally inferior to that demonstrated for click pairs presented at the other interclick intensity ratios.

Figure 18.--Percentage of correct discriminations by Subject 1, as a function of the interclick interval, at two levels of signal presentation. Performance at the high signal level is represented in the left-hand portion of the figure; performance at the low signal level is represented in the right-hand portion of the figure. The interclick intensity ratio was 3 dB (————), 6 dB (— — —), 12 dB (- — - —) or 24 dB (---------).

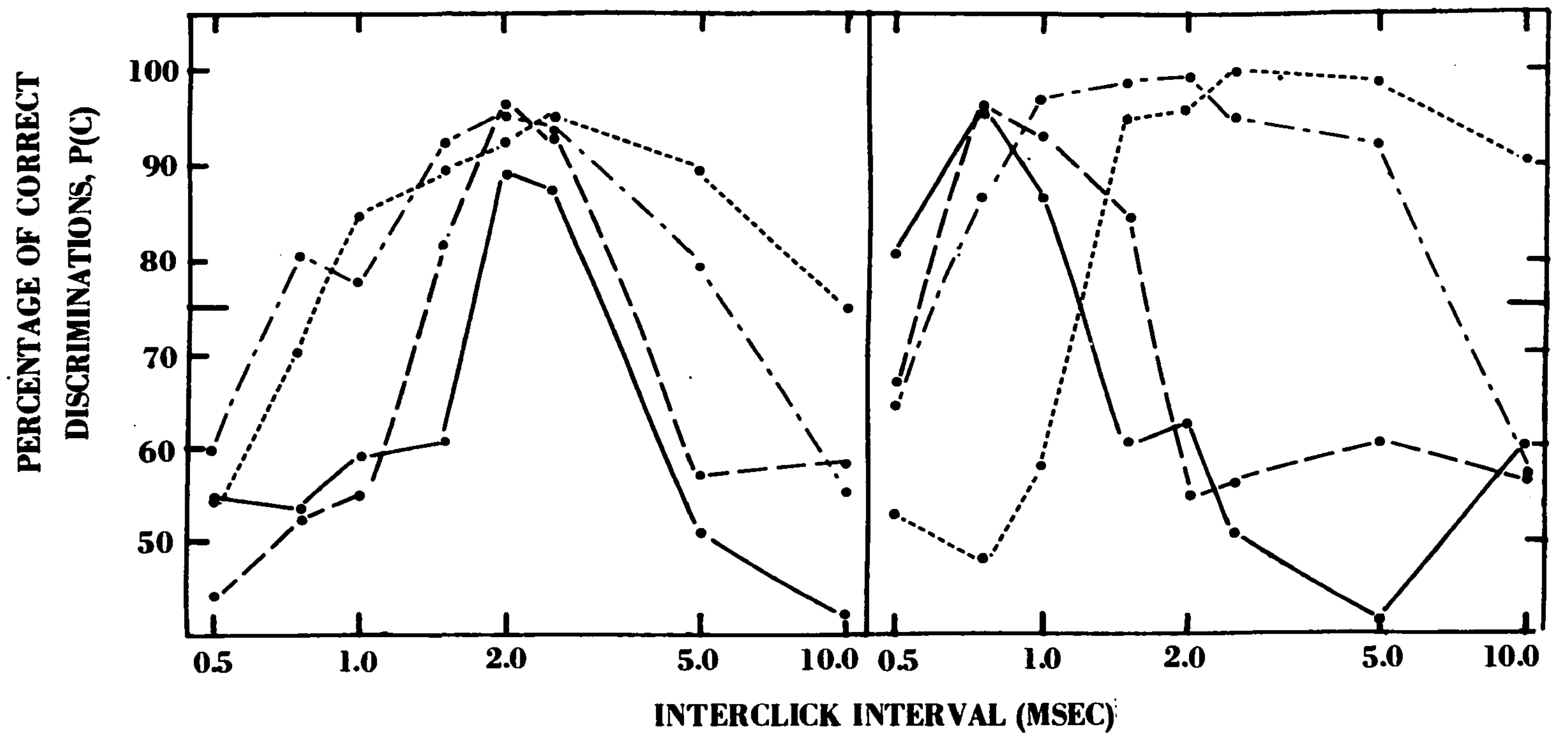

PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
100
90
80
70
60
50
0.5
1.0
2.0
5.0
10.0
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

Figure 19.--*Percentage of correct discriminations by Subject 2, as a function of the* interclick interval, at two levels of signal presentation. Performance at the high signal level is represented in the left-hand portion of the figure; performance at the low signal level is represented in the right-hand portion of the figure. The interclick intensity ratio was 3 dB (————), 6 dB (— — —), 12 dB (- — - —) or 24 dB (---------).

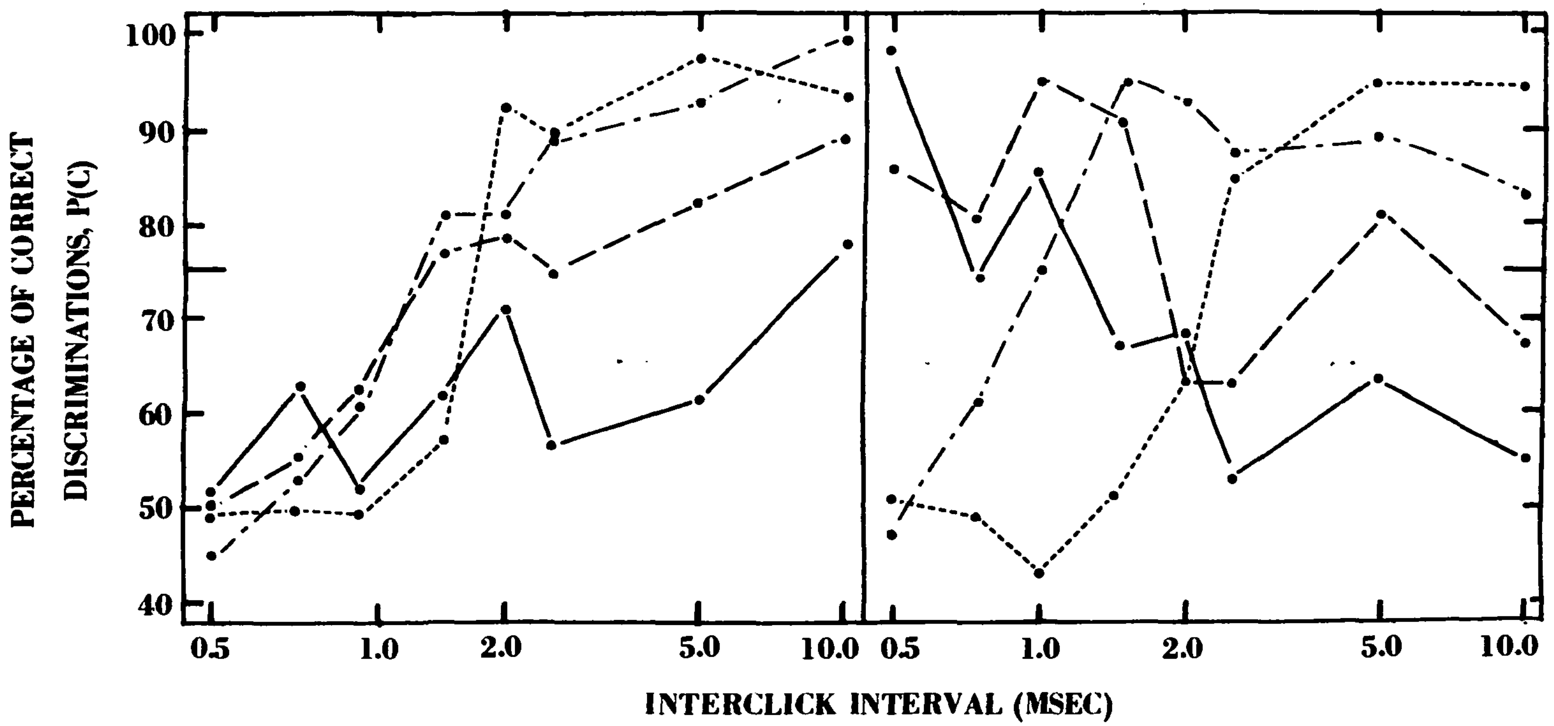
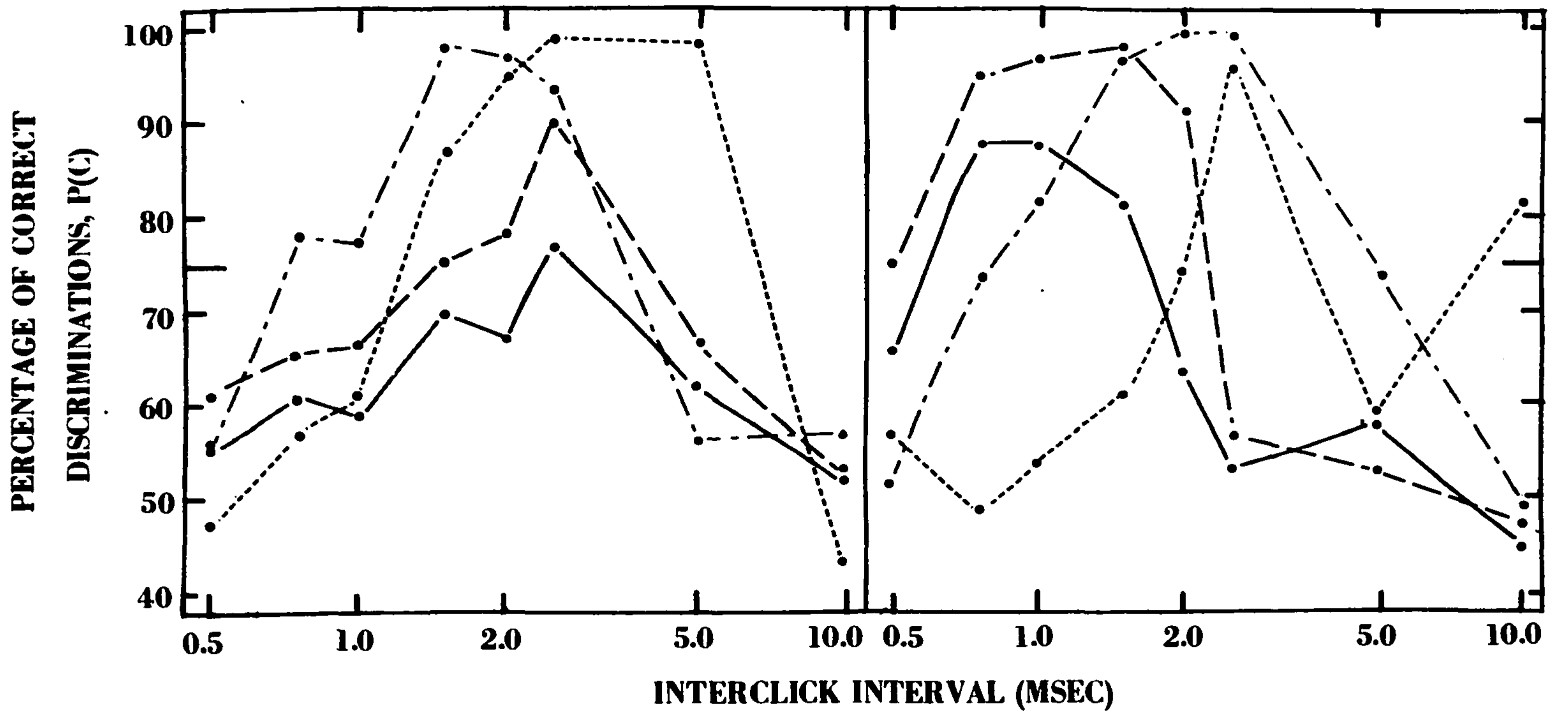

PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
100
90
80
70
60
50
40
0.5
1.0
2.0
5.0
10.0
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

Figure 20.--Percentage of correct discriminations by Subject 3, as a function of the interclick interval, at two levels of signal presentation. Performance at the high signal level is represented in the left-hand portion of the figure; performance at the low signal level is represented in the right-hand portion of the figure. The interclick intensity ratio was 3 dB (———), 6 dB (— — —), 12 dB (-—-—) or 24 dB (---------).



PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
100
90
80
70
60
50
40
0.5
1.0
2.0
5.0
10.0
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

Figure 21.--Percentage of correct discriminations by Subject 4, as a function of the interclick interval, at two levels of signal presentation. Performance at the high signal level is represented in the left-hand portion of the figure; performance at the low signal level is represented in the right-hand portion of the figure. The interclick intensity ratio was 3 dB (————), 6 dB (— — —), 12 dB (- — - —) or 24 dB (---------).

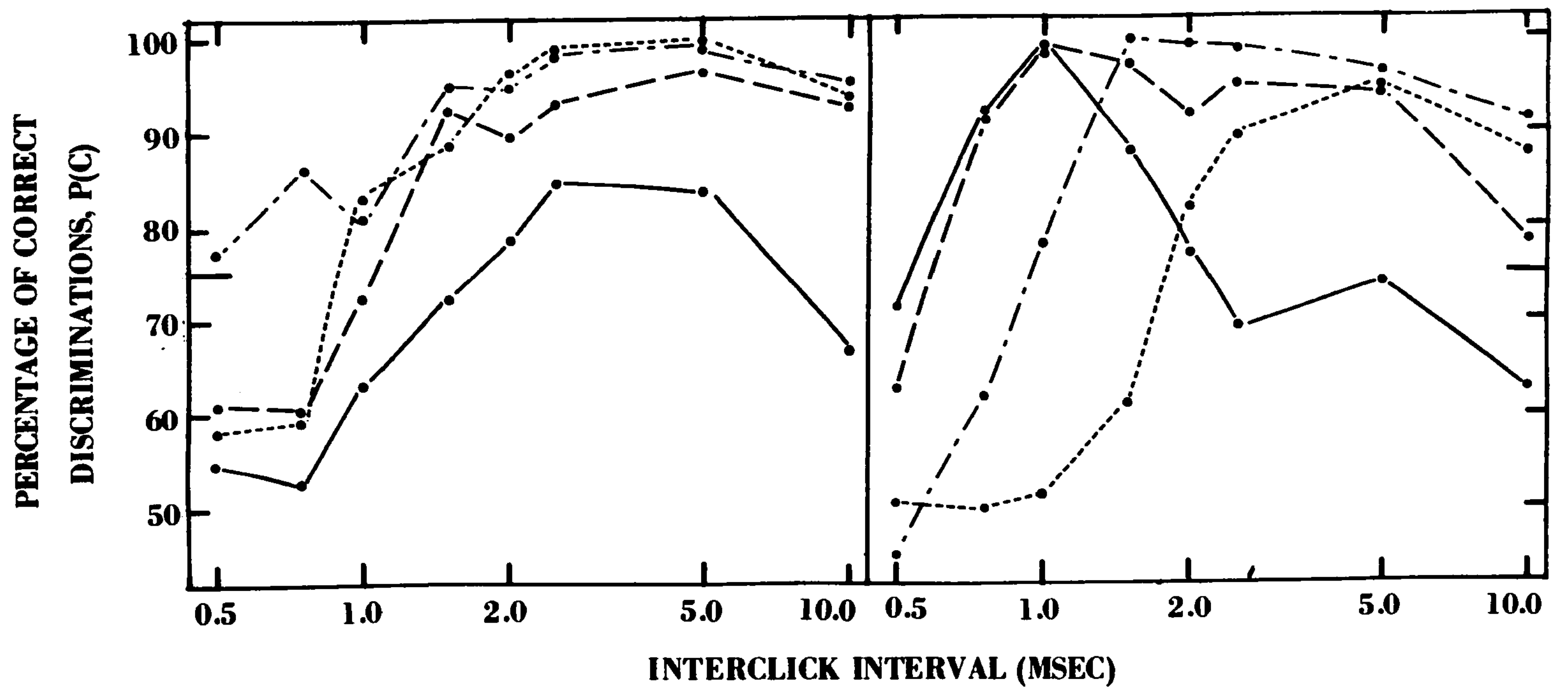
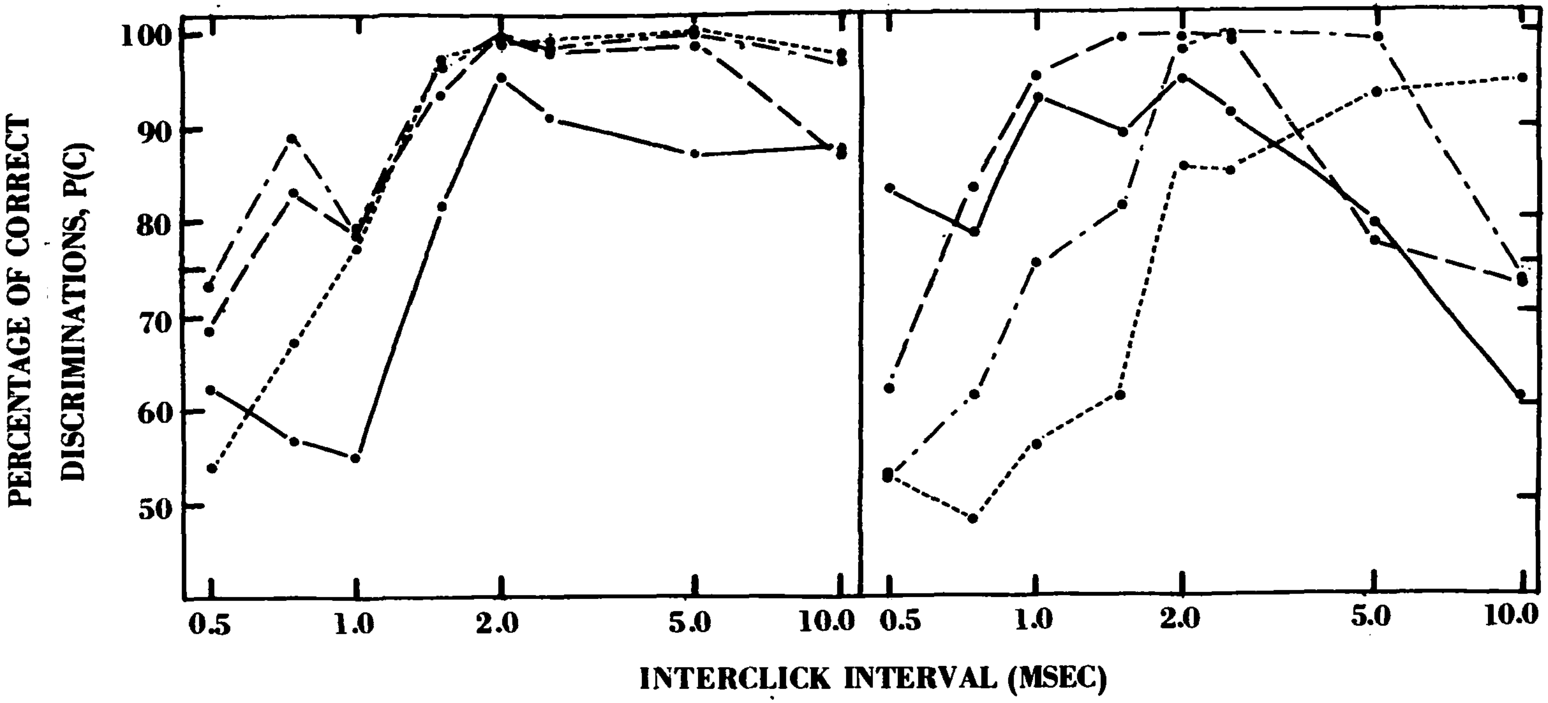

PERCENTAGE OF CORRECT
DISCRIMINATIONS, P(C)
100
90
80
70
60
50
0.5
1.0
2.0
5.0
10.0
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

Figure 22.--Percentage of correct discriminations by Subject 5, as a function of the interclick interval, at two levels of signal presentation. Performance at the high signal level is represented in the left-hand portion of the figure; performance at the low signal level is represented in the right-hand portion of the figure. The interclick intensity ratio was 3 dB (————), 6 dB (— — —), 12 dB (· — · —) or 24 dB (---------).


PERCENTAGE OF CORRECT
DISCRIMINATIONS, P(C)
100
90
80
70
60
50
0.5
1.0
2.0
5.0
10.0
0.5
1.0
2.0
5.0
10.0
INTERCLICK INTERVAL (MSEC)

At I_{45}, a direct relationship between ΔI and $\underline{T}$ was observed for the group data. That relationship appears to be descriptive of the individual data as well.

The ordering, in time, of the temporal psychometric functions generated at the various ΔI values for Subject 1 (Figure 18) and Subject 4 (Figure 21) is identical to that reported for the functions based on the median P(C) scores. The psychometric functions of the other three subjects, particularly those of Subject 2 (Figure 19), are less regular but are ordered comparably with minor exceptions. Subject 3 (Figure 20) demonstrated consistently better performance for ΔI_6 than for ΔI_3 at Δt equal to or shorter than 2.5 msec and showed an uncharacteristic reduction in performance for ΔI_{24} at interclick intervals longer than 2.5 msec. Examination of the functions for Subject 5 (Figure 22) indicates that the discriminability of the ΔI_3 click pairs remained high over a broader temporal range than was the case for the other subjects.

In the preceding portions of this chapter, generalizations were made regarding the effects of the experimental manipulations on the discriminability of the time-reversed click pairs, based on the group data. The implications of the experimental results for the relationship between the asymmetry of temporal masking and the discriminability of the time-reversed click pairs are discussed in the following section of this chapter.

Disparities between the Predicted and Observed Effects of the Experimental Manipulations

Information regarding the conditions which alter the asymmetry of temporal masking led to predictions regarding the effects of ΔI

and I_0 on the discriminability of the time-reversed click pairs. An increase in *I* as a consequence of either a reduction in ΔI or an increase in I_0 would be considered indicative of a relationship between the two psychoacoustic phenomena.

The prediction that an increase in I_0 would be accompanied by an increase in *I* had two bases. The prediction was based, in part, on the temporal masking data provided by Babkoff and Sutton (1968) and, in part, on an unstated assumption regarding the time course of temporal masking.

Interpretation of the data of Babkoff and Sutton (1968), as represented in Figure 3 (page 42), was offered in Chapter II. Babkoff and Sutton determined that the Δt necessary for detection of a probe click under conditions of forward masking became more comparable to that required for detection of that same probe click under conditions of backward masking, as the level of the masking click was increased. Thus, the amount by which a click (presented at a fixed ΔI and Δt) exceeds its masked threshold under backward masking becomes more comparable to the amount by which it exceeds masked threshold under forward masking, as the level of the masking click is increased. If the discriminability of the time-reversed click pairs is dependent upon differences in the level of the less intense click above its masked threshold in the L-M and M-L click pairs, I_0 should affect the discriminability of those signals. An increase in I_0 would be expected to produce a decrease in discriminability at a given Δt.

Recall that Ronken (1970) reported that increasing Δt produced an increase in the differences in masked threshold for a probe click under backward and forward masking. In the case of the time-reversed click pairs, increasing Δt should increase the difference in the amount by which the less intense click exceeds masked threshold in the L-M and M-L click pairs for a given ΔI. If the time course of temporal masking is independent of the level of the masking click, then an increase in I_0 should produce an increase in the interclick interval at which the click pairs become discriminable.

In the present investigation, the duration of the interclick interval required for discrimination of the click pairs (_T_) did increase when I_0 was increased but only for the low interclick intensity ratios (ΔI_3 and ΔI_6). The opposite relationship was observed at the highest interclick intensity ratio (ΔI_{24}).

The rationale for prediction of the effect of ΔI on the discriminability of the click pairs was similar to that involved in predicting the effect of I_0. Again, refer to the data of Babkoff and Sutton (1968), as represented in Figure 3 (page 42). Those investigators determined that the Δt necessary for detection of a probe click under forward masking became more comparable to that required for detection of that same probe click under backward masking, as the interclick intensity ratio was decreased. The amount by which a click (presented at a fixed Δt for a given I_0) exceeds its masked threshold under backward masking becomes more comparable to that by which it exceeds its masked threshold under forward masking, as the interclick intensity ratio is reduced. Therefore, a decrease in ΔI would be expected to produce a decrease in discriminability of the click pairs at a given Δt. If the time course of temporal masking is independent of the level of the masker, increasing Δt should increase the differences in the amount by which the less intense click exceeds its masked threshold in the two click pairs at both I_{45} and I_{75}. Consequently, as ΔI is decreased, the interclick interval at which the click pairs become discriminable should increase.

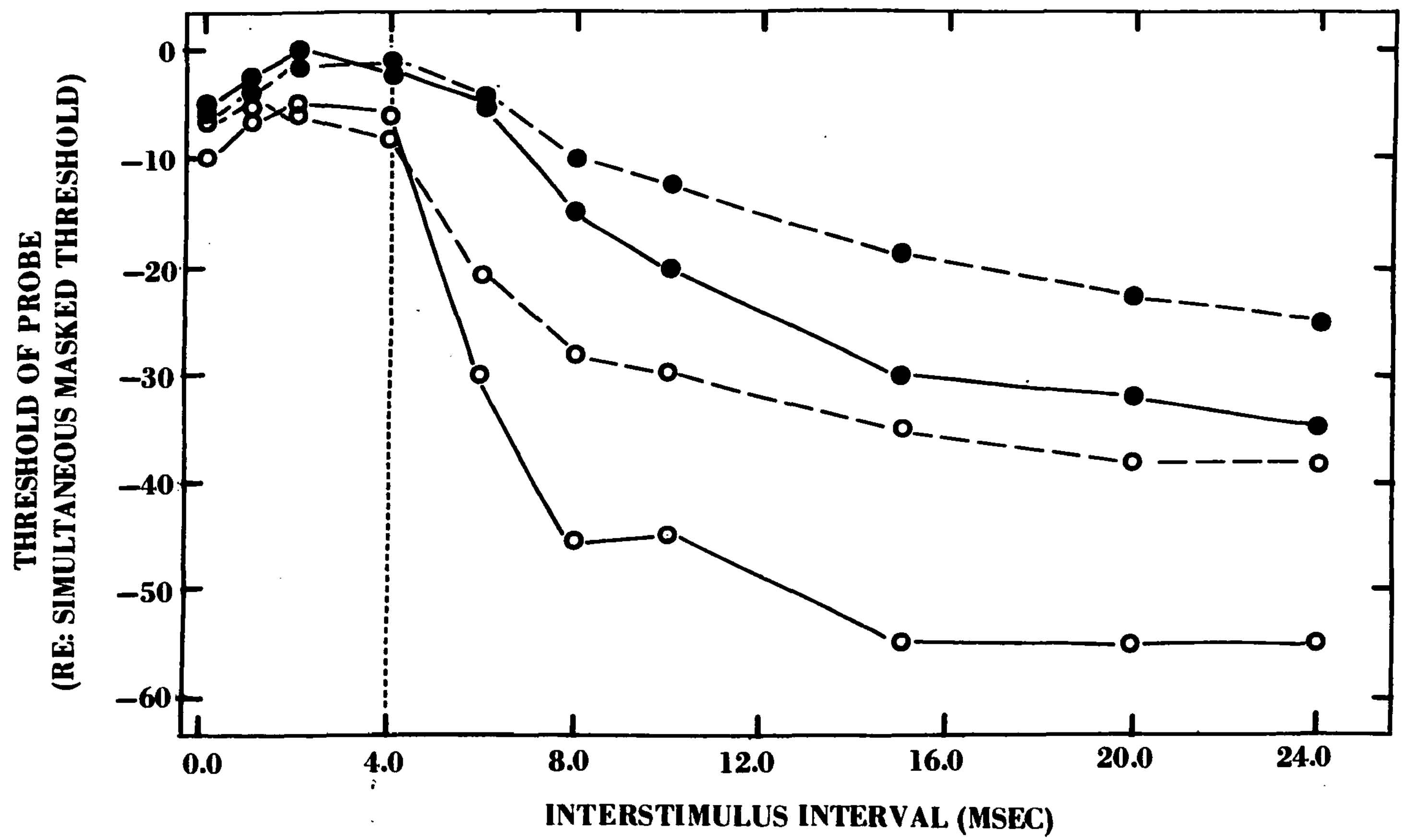
In the present investigation, a decrease in ΔI did produce an increase in $\underline{I}$ but only for the click pairs presented at the high signal level. At the low signal level, the opposite relationship was observed. The differential effect of ΔI at the two levels of signal presentation led to an examination of the validity of the unstated assumption that the time course of temporal masking is independent of the level of the masking click.

First, portions of the data presented by Babkoff and Sutton (1968) were re-examined. That re-examination revealed that the decrease in temporal masking appeared to occur more rapidly as a function of the interclick interval when the masking click was presented at 70 dB SL than when it was presented at 50 dB SL. Babkoff and Sutton confined their investigation to conditions under which the masking click exceeded the probe click by at least 20 dB. Hence, it is not possible to determine from their data whether the same relationship applies at lower interclick intensity ratios, i.e., whether the more rapid decline in temporal masking with the high-level maskers is apparent for probe clicks whose level more closely approximates that of the masking click.

In an attempt to gather additional information regarding the effects of masker level on the time course of temporal masking, consideration was given to the results of investigations in which the masking signal was not a click but a signal with a power spectrum similar to that of a click, that is, a broad-band noise burst. This is not intended to imply that the time course of the temporal masking produced by a noise burst is comparable to that produced by a click. Instead, the intent in examining the temporal masking of clicks by noise bursts was to determine whether there were additional indications that the time course of temporal masking is dependent upon the level of the masking signal, and whether the effects of the masker level are manifest similarly for all just-masked probe clicks, independent of the level of those probe clicks.

A recent publication by Robinson and Pollack (1971) offers the opportunity for evaluation of the time course of both backward and forward masking at brief interstimulus intervals. Robinson and Pollack investigated the temporal masking of a probe click produced by a burst of white noise which was 600 msec in duration. The temporal intervals between the masker and the probe (Δt) encompassed a range from 0.0 msec to 25.0 msec. The amount of masking was expressed in terms of the level of the probe click required for its detection at some Δt, relative to the level required for detection of the probe click when that click was centered in the noise burst. The masker was presented at 40, 55, 70, and 80 dB SPL. The graphically-presented results indicated similar trends in the data of the two subjects who participated in the study; portions of the data from one of those subjects, Subject PER, were selected for presentation in Figure 23. Only the temporal masking data for the noise bursts presented at 55 dB SPL and 80 dB SPL have been reproduced for the purposes of this discussion. For Subject PER, the noise bursts presented

Figure 23.--Masked threshold of a probe click, as a function of the interval between the noise masker and the probe, under conditions of backward masking (○) and forward masking (●). The masker was presented at 55 dB SPL (— — —) and 80 dB SPL (———). Modification of Figure 3, Robinson and Pollack (1971). The reader's attention is directed to the portion of the figure to the right of the dotted line.


THRESHOLD OF PROBE
(RE: SIMULTANEOUS MASKED THRESHOLD)
0
−10
−20
−30
−40
−50
−60
0.0
4.0
8.0
12.0
16.0
20.0
24.0
INTERSTIMULUS INTERVAL (MSEC)

at 55 dB SPL just masked a click presented at 40 dB SL when that click was centered in the noise burst; under the same conditions the noise burst presented at 80 dB SPL just masked a click presented at 65 dB SL.

Examination of the data in Figure 23 suggests that the level of the masker does alter the time course of temporal masking in a manner similar to that indicated by the data of Babkoff and Sutton. The decrease in masking in the 2 to 4 msec interval following the termination of the masker, or preceding its onset, is considerably more gradual when a noise burst of 600 msec duration is the masking signal than when a click is the masking signal. If one considers only the results obtained at interstimulus intervals in excess of 4 msec (at which point temporal masking began a rapid decline), it appears that temporal masking did decline more rapidly as a function of Δt for the masker presented at 80 dB SPL than for the masker presented at 55 dB SPL. The effects of the level of the masker on the time course of temporal masking seem to include those conditions in which the ratio of the intensity of the probe click centered in the noise burst, to the intensity of the probe click presented at some Δt was on the order of 10 dB.

It appears reasonable to conclude that the changes in the course of temporal masking produced by changes in the masker level, which are demonstrable when the masking signals are noise bursts are comparable in type (if not in degree) to those occurring when the masking signals are clicks.

In the presence of a relationship between the asymmetry of temporal masking and the discriminability of the time-reversed click pairs, it is to be anticipated that changes in the time course of temporal masking would affect the discriminability of the click pairs. In the following discussion, an explanation is proposed for the disparities between the obtained and predicted effects of each of the experimental manipulations; that explanation is based on the effect of the level of the more intense click on the time course of temporal masking.

The Effect of ΔI on the Discriminability of the Low-Level Click Pairs

For those click pairs in which the more intense click was presented at 45 dB SL, an increase in ΔI was accompanied by an increase in *I*. Thus, at the low signal level, the effect of ΔI was contrary to that predicted.

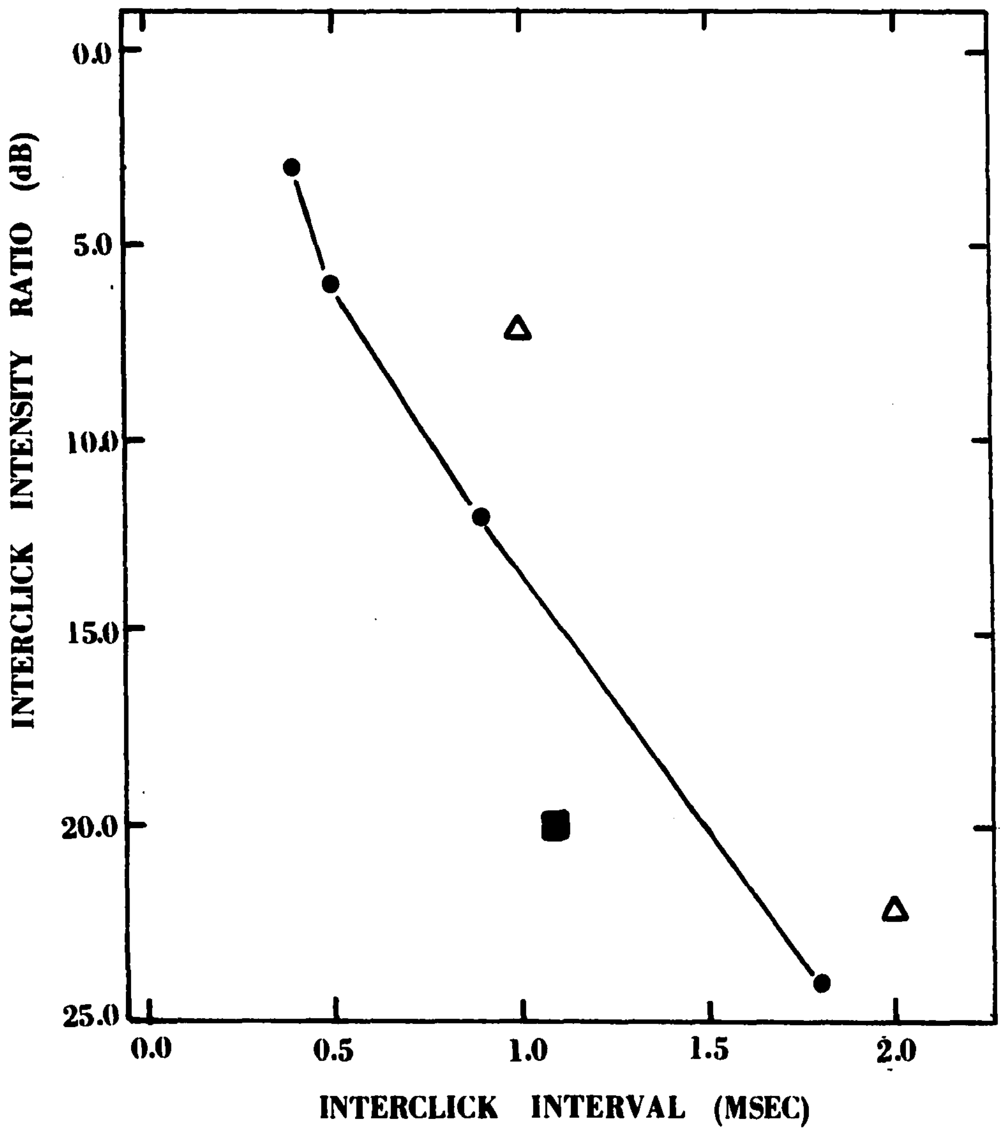
Re-examination of Ronken's (1970) data (Figure 2, page 40) indicates that when a masking click is presented at 55 dB SL, the probe click which precedes or follows it is detected at interclick intervals of 1.0 msec only when the probe click is no more than 5 to 6 dB below the masking click. Probe clicks that are 25 dB lower than the masking click are not detected until the interval between the masking click and the preceding probe click is increased to 2.0 msec; an interclick interval of 3.0 msec is required when that same probe click follows the masking click. Consider the information available from Ronken's study in combination with the evidence that a decrease in the level of the masking click produces a decrease in the rate at which temporal masking declines.

It is probable that for the time-reversed click pairs at I_{45}, those clicks which were 6 dB, 12 dB or 24 dB lower than the more intense click were simply not detectable at the briefest interclick intervals. That is, the masked threshold for the less intense click, even under conditions of backward masking as in the L-M pairs, exceeded the level at which the less intense click was presented. The probable consequence was that the listener had the task of discriminating between two perceptually identical events; he perceived both click pairs as only a single click.

As Δt was increased, the masked threshold for the less intense click in the L-M pairs was exceeded first by the clicks which were 6 dB, then 12 dB and finally, 24 dB below the more intense click. It appears that the click pairs became discriminable when Δt was sufficient to permit detection of the less intense click in the L-M pairs but was still insufficient to permit detection of the less intense click in the M-L pairs.

If the discriminability of the time-reversed click pairs at I_{45} is mediated by differences in the detectability of the less intense click in the two click pairs, _T_ should correspond to the Δt at which the less intense click becomes detectable under conditions of backward masking, for each ΔI. To determine the degree of correspondence, _T_ was determined for each ΔI by referring to the temporal psychometric functions represented in Figure 17. Only the first major peak in performance was considered. For ΔI_3, _T_ was determined by extension of the line joining the datum points at $\Delta t_{0.5}$ and $\Delta t_{0.75}$. The derived points are represented in Figure 24; the co-ordinates of those points correspond to ΔI and _T_. The points are joined by a solid line. That derived "backward masking" function indicates a degree of backward masking slightly greater than that reported by Babkoff and Sutton (1968) for a masking click presented at 50 dB SL; the datum point from their investigation is indicated by a square (■). The degree of backward masking reported by Ronken (1970) for a masking click at 55 dB SL (as represented by the upright triangles,

Figure 24.--"Derived backward masking" function for click pairs presented at the low signal level. The filled circles (●) represent the combination of the interclick intensity ratio and the interclick interval yielding 75% discriminability of the click pairs. Data from Ronken (1970) are represented by an upright triangle (△). Datum from Babkoff and Sutton (1968) is indicated by a filled square (■).


0.0
5.0
10.0
15.0
20.0
25.0
INTERCLICK INTENSITY RATIO (dB)
0.0
0.5
1.0
1.5
2.0
INTERCLICK INTERVAL (MSEC)

Δ) is greater than that indicated in the results of the present investigation or by the results reported by Babkoff and Sutton.

The apparent relationship between the discriminability of the click pairs and backward masking suggests a basis for the reduction in the discriminability of the ΔI_3, ΔI_6 and ΔI_{12} click pairs which was observed as Δt was extended beyond the duration at which optimal performance was obtained. The reduction in optimal performance may reflect the listener's inability to discriminate the signals when the less intense click is clearly audible in the M-L click pairs as well as in the L-M click pairs.

In summary, the effect of ΔI on <u>I</u> at I_{45} appears to be attributable to the direct relationship that exists (under conditions of temproal masking) between the level of the less intense click and the interclick interval required for its detection. At the low level of signal presentation, <u>I</u> may depend simply upon the differences in the detectability of the less intense click in the two click pairs.

The Effect of ΔI on the Discriminability of the High-Level Click Pairs

At the high level of signal presentation, a decrease in ΔI resulted in an increase in <u>I</u>, as predicted. The exception to that generalization was the ordering, in time, of the temporal psychometric functions for I_{75}- ΔI_{12} and I_{75}- ΔI_{24}. The interval required for discrimination of ΔI_{24} was greater than that required for discrimination of ΔI_{12}.

In an attempt to explain the ordering of those two conditions, the temporal masking data of Babkoff and Sutton were again consulted.

Those data indicate that a temporal separation of 1 msec between a masking click (at 70 dB SL) and a preceding click is sufficient to permit detection of the probe click when the interclick intensity ratio is 25 dB; a temporal separation of 1.5 msec is sufficient for detection of that probe click when it follows the masking click. Therefore, at I_{75}, the less intense click was detectable in both click pairs at very brief interclick intervals for ΔI_3, ΔI_6 and ΔI_{12}. Under those conditions, the prediction that _T_ would increase with decreases in ΔI (to compensate for the reduced temporal asymmetry at threshold) was applicable. At ΔI_{24}, however, the detectability (or undetectability) of the less intense click probably limited the discriminability of the click pairs. The listener may have been faced with the same dilemma for I_{75}-ΔI_{24} that confronted him in his attempts to discriminate between the click pairs presented at I_{45}. At the shortest interclick intervals, i.e., those briefer than 1.0 msec, the clicks presented at 24 dB below the level of the more intense click simply were not detectable in the L-M pairs. The listener was forced to discriminate between two click pairs, both of which were perceived as a single click.

A decrease in discriminability for ΔI_3, at interclick intervals longer than those at which optimal performance was demonstrated, is apparent upon inspection of the group data displayed in Figure 16. That decrease in discriminability for ΔI_3 characterizes the data of four of the subjects. The basis for that reduction in discriminability is not clear.

The Effect of I_0 on the Discriminability of the Click Pairs

In the present investigation, an increase in I_0 was accompanied by an increase in I for the ΔI_3 and ΔI_6 click pairs. An increase in I_0 was not accompanied by a similar increase in I for ΔI_{12}. For ΔI_{24}, however, an increase in I_0 resulted in a decrease in I.

In predicting the effects of I_0 on the discriminability of the signals, an increase in I was anticipated to be necessary as I_0 was increased in order to compensate for the reduced temporal asymmetry at threshold. In an earlier part of this discussion, the suggestion was made that I for the I_{45} click pairs depended upon the detectability of the less intense click. The discriminability of the I_{75} click pairs did not appear to depend, to the same degree, upon the detectability of the less intense click except for I_{75}-ΔI_{24}. The differences in the basis of the discrimination at the high and low signal levels are reflected in the differential effect of I_0 on I at the four ΔI values.

For ΔI_3 and ΔI_6, the less intense click was detectable in the L-M pairs at both I_{45} and I_{75}. The less intense click was also detectable in the M-L pairs at I_{75}. Therefore, in order for the click pairs at I_{75} to become discriminable, it was necessary to compensate for the reduced temporal asymmetry at threshold by increasing the interclick interval (relative to that required at I_{45}).

For ΔI_{12}, the apparent absence of an effect of I_0 on the discriminability of the click pairs may be explained similarly. At I_{45}, an increase in ΔI to 12 dB produced an increase in the interclick interval necessary for detection of the less intense click in the L-M pairs (relative to that required for I_{45}-ΔI_3 and I_{45}-ΔI_6). The increase in the interclick interval for detection of the less intense click was accompanied by an increase in I for I_{45}-ΔI_{12}. At I_{75}, however, an increase in ΔI to 12 dB produced a decrease in *I* (relative to *I* for I_{75}-ΔI_3 and I_{75}-ΔI_6). As a consequence, the temporal psychometric functions for I_{45}-ΔI_{12} came to approximate those for I_{75}-ΔI_{12}.

For ΔI_{24}, the suggestion has been made that the discriminability of the signals at both I_{45} and I_{75} was determined by the detectability of the less intense click in the L-M pairs. In investigations of temporal masking, a reduction in the level of the masker has been shown to produce a more gradual decline in backward masking as a function of time. In the L-M click pairs, the interclick interval required for detection of the less intense click for ΔI_{24} was greater when the more intense click is presented at 45 dB SL than when it is presented at 75 dB SL. As a consequence, *I* for the ΔI_{24} click pairs (which is presumably related to the interval required for detection of the less intense click in the L-M pairs) was understandably greater at I_{45} than at I_{75}.

In review, the results of the present study provide substantial evidence that the discriminability of the time-reversed click pairs is related to temporal masking. The discriminability of those signals appears to be dependent upon both the time course and the asymmetry of temporal masking. The correspondence between the results obtained in this investigation and those obtained by investigators using similar stimuli must be examined before the suggestion is made that the discriminability of those stimuli is related to temporal masking.

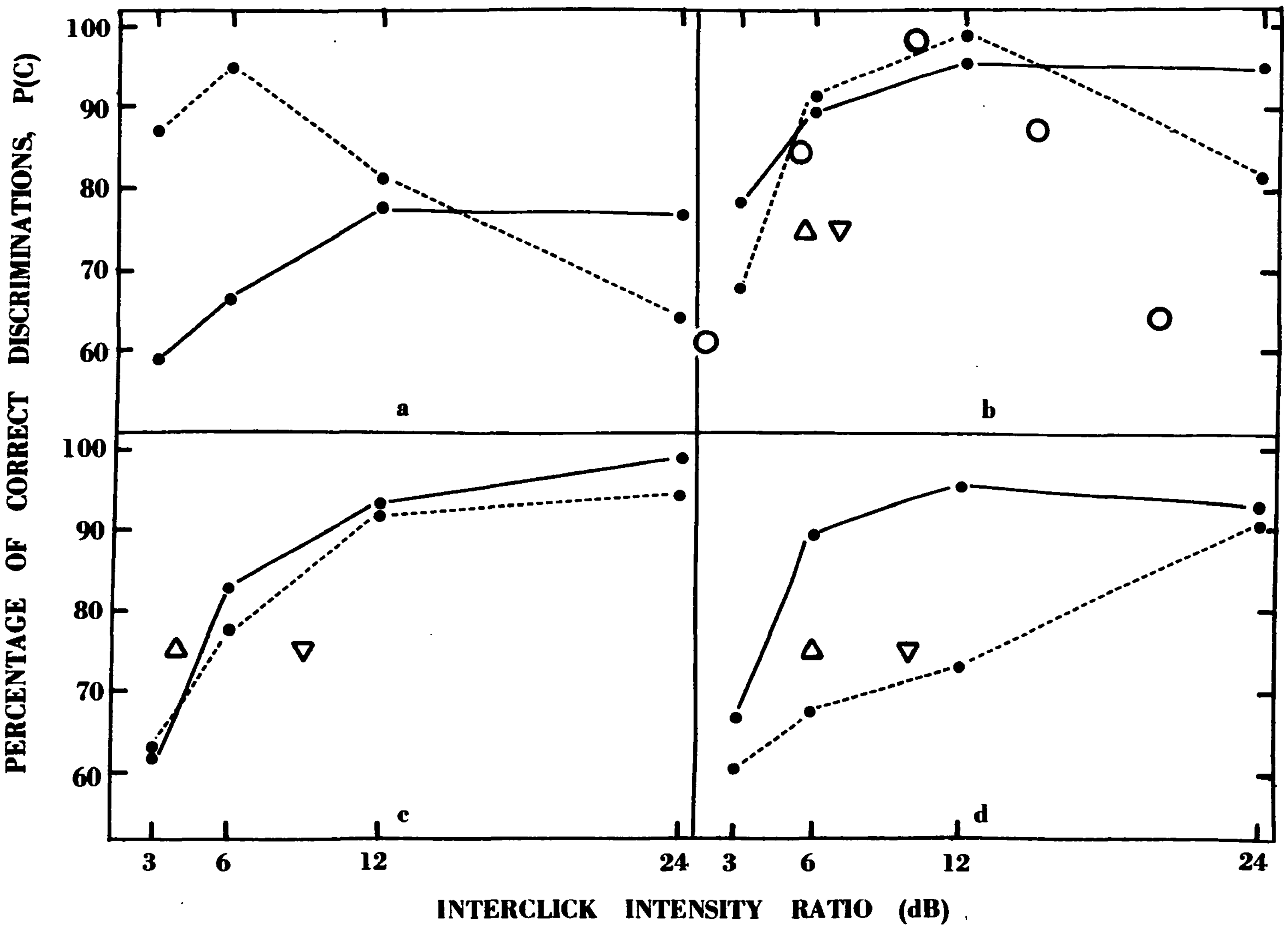
Comparison of the Results of the Present Investigation with Those of Previous Investigations

To facilitate comparison of the results of this investigation and of other investigations, the results of this study are represented graphically in Figure 25, in a manner not previously employed for the presentation of the data. In Figure 25, the results obtained at selected interclick intervals are presented in the form of intensive psychometric functions (definition on page 66). Each of the four sections, into which Figure 25 is divided, presents the intensive psychometric functions at one of four interclick intervals, 1.0, 2.0, 5.0 and 10.0 msec. The functions are based on the median P(C) scores and the parameter is I_0. Inspection of Figure 25 reveals that the values of ΔI yielding optimal performance are not constant across interclick intervals or across signal levels. This information has been conveyed in the previous description of the experimental results.

Despite the similarity of the stimuli employed in the present investigation to those employed by Ronken (1970), comparison of the results of the two investigations is complicated by differences in the experimental procedure and in the dependent variable. Ronken used PEST in conjunction with a two-alternative forced-choice procedure for determination of the ΔI which yielded 75% correct discrimination of the time-reversed click pairs at specified interclick intervals. I_0 was fixed at approximately 55 dB SL.

The comparison was further complicated by Ronken's report of differences in the effect of the interclick interval on the ΔI estimates obtained for his two subjects. In addition to those intersubject differences, the intrasubject differences in the PEST estimates of ΔI at a particular Δt were as great as 10 to 12 dB. Ronken represented the performance of each of the subjects by averaging the PEST estimates of ΔI obtained at a given Δt for that subject. Those average ΔI values,

Figure 25.--Median percentage of correct discriminations, as a function of the interclick intensity ratio, for four values of the interclick interval. Each section of the figure represents performance for a single value of the interclick interval: a) 1.0 msec; b) 2.0 msec; c) 5.0 msec; and d) 10.0 msec. The level of signal presentation was either 75 dB SL (————) or 45 dB SL (---------). Data from Ronken (1970) are represented by upright and inverted triangles (△ and ▽). Data from Green (1973) are represented by open circles (○).


PERCENTAGE OF CORRECT DISCRIMINATIONS, P(C)
100
90
80
70
60
a
b
c
d
3
6
12
24
INTERCLICK INTENSITY RATIO (dB)

obtained at interclick intervals of 2.0, 5.0 and 10.0 msec have been used for comparison of the results of the two investigations. The average ΔI values reported by Ronken are indicated in Figure 25; the results for one subject, SB, are represented by an upright triangle ($\triangle$) and those for the other subject, JL, are represented by an inverted triangle (∇). The ΔI values reported for each of Ronken's subjects differ by no more than 5 to 6 dB from those estimates that would be derived on the basis of our results (provided the intensive psychometric function for I_{55} falls between that for I_{45} and that for I_{75}).

The results of the two investigations appear to differ in one respect. No estimates of ΔI could be obtained by Ronken at interclick intervals of 1.0 msec using PEST. On those runs in which the subject's performance remained below 75%, PEST caused the level of the less intense click to be increased until ΔI reached zero, at which point the time-reversed click pairs were identical and the run was discontinued. Consideration of the intensive psychometric functions obtained in the present investigation at $\Delta t_{1.0}$ suggests the cause of Ronken's failure to obtain estimates of ΔI. At an interclick interval of 1.0 msec, decreasing ΔI would have served only to decrease the subject's performance. Optimal discrimination performance was obtained for ΔI_6 at I_{45} but performance declined as ΔI was increased or decreased. At I_{75} optimal performance was obtained for ΔI values in excess of 12 dB. Thus, despite the presence of procedural differences in the two studies, the results obtained by Ronken appear to be reasonably comparable to those obtained in the present investigation for click pairs in which the interclick intensity ratio was low.

Comparison of our results for time-reversed click pairs with those reported by Green (1973) for time-reversed sinusoidal signals also is simplified by referring to Figure 25. In making comparisons between our results and those of Green, the results obtained by Green for the time-reversed 4000 Hz signals (rather than those for the 1000 Hz or 2000 Hz signals) were selected for consideration. The selection was based on the evidence that the neural encoding of clicks, like that of high-frequency sinusoids is mediated at the basal portion of the cochlea (David, Guttman and van Bergeijk, 1959; Deatherage and Hirsh, 1959; Teas, Eldredge and Davis, 1962).

Green examined the effect of ΔI on the discriminability of the time-reversed signals only under those conditions in which the total duration of the signals was fixed at 2.0 msec. The level of the more intense half of the signal was 100 dB SPL "measured when the sinusoids were presented continuously." The sensation level of the more intense portion of the time-reversed sinusoidal signals probably approximated that of the more intense click in those click pairs presented at I_{75} (Plomp and Bouman, 1959). The mean P(C) values reported by Green for those signals which were 2 msec in duration are represented by open circles (**O**) in Figure 25b. Green's results are clearly comparable to our own for ΔI's smaller than 15 dB; the P(C) values obtained in the two investigations differ by less than 10%. Additional increases in ΔI had little effect on the discriminability of the time-reversed click pairs at I_{75} but the discriminability of the time-reversed sinusoidal signals was reduced markedly. The basis for the divergence in results at the larger ΔI values is not clear.

Additional comparisons between our data and those of Green are based on consideration of the temporal psychometric functions, rather than of the intensive psychometric functions discussed to this point. Green obtained temporal psychometric functions only for those time-reversed sinusoidal signals in which the difference between the two halves of the signal was fixed at 10 dB. The P(C) values reported by Green for the 4000 Hz signals were compared with the results obtained in the present investigation for the ΔI_{12} click pairs. Green's results are represented by open circles (**O**) in Figure 9 (page 74). The correspondence between the results of the two investigations is unmistakable. Green observed that the "absolute levels" at which the time-reversed sinusoidal signals were presented ("either 80-70 dB or 100-90 dB SPL") had "no major effect on the discriminability of the signals." In the present investigation, I_0 exerted a minimal effect on discriminability for ΔI_{12} but did alter the discriminability of those click pairs in which ΔI was 3, 6 or 24 dB. The deterioration in the discriminability of the time-reversed sinusoidal signals noted for signals whose duration exceeded 4 msec was observed for only two of our subjects at I_{75}. The disparity between the results which appeared as the duration of the sinusoidal signals increased was understandable. For the sinusoidal signals, an increase in duration is accompanied by a narrowing of the energy density spectra of the signals as well as an increase in their sensation level. In addition, the movements of the basilar membrane increasingly depart from those produced in response to impulsive stimuli as the signal duration is increased (Legouix, 1969).

The correspondence between the results reported by Green and those observed in the present investigation suggests that the discriminability of the two types of time-reversed signals is altered similarly by manipulation of ΔI (for values of ΔI less than 15 dB) and of total duration (for durations less than 4 msec).

Confirmation of the effects of Δt on the discriminability of the time-reversed click pairs (for ΔI greater than 10 dB) is provided by comparison of our data with that obtained by Babkoff and Sutton (1971) in their investigation of the discriminability of time-reversed click pairs. Comparison of the results of the two investigations required that the "adjusted per cent correct" scores (i.e., corrected for chance) which were reported by Babkoff and Sutton be converted to P(C) scores comparable to those obtained in our investigation. On the assumption that the adjusted per cent correct scores for a three-interval forced-choice procedure would be equal to the adjusted per cent correct scores for a two-interval forced-choice procedure, the scores reported by Babkoff and Sutton were converted to P(C) scores using the following formula: P(C) = 1/2 (per cent correct as reported by Babkoff and Sutton) + 50%. Babkoff and Sutton reported the results obtained for individual subjects, exclusively; average performance could not be determined due to the differences in conditions administered to the subjects. The results for each of the two subjects under conditions most comparable to those of the present investigation are represented in Figures 9 and 10 (pages 74 and 75, respectively). The discrimination performance of one of the subjects, SK, for click pairs at I_{65}-ΔI_{15} is represented by crosses (X) in Figure 9. The performance of that same subject for I_{65}-ΔI_{30} click pairs is represented by the same symbol in Figure 10. The performance of a second subject, JL, for I_{40}-ΔI_{25} click pairs is represented by squares (□) in Figure 9. The results reported by Babkoff and Sutton are in general agreement with those obtained in the present study. Disparities between the results are apparent only at the longest interclick intervals, at which point a decline in the discrimination performance of the subjects in the study by Babkoff and Sutton is observed. As noted earlier, two of our subjects did demonstrate a reduction in the discriminability of the I_{75}-ΔI_{24} click pairs at the longer interclick intervals. A marked reduction in the discriminability of the I_{45}-ΔI_{24} pairs was not observed in the present investigation. The basis for these differences in performance at the long interclick intervals is not clear. In the initial stages of practice, all of the subjects in our investigation demonstrated low discrimination performance at the longest interclick intervals for all the click pairs; this uniformly low performance was not apparent following additional practice under those conditions.

In review, the results of the present investigation are compatible with those obtained in three other investigations devoted to determination of the discriminability of time-reversed signals. The experimental design of the present investigation, unlike those of the other investigations, permitted evaluation of the interactive effects of I_0, ΔI and Δt on the discriminability of the time-reversed signals. The nature of the interaction among those three signal parameters provides evidence of a relationship between temporal masking and the discriminability of the time-reversed click pairs.

Conclusions

The results of the present investigation indicate that the discriminability of the time-reversed click pairs is inextricably and systematically related to the level of presentation of those click pairs and to the ratio of the intensities of the clicks within those click pairs. The effect of the level of signal presentation on discrimination performance (for a given interclick intensity ratio) casts doubt on the assertion that the discriminability of the time-reversed click pairs reflects discrimination of the order of events within a waveform by the auditory system. The order of events within the waveform is not altered by changes in I_0, but discriminability is affected.

In view of the effects of intensity manipulations on the discriminability of the time-reversed click pairs, determination of the discriminability of those signals, as a function of the interclick interval, cannot be presumed to provide a valid method for estimation of "the temporal threshold" of the auditory system. The dependence of such a measure on signal level and interclick intensity ratio may preclude its use for determination of an alteration in the temporal threshold of the impaired auditory system. The utility of the time-reversed sinusoidal signals as stimuli for determination of the temporal threshold of the auditory system appears to be limited similarly. Given the observed intensity effects on the discriminability of the click pairs, determination of the effects of intensity manipulations for more complex stimuli (such as Huffman sequences) seems to be warranted. In the absence of such intensity effects, determination of the discriminability of Huffman sequences as a function of their total duration may offer a method (as suggested by Patterson and Green, 1971) for evaluation of the temporal resolving power of the normal or impaired auditory system.

CHAPTER V

SUMMARY

Introduction

Investigations of the temporal resolving power of the auditory system typically have yielded estimates of the "temporal threshold" in the 2.0-msec region, despite differences in the procedures employed to obtain those estimates. The estimates derived in the majority of the investigations represent the duration of a silent interval between stimuli of equal intensity that is required for the listener either to perceive those stimuli as successive in time or to detect the temporal discontinuity between them. Estimates based on the duration of that silent interval have been shown to be affected only minimally by changes in the intensity of the stimuli which bound the silent interval.

A few investigators have offered estimates of the temporal threshold which represent the minimal duration of a stimulus required for discrimination of the order of events within the waveform of that stimulus. The time-reversed click pairs employed by Ronken (1970) typify the stimuli presented in investigations of this type. Each click pair may be considered to be a single transient. In one of the click pairs, a less intense click precedes a more intense click; in the other, the order of the clicks is reversed. The click pairs offer identical energy density spectra and are of equal duration; they differ only with respect to waveform. Determination of the listener's ability to discriminate between the click pairs, as a function of the interclick interval, is presumed to provide a method for evaluating the temporal resolving power of the auditory system. There is evidence that measures obtained for click pairs are affected by changes in signal intensity. The present investigation was designed to document the effects of intensity on the discriminability of the time-reversed click pairs.

Method

The discriminability of the time-reversed click pairs was assessed for five normal-hearing subjects using a two-interval forced-choice procedure with feedback. The three parameters which defined the click pairs were the level of the more intense click (I_0), the interclick intensity ratio (ΔI) and the interval between the onsets of the clicks within a pair (Δt). The discrimination performance of the subjects was determined for two levels of the more intense click (45 dB SL and 75 dB SL) and four interclick intensity ratios (3, 6, 12 and 24 dB) at eight interclick intervals (0.5, 0.75, 1.0, 1.5, 2.0, 2.5, 5.0 and 10.0 msec). The click pairs were presented monaurally to the right ear.

The subjects' task was to identify the interval of occurrence of the click pair in which the less intense click preceded the more intense click. Prior to the initiation of data collection, the subjects were exposed to at least 10,000 practice trials. The computation of P(C) for each subject in each of the 64 experimental conditions was based on two blocks of 100 trials. The interclick interval at which a given set of click pairs became just discriminable (75% correct discrimination) is designated *T*.

Results

The discriminability of the time-reversed click pairs was altered by changes in both I_0 and ΔI for Δt between 0.5 and 10.0 msec. The effect of each of the intensity variables depended upon the level of the other intensity variable. The effects of I_0 and ΔI, as determined from the median P(C) scores for the group data, were comparable to those observed in the individual data.

Effect of I_0

For ΔI_3 and ΔI_6, an increase in I_0 from I_{45} to I_{75} resulted in an increase in *T*. The same manipulation produced the opposite effect for ΔI_{24}; an increase in I_0 was accompanied by a reduction in *T*. An increase in I_0 for ΔI_{12} did not alter *T*.

Effect of ΔI

At I_{75}, a decrease in ΔI was associated with an increase in *T*, with one exception; the duration of *T* for the I_{75}-ΔI_{12} click pairs exceeded that for the I_{75}-ΔI_{24} click pairs.

At I_{45}, the same decrease in ΔI produced an effect opposite to that observed at the high level of signal presentation. A decrease in ΔI was accompanied by a decrease in *T*.

Conclusions

The results of the present investigation are compatible with the notion that the discriminability of the click pairs (at interclick intervals briefer than 10.0 msec) is related to the asymmetry of temporal masking and is dependent upon the time course of temporal masking.

The dependence of the discriminability of the time-reversed click pairs on both the level of the more intense click and the inter-click intensity ratio suggests that estimates of the "temporal threshold" obtained using those stimuli may be of questionable validity and limited utility.

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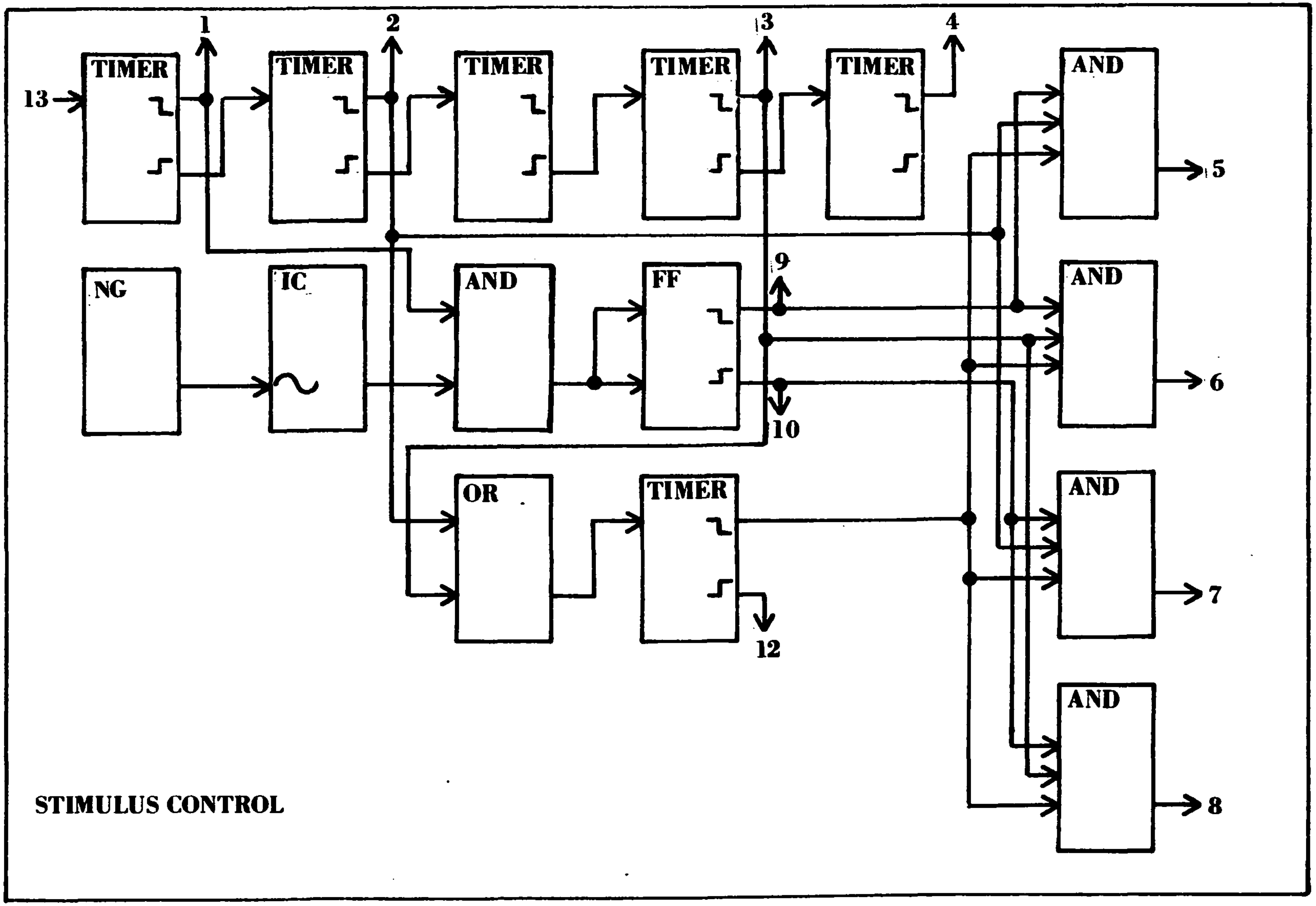
APPENDIX A

Detailed Schematic Illustration of the Equipment Used for Automation of the Two-Interval Forced-Choice Procedure



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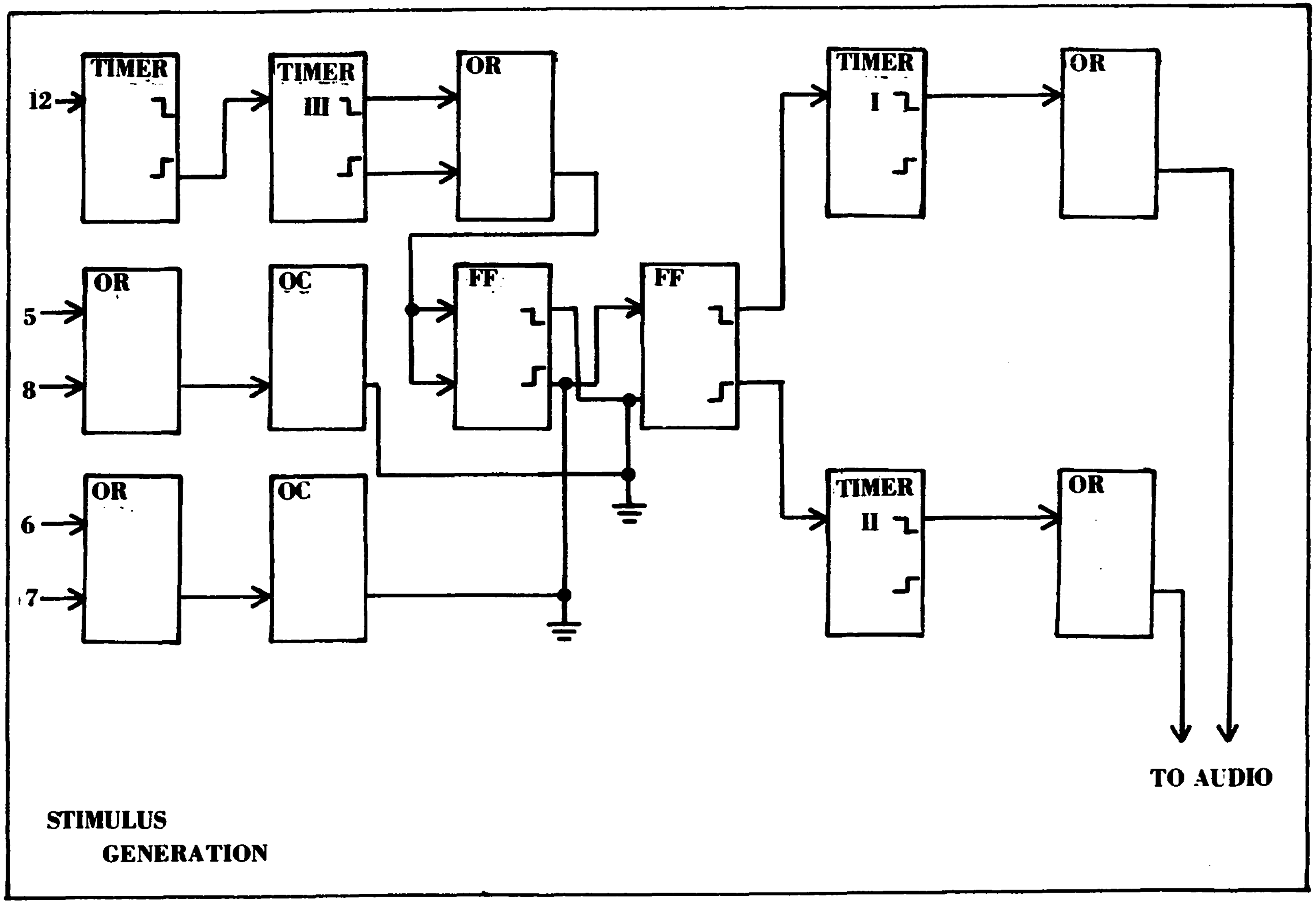
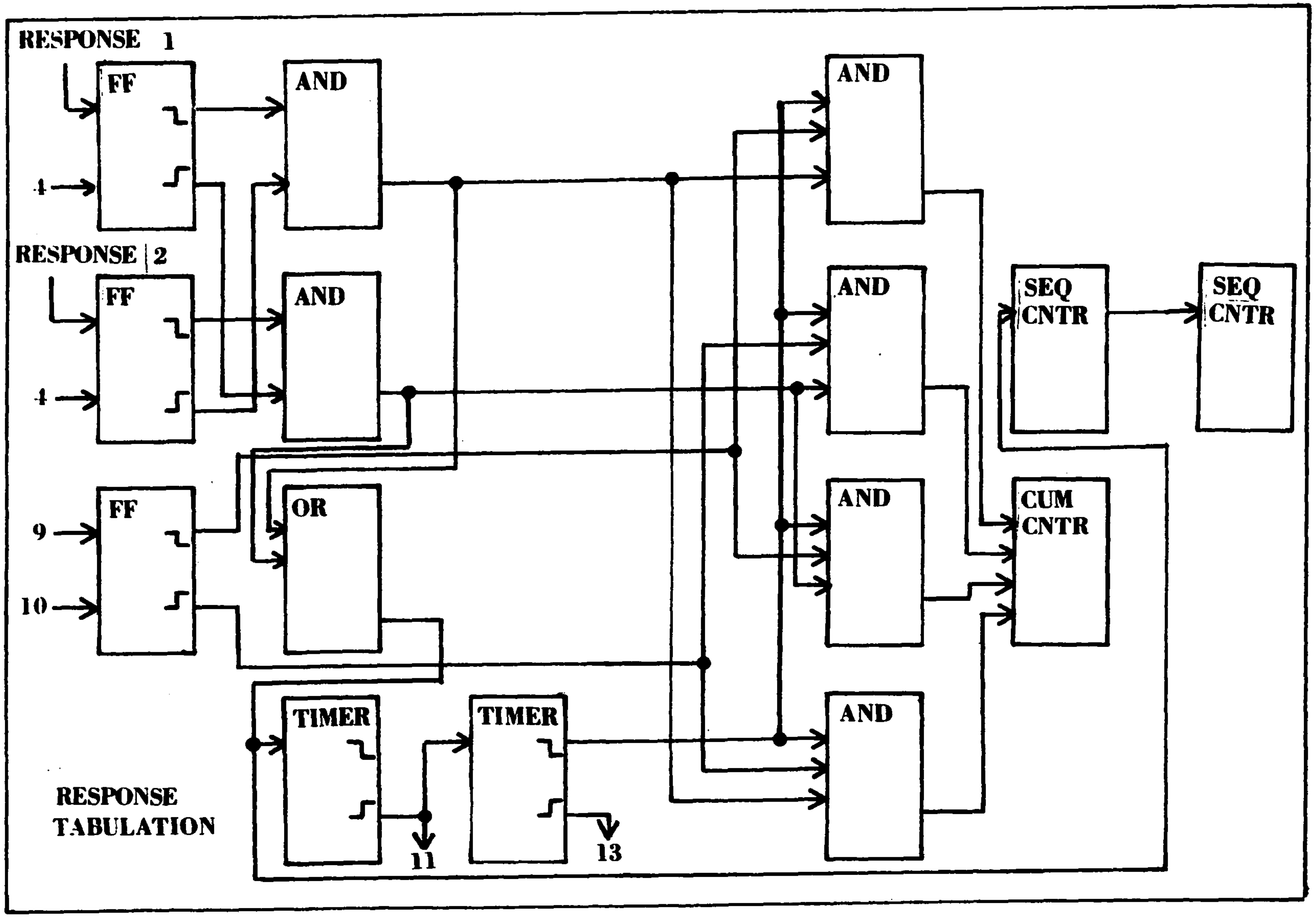
STIMULUS CONTROL



STIMULUS
GENERATION


RESPONSE 1
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RESPONSE 2
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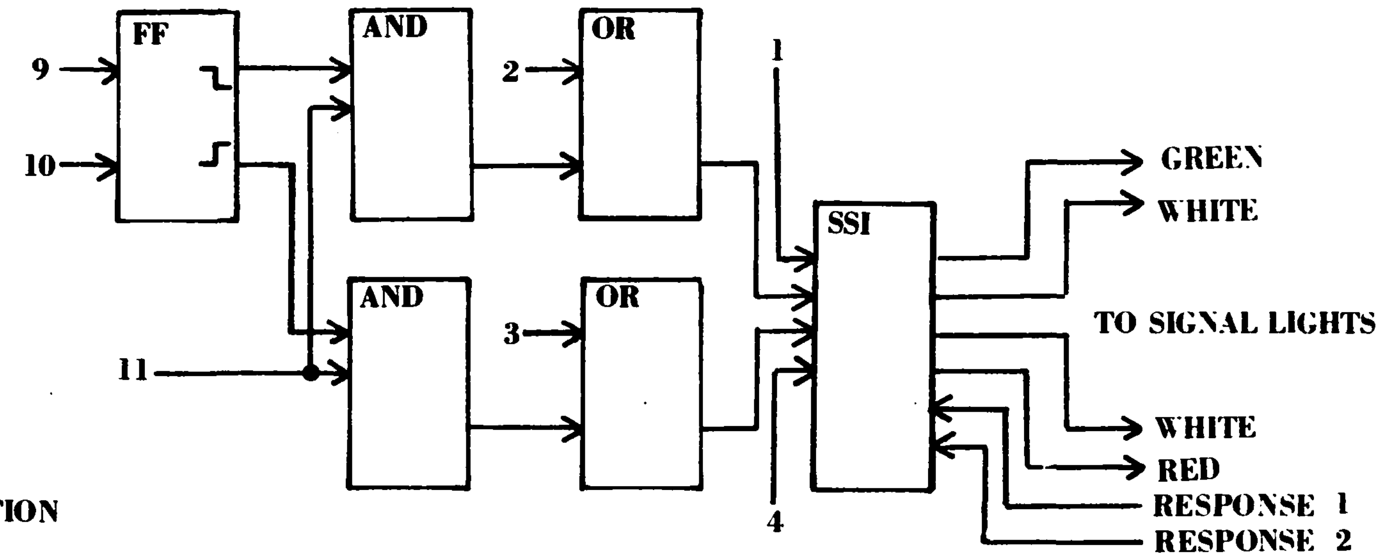
RESPONSE TABULATION

FEEDBACK PRESENTATION



NG: NOISE GENERATOR

IC: INPUT CONVERTER

FF: FLIP-FLOP

SSI: SUBJECT STATION INTERFACE

OC: OUTPUT CONTROL

APPENDIX B

Percentage of Correct Discriminations, P(C), by Individual Subjects for All Experimental Conditions

Percentage of Correct Discriminations, P(C), by Individual Subjects for All Experimental Conditions

I. Signal Level of 75 dB SL

Interclick Intensity Ratio	Interclick Interval (in msec) 0.5	0.75	1.0	1.5	2.0	2.5	5.0	10.0
3 dB								
Sub. # 1	54.7	53.9	59.4	60.6	89.8	87.7	51.0	42.0
2	50.2	62.9	52.0	62.0	71.1	56.5	61.7	77.9
3	55.0	60.5	59.0	70.1	66.8	77.4	62.2	52.1
4	54.8	53.5	63.8	72.4	78.6	84.5	84.0	67.1
5	61.9	56.4	54.4	81.7	95.4	91.1	86.4	87.4
6 dB								
Sub. # 1	44.4	53.4	55.0	81.9	96.5	94.4	57.1	57.7
2	51.4	55.9	62.5	77.1	78.7	75.1	82.3	89.7
3	60.9	65.8	66.5	75.9	78.2	90.2	66.6	53.2
4	61.3	60.8	72.6	92.5	89.7	93.8	96.5	92.6
5	68.5	82.8	79.3	93.4	99.0	98.1	98.3	87.7
12 dB								
Sub. # 1	59.5	80.3	77.9	92.7	95.9	94.1	79.1	55.2
2	45.4	53.3	60.7	80.8	80.7	88.8	92.9	99.5
3	55.4	78.1	77.5	98.0	96.9	93.8	56.5	56.9
4	77.5	86.5	81.4	95.4	95.1	99.0	99.6	95.7
5	72.8	88.3	79.8	97.4	99.5	98.9	100.0	96.4
24 dB								
Sub. # 1	54.7	70.2	85.3	90.2	92.7	95.9	89.4	74.6
2	48.5	49.5	49.8	57.3	92.3	89.5	97.5	93.4
3	47.3	57.6	61.1	87.3	94.7	99.5	98.5	43.8
4	58.5	60.2	82.9	88.6	96.5	99.0	99.5	93.0
5	53.9	67.3	77.1	97.4	98.5	99.1	100.0	97.9

Percentage of Correct Discriminations, P(C), by Individual Subjects for All Experimental Conditions (Continued)

II. Signal Level of 45 dB SL

Interclick Intensity Ratio	Interclick Interval (in msec) 0.5	0.75	1.0	1.5	2.0	2.5	5.0	10.0
3 dB								
Sub. # 1	80.8	95.8	87.0	60.9	63.2	51.0	42.2	60.3
2	98.0	74.6	85.9	66.8	68.1	53.6	63.6	54.8
3	65.9	87.7	87.5	80.9	63.4	53.3	57.9	44.7
4	70.7	91.9	99.0	87.5	76.3	68.8	73.7	62.6
5	82.9	78.5	92.6	88.9	94.5	91.3	79.6	60.5
6 dB								
Sub. # 1	66.9	96.7	93.7	85.4	54.9	56.4	61.1	57.2
2	86.0	80.3	95.0	91.0	63.4	63.2	80.4	67.7
3	75.7	92.6	96.4	97.9	91.3	56.4	53.1	47.0
4	62.6	91.3	98.5	97.0	91.6	94.9	94.1	78.1
5	62.2	83.7	94.9	99.1	99.5	99.0	77.7	73.0
12 dB								
Sub. # 1	64.6	86.9	97.6	99.0	99.4	95.4	92.6	57.6
2	47.5	61.5	74.9	95.2	93.4	87.9	89.7	83.8
3	51.5	73.0	81.6	97.0	99.5	99.5	74.0	49.6
4	44.8	61.6	77.6	99.5	99.0	99.2	96.0	91.0
5	53.2	61.6	85.2	91.0	97.9	99.4	98.5	73.1
24 dB								
Sub. # 1	53.5	48.2	58.0	95.0	96.2	100.0	98.8	10.0
2	50.8	48.6	43.4	53.2	64.2	85.0	95.0	94.6
3	56.2	48.4	54.1	60.8	74.4	95.9	58.8	81.3
4	50.1	49.5	51.1	60.9	81.8	89.9	94.4	87.6
5	53.0	48.1	56.2	60.8	85.7	85.5	93.0	94.6