SIMULTANEOUS TEMPORAL INTERVAL PRODUCTION AND DURATION DISCRIMINATION IN PRACTISED SUBJECTS

By

JOAN MARTHA BREWSTER, B.A., M.A

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AUTHOR: Joan Martha Brewster, B.A. (McMaster University)
M.A. (University of Western Ontario)

SUPERVISOR: Professor A.B. Kristofferson

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Abstract

Theories of the perception of short time intervals have generally postulated a single timing mechanism which serves in all experimental situations, including both duration discrimination and interval production. Despite this hypothesis, the characteristics of timing behaviour are not always the same for different timing tasks.

A dual timing task was devised, in which subjects concurrently perform both response-stimulus synchronization and duration discrimination. They were required to discriminate the time of occurrence of a brief auditory stimulus presented during a 460-msec. synchronization interval, also marked by brief auditory stimuli. The internal interval produced to perform response-stimulus synchronization can be deterministic and, if this interval could be used as a criterion for duration discrimination in the dual task, "perfect" discrimination might result. This end was not attained but both synchronization and duration discrimination were performed as well concurrently as they are when they are performed separately. The independence of the variability found in the two tasks suggests that they may not be accomplished by the same timing mechanism.

Although performances on the concurrent tasks were largely independent, the stimuli marking the duration discrimination interval had systematic effects on synchronization performance. A qualitative model was proposed to account for these effects. When stimuli are expected during the synchronization interval, the produced interval is occasionally interrupted, until the stimulus is observed. The momentary

discontinuities, each of which adds a small amount of time to the final response, occur within a temporal "observation window" which is established after experience with a particular stimulus set.

The variances of the two concurrent tasks were independent, indicating that a single timing mechanism will not easily account for behaviour in all situations involving the timing of brief intervals. However, the systematic effects of the duration discrimination stimuli on synchronization behaviour suggest that the two tasks do share some processing resources.

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TABLE OF CONTENTS

TABLE OF CONTENTS

CHAPTER PAGE

TABLE OF CONTENTS

CHAPTER PAGE

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

SYMBOL TABLE

A carry-along guide through the maze of symbols in this thesis

P_1, P_2, P_3 - tone bursts marking the stimulus intervals

P_1-P_2 - stimulus synchronization interval

P_1-P_3 - duration discrimination stimulus interval

P_1-P_3MP - mid-point or base duration of each set of duration discrimination stimuli

ΔD - difference between each pair of P_1-P_3 intervals

α_p - afferent latency of marker stimulus

β_p - central arrival time of marker stimulus

e - efferent latency of response

d - internal interval produced to perform synchronization

I_1 - first internal interval produced in sequential model (Figure 4)

I_2 - second internal interval produced in sequential model (Figure 4)

q - duration of internal time quantum

C - time of internal duration discrimination criterion

O_1 - beginning of observation window (Figure 30)

O_2 - end of observation window (Figure 30)

R_S - "short" duration discrimination response

R_L - "long" duration discrimination response

Introduction

Previous research on time perception has usually approached the area as if there were a single "time sense". That is, investigators using different methods and studying different time interval lengths have assumed they were dealing with a unitary process - the perception of time. Despite this, theorizing associated with the perception of different ranges of temporal interval lengths has been qualitatively different. Relatively long intervals (more than several seconds) have usually been studied within a cognitive framework (Doob, 1971; Fraisse, 1963; Ornstein, 1969), while quantitative models of time perception have been based on experiments involving shorter intervals of less than a few seconds. The present research is concerned with the perception of very short intervals of time - less than 1 sec.

In a recent review of the experimental literature on the perception of short intervals of time, Allan (1979) summarized the methods commonly used. She grouped these into two general categories: duration scaling and duration discrimination. In duration scaling, which includes the method of response-stimulus synchronization, subjects (Ss) are required to estimate, produce, or reproduce stimulus intervals. In duration discrimination experiments, Ss must distinguish among very similar stimulus intervals. Although the different methods used to study time perception have not always produced the same results, most authors assume, at least implicitly, that a single mechanism is being studied.

Some models of the perception of short intervals are based on both temporal interval production and duration discrimination tasks, and are explicitly formulated to account for the behaviour in both situations. In Eisler's (1975, 1981a,b) model, stimulus durations are accumulated in two temporal sensory registers whose contents can be compared to perform duration discrimination or interval production. In a model proposed by Treisman (1963), pulses which are output by a pacemaker are counted during a stimulus interval and these counts can be stored and retrieved for comparison purposes. In both models the same timekeeper and decision process serve in both duration discrimination and temporal production and reproduction experiments. Although he does not propose a specific mechanism, Getty (1975, 1976) has shown that both duration discrimination and the reproduction of short intervals are sometimes well described by a Weber's Law relationship between the standard deviation of the psychometric density function or the distribution of reproduced durations and the mean stimulus duration or reproduced duration. Getty does not select among the possible models that would lead to a Weber's Law relationship but he does find that this relationship best fits the data obtained by him from both types of tasks. Although Creelman's (1962) experiments dealt only with duration discrimination, he suggested that his Poisson counter mechanism could time observation intervals in addition to evaluating the duration of stimuli. Thus, Creelman also proposed that the same mechanism could be used for both interval production and duration discrimination. Thomas and Brown (1974) presented a schema for relating different time perception tasks. Although different decision and response mechanisms are hypothesized for duration discrimination and interval production tasks, both are dependent upon the same encoding of the stimulus interval. The accuracy of duration discrimination and the variance of produced intervals are inversely dependent on the same encoding function. Hence, several theorists who have discussed both duration discrimination and interval production tasks have assumed that both tasks are performed by a single temporal mechanism.

The assumption has been made throughout the time perception literature that a single mechanism is used for the processing of short durations in all psychophysical tasks. However, a review of published research on response-stimulus synchronization and duration discrimination suggests that there may be some differences in the mechanisms used to perform the two tasks.

Response-Stimulus Synchronization

In response-stimulus synchronization, Ss are required to time a short interval so that they can make a response in synchrony with the second of two brief stimulus pulses separated by a duration which is the same from trial to trial. Recent experiments have shown that Ss can perform this task with remarkable accuracy (Hopkins & Kristofferson, 1980; Kristofferson, 1976). The mean response latency quickly stabilizes to within a few milliseconds of the required latency. After extended practice (at least 30 sessions of 400 trials per session), the synchronization response latency distribution is sharply-peaked and symmetrical and its variance is constant when the mean latency is anywhere in the range from 170 to 550 msec. Kristofferson (1976) found variances of about 100 msec^2. within this constant-variance range. However, using a refined procedure, Hopkins (1982; Hopkins &

Kristofferson, 1980) has produced variances as low as 35 msec^2. The fact that, within this range, mean latency can be changed without a change in variance, implies that deterministic, or invariant, delays of up to 400 msec. can be inserted into the stimulus-response (S-R) chain under some conditions.

There is also evidence from other laboratories supporting the idea of deterministic internal delays. Using different synchronization paradigms, other researchers have found that synchronization response variance is constant, or nearly so, when the mean latency is between the lower limit set by reaction time and an upper limit of about 500 msec. (Bartlett & Bartlett, 1959; Naatanen et al., 1974; Saslow, 1974). Although Saslow (1974) reports that the ratio of standard deviation to mean synchronization latency is constant, her tabled data do not support this assertion. Examination of the data reveals that the standard deviation is almost constant as the mean changes. Although these investigators did not conclude that deterministic delays can be used in temporal production experiments, their data support Kristofferson's (1976) finding that, within the range of mean latencies of interest here, additional delays can be inserted into the S-R chain of the synchronization task without increasing the response latency variance.

Another characteristic of these variance-free delays is the ease with which they may be reset. Small changes in the required mean synchronization interval can be accomodated with no increase in variance (Kristofferson, 1976). In fact, Hopkins and Kristofferson (1980) found that Ss could change their mean synchronization interval by nearly 100 msec. between sessions without disrupting performance. However, large changes in the synchronization interval, within the constant variance range, do produce short-lived disruptions in performance which are overcome by practice with the new interval.

When the mean synchronization response latencies are in the constant variance range, the latency distributions are sharply-peaked with straight sides and narrow skirts. Hopkins and Kristofferson (1980) suggested that such distributions could result from the convolution of a distribution which is an isoceles triangle (which would contribute most of the variance) with a low-variance normal distribution. The existence of a triangular distribution in timing responses would be consistent with Kristofferson's (1967 a,b) quantum theory of temporal processing. This theory postulates that an internal clock produces a succession of equally-spaced time points which occur independently of external stimuli. The switching of attention, and possibly other acts of central information processing, are regulated by the internal clock so that a processing step can only begin when a time point occurs. Thus, the distribution of minimum times that an unattended stimulus must wait to be attended is uniform with a range of q msec. (the time between successive time points). The convolution of two independent uniform distributions, which would result if two independent quantal delays were added together, is an isoceles triangular distribution with a range of 2q msec. The synchronization S-R chain would not contain two independent quantal delays if all timing were under the control of a single quantal timer. However, if two links in the chain (for example, attention to the incoming stimulus and response emission) were under the control of separate quantal timers with different periods, two effectively independent quantal delays would result. If the two quantal periods differed by only a very small amount, the resulting triangular distribution would look almost the same as that produced by the convolution of two independent, but equal, uniform distributions. Thus, a triangular distribution is consistent with control of information processing by more than one quantal timer. Indeed, visual inspection of the synchronization response distributions of Kristofferson (1976) and Hopkins and Kristofferson (1980) suggests that a triangle makes an overriding contribution to their form. Also, Hopkins (1982) has shown that a triangular distribution, combined with a low-variance normal distribution, provides a better description of the synchronization response distribution than that provided by several other possible theoretical distributions.

Michaels (1977) studied the distribution of hypothetical response triggers in a synchronization task by inserting a countermanding stimulus on some trials. When the countermanding stimulus occurred, Ss were to withhold their synchronization response. If the response trigger is the point beyond which the synchronization response cannot be recalled, the distribution of this trigger will be revealed by the proportion of synchronization responses that are suppressed at each temporal location of the countermanding stimulus as it is moved closer to the synchronization stimulus. Michaels found that half of the synchronization responses were suppressed when the countermanding stimulus occurred about 120 msec. before the synchronization stimulus. The range of effectiveness of the countermanding stimulus, from the point where all responses were suppressed to the point where no responses were suppressed, was about 50 msec. This experiment characterized the synchronization response trigger distribution as narrow, fully-bounded, and sharply-peaked, like a triangle. This suggests that the triangular form of the synchronization response distribution arises before the response trigger and is not due to the efferent component of the S-R chain.

Wing and Kristofferson (1973b) modelled an interresponse timing task (a repetitive key-tapping task) with two components: a central timing process and an efferent latency component. They were able to separate the contributions of each of these two components to the total response time variance. Their estimates of the efferent latency variance ranged from 10 to 50 msec^2. These limits include some of the total synchronization response distribution variances obtained by Hopkins & Kristofferson (1980; Hopkins, 1982). However, Hopkins' Ss had more extended practice than had those of Wing and Kristofferson. In addition, Hopkins' experiments were conducted using a touch-sensitive response button which eliminated any variance due to the movement of a mechanical response button. Any variance from such a source would enter into the efferent response component of Wing and Kristofferson's model. Kristofferson (1976) pointed out that subtracting an estimate of the efferent latency variance such as that obtained by Wing & Kristofferson, from the response variances obtained in his synchronization task leaves an amount which could be the variance of a triangular distribution with a base of somewhat less than 50 msec. Thus, by dividing the S-R chain of the synchronization task into afferent, central, and efferent components, it was found that the entire response variance could be accounted for by a central triangular component and the efferent latency variance. Kristofferson concluded that the afferent latency component of the S-R chain is without significant variance, at least when the initiating signal is auditory, and he speculated that this may be the locus of the additional deterministic delays which can be inserted into the chain. Additional evidence for deterministic afferent latencies in the synchronization task comes from the Hopkins and Kristofferson (1980) experiment. Synchronization response variances were the same whether the stimulus beginning the interval was auditory or tactile. Rather than postulate that the afferent latencies have the same non-zero variance in the two modalities, it is more parsimonious to assume zero variance.

We have seen that, after extended practice, response-stimulus synchronization performance can be extremely stable and accurate. Response distributions are triangular in shape and the mean synchronization latency can be changed, within the range from 170 to 550 msec., without affecting the response variance. Figure 1, which is Kristofferson's (1976) Figure 7, clearly shows these features of synchronization performance. Two synchronization response latency distributions, produced by the same S, have different means but the same variance, and are both distinctly triangular in shape. Arguments have been made above for the inclusion of various components in the S-R chain of the synchronization task: an invariant afferent latency; a deterministic delay whose duration can be easily adjusted; two independent quantal processing steps, each uniformly distributed; an efferent delay component which adds a low-variance (possibly normal) distribution to the final responses. This hypothesized chain of events, which would produce the above-described behaviour in the response-stimulus synchronization task, is illustrated in Figure 2. The efferent delay component (e) has low variance and is normally distributed. The uniform distributions of central waiting times are represented as

Figure 1. Distributions of synchronization responses for two different synchronization intervals. Filled circles: $\overline{X} = 547$ msec., $S^2 = 144$ msec.^{2}, N = 600. Open circles: $\overline{X} = 307$ msec., $S^2 = 144$ msec.^{2}, N = 900. (This figure is Figure 7 from Kristofferson, 1976.)

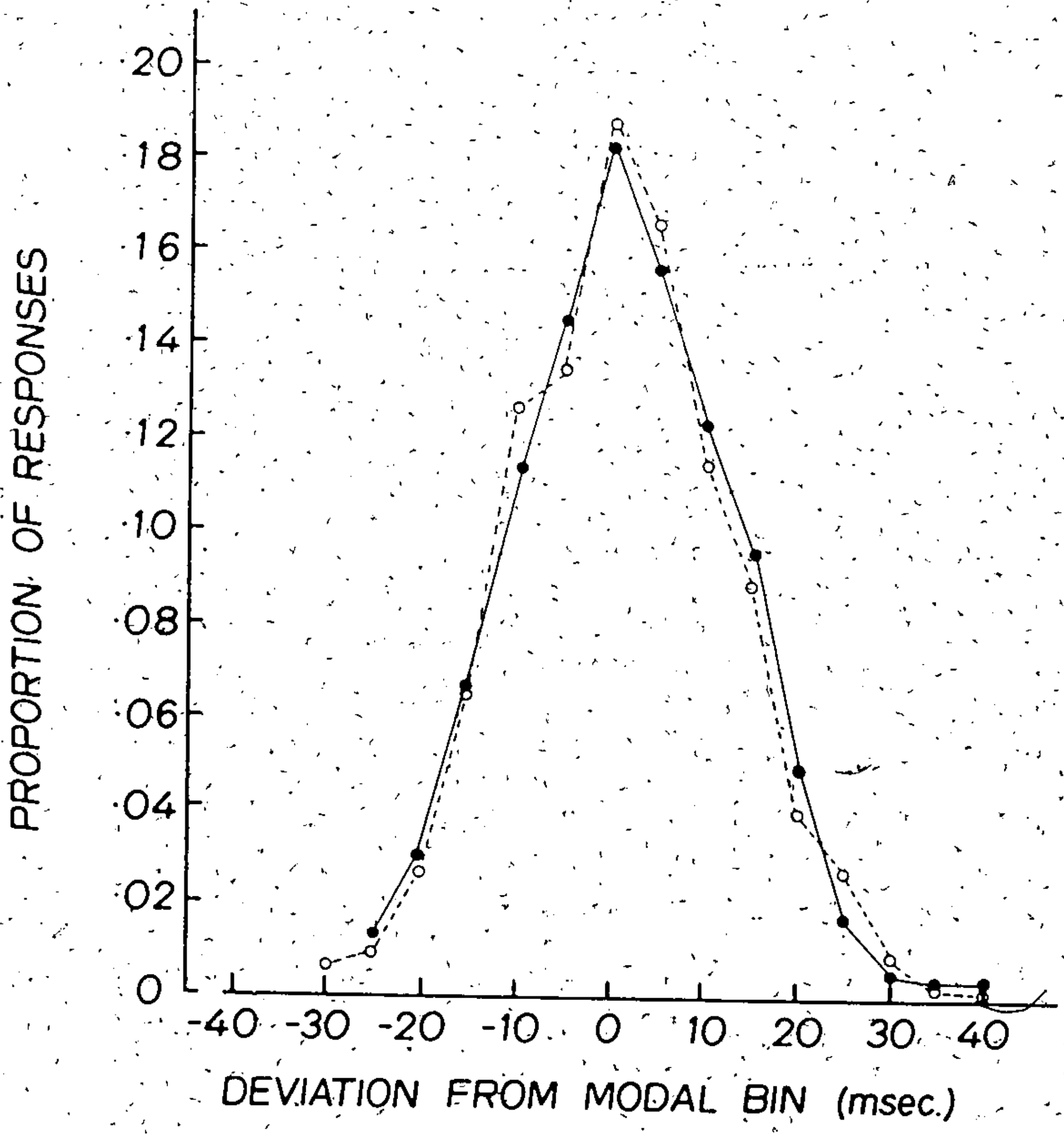
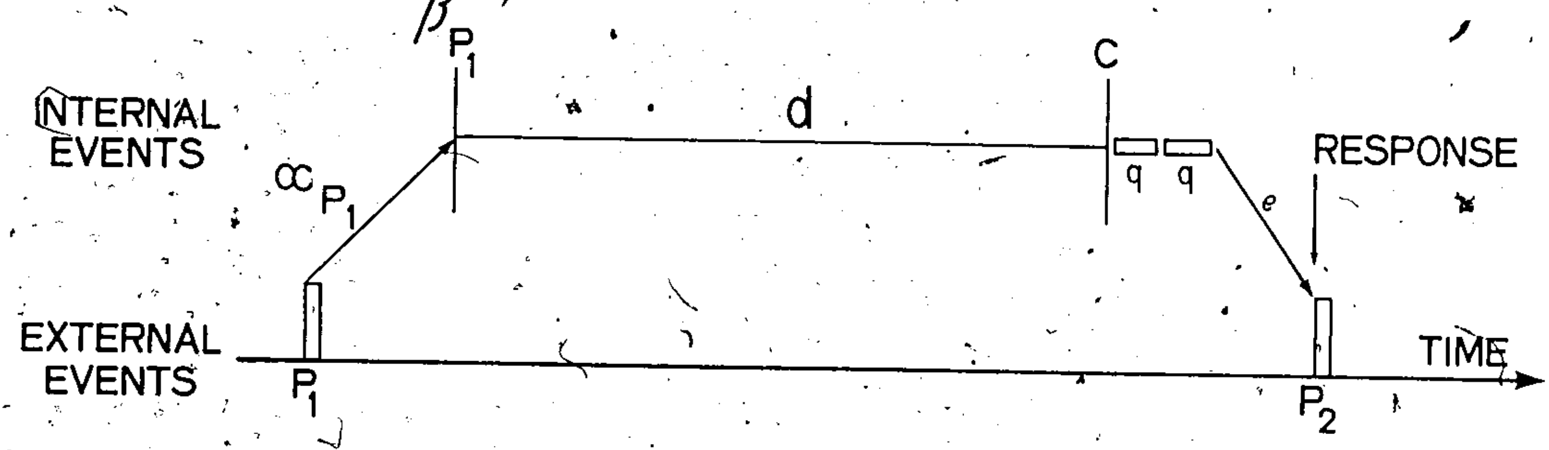

PROPORTION OF RESPONSES
·20
·18
·16
·14
·12
·10
·08
·06
·04
·02
0
-40
-30
-20
-10
0
10
20
30
40
DEVIATION FROM MODAL BIN (msec.)

Figure 2. Hypothetical chain of internal events in response-stimulus synchronization. α_{P_1}: afferent latency of marker stimulus; β_{P_1}: central arrival time of marker stimulus; d: internally-timed deterministic interval; C: end-point of d; q: range of uniform distribution of waiting times; e: efferent latency of motor response; P_1 and P_2: auditory stimuli marking synchronization interval.


INTERNAL EVENTS
EXTERNAL EVENTS
α_{P_1}
β_{P_1}
d
C
q
q
e
RESPONSE
TIME
P_1
P_2

rectangles. The location of these variable components within the chain is not known but Kristofferson (1976) has speculated that the deterministic delay may be part of the stimulus afferent latency. This is the way the components are ordered in Figure 2, with no variance arising before C, the end-point of d, the adjustable deterministic delay.

Duration Discrimination

In duration discrimination, Ss are required to classify or distinguish among stimulus intervals which are very similar to one another. When the single stimulus method is used, Ss are presented with a single duration stimulus on each trial, which they must classify as "short" or "long". In the forced choice method, two duration stimuli are presented on each trial and Ss must say whether the shorter (or longer) stimulus was presented first or second. For a given set of duration stimuli, the base duration is the standard against which the stimuli are compared. The stimulus set is created by adding small positive or negative increments to the base duration, which usually forms the mid-point of the stimulus set. A stimulus interval equal to the base duration may or may not be included in the set of stimulus intervals presented to Ss.

Researchers who have studied the discrimination of short temporal intervals marked by auditory stimuli have generally found that the standard deviation (SD) of the psychometric density function is an increasing function of the base duration (Abel, 1972 a,b; Creelman, 1962; Divenyi & Danner, 1977; Getty, 1975). In other words, as the base duration increases, a comparison duration stimulus needs to be increasingly different from the base duration to be discriminated from it at a constant level of performance. Getty (1975) found that his duration discrimination data were well fit by a modified form of Weber's Law, the original of which states that the ratio of the SD of the psychometric density function to the base duration is constant. Getty's modified form of Weber's Law introduces a term for residual variance which is independent of duration. The ratio of SD to base duration differs from the original Weber's Law model only at very short base durations. Most investigators have not found a constant Weber fraction, although they have found that the SD of the psychometric density function increases as the base duration increases.

Most theories of duration discrimination assume that the mean and variance of an internal duration measure are some function of the presented stimulus duration (Creelman, 1962; Divenyi & Danner, 1977; Getty, 1975; Massaro & Idson, 1976, 1978; Thomas & Brown, 1974). This assumption is based on the general finding, described above, that the SD of the psychometric density function is an increasing function of base duration. It is also based on the interval measure hypothesis, which assumes that Ss somehow measure the duration of a presented stimulus by observing the entire interval. Thus, according to most theories of duration discrimination, Ss observe and measure the entire duration of a stimulus interval, resulting in an internal measure which is some function of the stimulus duration.

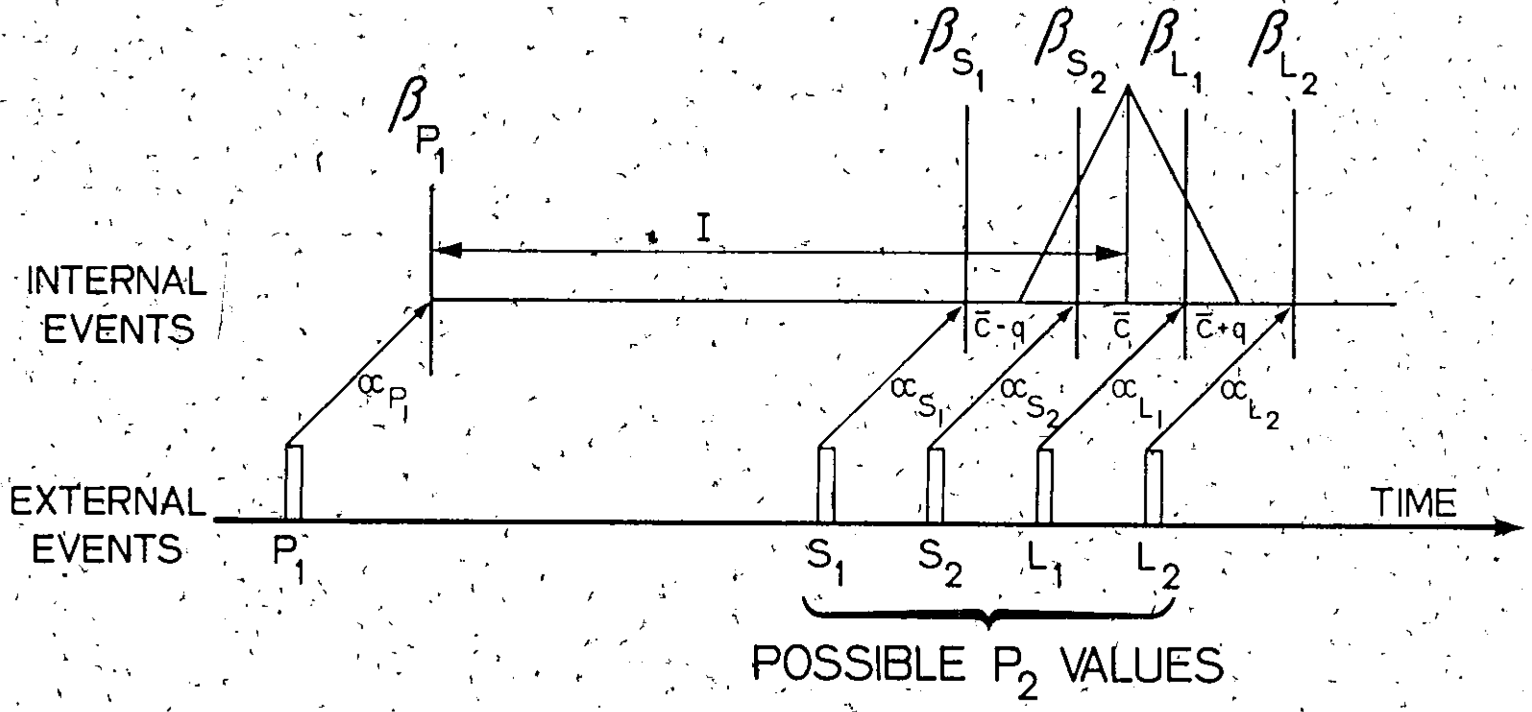
Allan and Kristofferson (1974a; Allan, Kristofferson, & Wiens, 1971), using filled durations marked by visual stimuli, showed that the variance of the internal duration corresponding to each stimulus duration is the same for all stimulus durations within a set. That is, each member of the set of stimuli associated with a given base duration appears to produce an internal duration with the same variance as that produced by the other members of the same set. However, the variance of all members may increase between sets if the base duration is increased. In a later experiment, Kristofferson (1980) showed that, after extensive practice (at least 17 sessions at each base duration), steps unfold from the function relating the SD of the psychometric density function to the base duration so that the SD is almost constant over each of several ranges of base durations. Steps occur at base durations of 200, 400, and 800 msec. At each step, the SD becomes twice as large as it had been for the next lower range of base durations. For example, when the base duration was between 400 and 800 msec., the estimated SD of the psychometric density function was about twice as large as that found when the base duration was between 200 and 400 msec., which in turn was about twice as large as the estimated SD for base durations between 100 and 200 msec. Within each of these ranges of base durations, the estimated SD was almost constant.

We have seen above that in a response-stimulus synchronization task, the synchronization response latency distributions have the same variance when the mean latency is anywhere within the range from 170 to 550 msec. (Hopkins & Kristofferson, 1980; Kristofferson, 1976). In duration discrimination, Kristofferson (1980) has shown that the psychometric variance can be almost constant over each of several ranges of base durations. However, the range of durations for which the psychometric variance is constant is smaller than the range of synchronization response latencies for which response variance is constant. Specifically, the function relating psychometric variance to base duration in duration discrimination has steps, where the SD doubles, at base durations of 200 and 400 msec., both of which are within the range of latencies for which synchronization response variances are constant.

Rejecting the interval measure hypothesis, Kristofferson (1977) showed that duration discrimination may be performed by the production of an internal time interval. He used empty auditory intervals with base durations of 850 and 1150 msec., and speeded discrimination responses. Ss were required to press a button indicating whether the presented interval was "short" or "long" as quickly as possible, as soon as they knew which interval had been presented. Kristofferson modelled the internal events in the following way: When the onset of the duration stimulus arrives at the central processor, the production of an internal interval is begun. The end of this interval functions as a criterion (C) for duration discrimination. The discrimination response is initiated by the end of the internal interval or by the central arrival of the end of the presented duration stimulus, whichever occurs first. If the end of the duration stimulus does not occur before C, the end of the internal interval, S can initiate the response indicating that the presented duration is "long" before the end of the stimulus interval has occurred. Thus, duration discrimination becomes a task which involves the production of an internal temporal interval, rather than one which involves the observation and measurement of the entire duration stimulus. Kristofferson called this view of duration discrimination the real-time criterion theory. Thomas and Cantor (1978) have also recently interpreted duration discrimination as a temporal interval production task.

In Kristofferson's (1977) formulation of the real-time criterion theory of duration discrimination, he concluded that the times of occurrence of C, the end of the internally-produced interval, are triangularly distributed. The internal events are diagrammed in Figure 3. The afferent latencies of the auditory stimuli are represented by α, and β represents their central arrival times. "Long" responses are initiated by C when it occurs before the end of the duration stimulus (β), while "short" responses are initiated by the end of the duration stimulus when it occurs first. Kristofferson selected the duration stimuli so that two would fall within the range of the distribution of C and two were outside this range. Therefore, the variance of C could be calculated in two ways: 1) using the proportion of errors on the stimuli falling within the range of the criterion (S_2 and L_1 in Figure 3) and 2) using the difference between the variances of the discrimination response latencies when the stimuli falling outside the criterion range (S_1 and L_2 in Figure 3) are presented. All responses to L_2 will be "long" and will be initiated by C whereas responses to S_1 will all be "short" and will be initiated by β_{S_1}, which is without significant variance when the marker stimuli are auditory. The distribution of "short" responses to stimulus S_1 will be reactions to the deterministic β_{S_1}, while the distribution of "long" responses to stimulus L_2 will have added to it the distribution of C, which forms part of the S-R chain beginning at P_1. The variances of these two distributions of discrimination responses will differ by the variance of C. In Kristofferson's experiment, the estimates of the variance of C that were obtained in these two ways agreed almost exactly. Both were the variance of a triangle with a base of about 190 msec. Also, there

Figure 3. Kristoffersons's (1977) real-time criterion model of duration discrimination. α: afferent latency of marker stimulus; β: central arrival time of marker stimulus; I: internally-timed interval; C: triangularly distributed duration discrimination criterion (I ends at C); q: duration of quantal step; P_1, S_1, S_2, L_1, L_2,: auditory stimuli marking presented duration. Only one of S_1, S_2, L_1, or L_2 is presented on each trial.



β_{P_1}
β_{S_1}
β_{S_2}
β_{L_1}
β_{L_2}
I
INTERNAL EVENTS
$\bar{c}-q$
$\bar{c}$
$\bar{c}+q$
α_{P_1}
α_{S_1}
α_{S_2}
α_{L_1}
α_{L_2}
EXTERNAL EVENTS
TIME
P_1
S_1
S_2
L_1
L_2
POSSIBLE P_2 VALUES

were no discrimination errors when S_1 and L_2 were presented. The distributions of "short" responses when S_1 was presented looked like reaction times to S_1. Distributions of "long" responses to L_2 were time-locked to P_1 and were more variable than reaction times, by the variance of C. Thus, there is good evidence that C is triangularly distributed. Such a distribution is consistent with the existence of one or more quantal timers like that described by Kristofferson (1967a,b).

Another significant finding in Kristofferson's (1977) duration discrimination study is that the variance of the triangular distribution of C accounts for the entire psychometric variance, leaving no variance for the afferent latencies of the stimuli. This provides additional evidence that the afferent latencies of auditory marker stimuli are essentially deterministic.

Comparison between Response-Stimulus Synchronization and Duration Discrimination

We have seen that the stimulus-response chains involved in practised response-stimulus synchronization and in speeded duration discrimination involve many of the same components. Apparently the afferent latency of the auditory pulse marking the beginning of the stimulus duration is without significant variance. Both tasks involve the production of an internal time interval whose duration can be adjusted within a certain range without affecting its variance. In addition, there is evidence that the end of the internal time interval is triangularly distributed in both tasks. Such a distribution would result from the inclusion of two independent quantal processing steps, each of which is uniformly distributed in time.

Despite these similarities, there are some important differences between the performances found in response-stimulus synchronization and duration discrimination. The range of base durations which produce the same psychometric variance in duration discrimination is smaller than the constant-variance range of synchronization latencies. Specifically, synchronization response variances are constant when the mean latency is anywhere in the range from 170 to 550 msec. (Kristofferson, 1976), while the standard deviation of the psychometric density function in duration discrimination doubles twice (at 200 and 400 msec.) within this range of base durations (Kristofferson, 1980). Although Ss can adjust the mean latency of their synchronization responses easily from one session to another without disrupting performance (Hopkins & Kristofferson, 1980; Kristofferson, 1976), practice at one base duration in a duration discrimination task does not transfer as easily to a new base duration (Allan & Kristofferson, 1974a; Kristofferson, 1980). Many sessions of practice are required to reduce the psychometric variance after each change in base duration. Another difference between the two tasks is that Ss may be able to use smaller "quantal steps" in temporal processing for the synchronization task than for duration discrimination. In the quantal step function for duration discrimination (Kristofferson, 1980), the estimate of q (the quantum size in msec.) is never smaller than one sixteenth of the base duration. In the synchronization task, much smaller estimates of q, relative to base duration, have been obtained. For example, with a mean synchronization latency of 460 msec., q estimates of as low as 12 msec. have been obtained (Hopkins, 1982).

The customary experimental procedures in response–stimulus synchronization and duration discrimination paradigms differ in a way that may contribute to the usual finding of higher variance in duration discrimination. In response–stimulus synchronization, immediate feedback on response accuracy is obtained by observing the temporal order of the stimulus marking the end of the interval and the tactile and/or auditory stimulation produced by making the response (Hopkins & Kristofferson, 1980; Kristofferson, 1976). In a duration discrimination paradigm, responses are typically withheld until the complete duration has been presented, and feedback on the response accuracy is presented at some time following the response. Kristofferson (1977) used a speeded response procedure in duration discrimination, but the signal telling S whether the presented duration was "short" or "long" was not presented immediately. Hopkins and Kristofferson (1980) have shown that removal of the P_2 stimulus ending the presented interval, and hence the immediate feedback, in a response–stimulus synchronization task, produces a sustained increase in response variance even though delayed feedback is retained. It may be that the provision of immediate feedback in duration discrimination would lead to increased accuracy of performance, thus eliminating one of the differences between duration discrimination and response–stimulus synchronization.

Are response–stimulus synchronization and duration discrimination performed by the same temporal mechanism? We have seen that both of these "time perception" tasks can be performed by the generation of an internal time interval and may in part involve the same internal chain of events. Evidence has been presented that the afferent latency of an auditory stimulus makes no contribution to the variance exhibited in either of these tasks. Additional support for essentially deterministic afferent latencies comes from another duration discrimination study. Divenyi and Danner (1977) studied duration discrimination using time intervals marked by brief auditory stimuli. They modified Creelman's (1962) counter model of duration discrimination so that the rate of firing or intensity (λ) of the neural pulse source is a function of the time since the beginning of the duration stimulus. Their model allowed them to estimate the variance of the afferent latency of the acoustic pulses marking the stimulus intervals. When the markers were tone bursts with an intensity of 65 or 86 dB, their average estimate of the standard deviation of the perceptual latency was about 1 msec. Elsewhere, Divenyi (1976) has stated that the latency of auditory detection has a standard deviation of 0.45 msec. We know that the internally-produced interval in response-stimulus synchronization can be deterministic and Kristofferson (1976) has speculated that such a deterministic delay may be part of the afferent latency. That is, the delay may occur within the S-R chain before any variability arises. This is the order in which the hypothesized internal events were drawn in Figure 2. If the S-R chain were that illustrated in Figure 2, there would be a point, labelled C in that Figure, that is invariant with respect to P_1 although it is temporally distant from it. If such a point could be accessed and used as a criterion for duration discrimination judgements, it might be possible to make accurate judgements about very small differences in duration. Indeed, Kristofferson (1977) suggested that, under these circumstances, "virtually perfect" duration discrimination should occur.

There have been no reports of perfect duration discrimination. However, other types of temporal discrimination can be extremely precise. For accurate localization of auditory stimuli in space, the difference in arrival times of the stimuli at the two ears can be less than one-tenth of a millisecond (Rosenzweig, 1961). This level of discrimination of auditory stimuli also provides evidence that the afferent latency of auditory stimuli can have virtually zero variance. In auditory localization, Ss do not make a conscious judgement about which ear the stimulus reached first, but they experience a single sound, the spatial location of which depends on the difference in arrival times. Yasargil and Diamond (1968) have described a neural circuit which mediates a startle response in fish and can discriminate between inputs which are as little as 0.15 msec. apart. In a pitch discrimination experiment, Jenkins-Lee (1971) presented Ss with a single cycle of the stimulus tone. He found that Ss could discriminate a 10% difference in frequency at a level of 75% correct. Thus, for example, Ss correctly discriminated a stimulus 1 msec. in duration (1000 Hz tone) from a stimulus 1.1 msec. in duration (1100 Hz tone), 75% of the time.

The present research was an attempt to achieve "virtually perfect" duration discrimination in human Ss. If the internal events in response-stimulus synchronization are as illustrated in Figure 2, C will follow P_1 by a fixed duration. If the possible times of occurrence of the stimuli marking the end of intervals to be discriminated were arranged so that their central arrival times fall on either side of C, perfect duration discrimination might be possible. In the present research, a synchronization task is used to enable Ss to generate a stable internal interval. On some trials, a third auditory stimulus (P_3) intervenes between P_1 and P_2 (the stimuli marking the synchronization interval). On these trials, Ss must make a discrimination response, following their synchronization response, which indicates whether the interval between P_1 and P_3 was "short" or "long". Thus, Ss are being asked to discriminate the duration of stimuli presented during the synchronization interval. This paradigm should optimize the chances of using the extremely accurate synchronization timer for duration discrimination. It might also allow us to see whether the elements of the synchronization chain are as diagrammed in Figure 2.

One previous study that has combined temporal interval production and duration discrimination in a single task is in the animal literature (Stubbs et al., 1978). Pigeons produced a temporal interval on a fixed interval (FI) schedule, where the first response after a set period of time has elapsed is reinforced. On an FI schedule, Ss typically wait some time after the interval begins before starting to respond. The response rate increases as the end of the interval approaches. Timing accuracy is measured by the duration of the wait before S starts to respond and by the rate of increase in the response rate. In the Stubbs et al. study, on some proportion of the FI trials, the pigeons were interrupted by the presentation of a choice response problem during the FI. The temporal placement of the choice problem within the FI determined which of two alternative responses was correct. There were only two possible locations of the choice problem within the FI: 20% or 100% of the FI duration. That is, the choice response was actually a duration discrimination task. Ss were required to discriminate the time from the beginning of the fixed interval to the presentation of the choice problem. One response indicated that this duration had been "short"; the other indicated a "long" duration. Accuracy of the choice response was highly correlated with the accuracy of timing the FI. That is, manipulations of stimuli and task requirements that produced decrements in FI performance also reduced choice discrimination accuracy. This suggests that, at least in this particular experiment, the same timing mechanism was used to perform both tasks. In the Stubbs et al. (1978) study, the fixed interval (the produced interval) was the same on every trial. Rilling (1967) required pigeons to respond in accordance with one of two possible different fixed intervals on every trial. After the completion of the interval, Ss were required to indicate, by pecking the appropriate choice key, which interval had been presented. Reynolds (1966) also showed that pigeons can discriminate the duration of an interval they have just produced. Pecking was reinforced in the second part of each trial only if the first two key-pecks on each trial were separated by more than 18 sec. Although the birds did not learn to consistently interpolate more than 18 sec. between their first two responses, they were able to discriminate whether or not they had done so - they made more pecks in the second part of each trial when the first two pecks had been widely spaced. In the Rilling (1967) and Reynolds (1966) studies, both temporal interval production and duration discrimination were involved, but the produced interval was not constant from trial to trial and Ss were required to discriminate the duration of the interval they had just produced. The Stubbs et al. (1978) study, with a constant produced interval interrupted by a discrimination task, is most similar to the task used in the present research. It is difficult to relate the results of animal experiments directly to human time perception. However, the existence of these studies, which involved both temporal interval production and duration discrimination, deserves mention.

Possible Mechanisms for Performing the Dual Synchronization-Duration Discrimination Task

Single Deterministic Interval

In human subjects, can the apparently deterministic synchronization timer be used to perform perfect duration discrimination? In order for the dual synchronization-duration discrimination task to produce perfect duration discrimination performance, several assumptions must be met: (1) The components of the synchronization S-R chain must be arranged as they are shown in Figure 2. If any variability were to arise before C, the decision criterion would be variable. In addition, it must be assumed that the variable quantal components can be separated from the end-point of d. That is, C must be accessible to the discrimination decision mechanism without variance being added to it. (2) Ss must be able to accurately discriminate the temporal order of C and β_{P_3}, the central arrival time of the end of the duration stimulus (see Figure 3), when these two events are in close temporal proximity. (3) The presence of an occasional stimulus in the P_1-P_2 interval must not disrupt the timing of d or add variability to it. The synchronization S-R chain must continue in spite of the presentation of duration discrimination stimuli.

Assumption (2) above deserves further discussion. If a deterministic internal criterion were generated, duration discrimination would involve an order discrimination between the criterion and the time of occurrence of the stimulus marking the end of the discrimination interval. Thus, even if a deterministic internal criterion were generated, perfect duration discrimination would not result unless the temporal order discrimination could be performed perfectly. An onset asynchrony of only a few milliseconds is required to discriminate correctly the order of presentation of two brief tones that differ in frequency (Efron, 1973; Patterson & Green, 1970). However, judging the temporal order of two stimuli in different modalities (auditory and visual) requires a much larger time difference between the stimuli (Allan, 1975). Despite the apparent inability of Ss to perfectly discriminate the order of two external stimuli, it may be possible to perfectly discriminate the order of an external event, the central-arrival time of which is without variance, and an internal event. We do know that extremely accurate temporal discriminations are performed in auditory localization (Rosenzweig, 1961). Also, Kristofferson's (1977) real-time theory of duration discrimination assumes that the temporal order of C and β_{P_3} can be perfectly discriminated (refer to Figure 3). Including this assumption, the real-time criterion theory provides an extremely good description of Kristofferson's duration discrimination data. The assumption that Ss will be able to perfectly discriminate the order of these two events is also necessary to the prediction of perfect duration discrimination in the present paradigm.

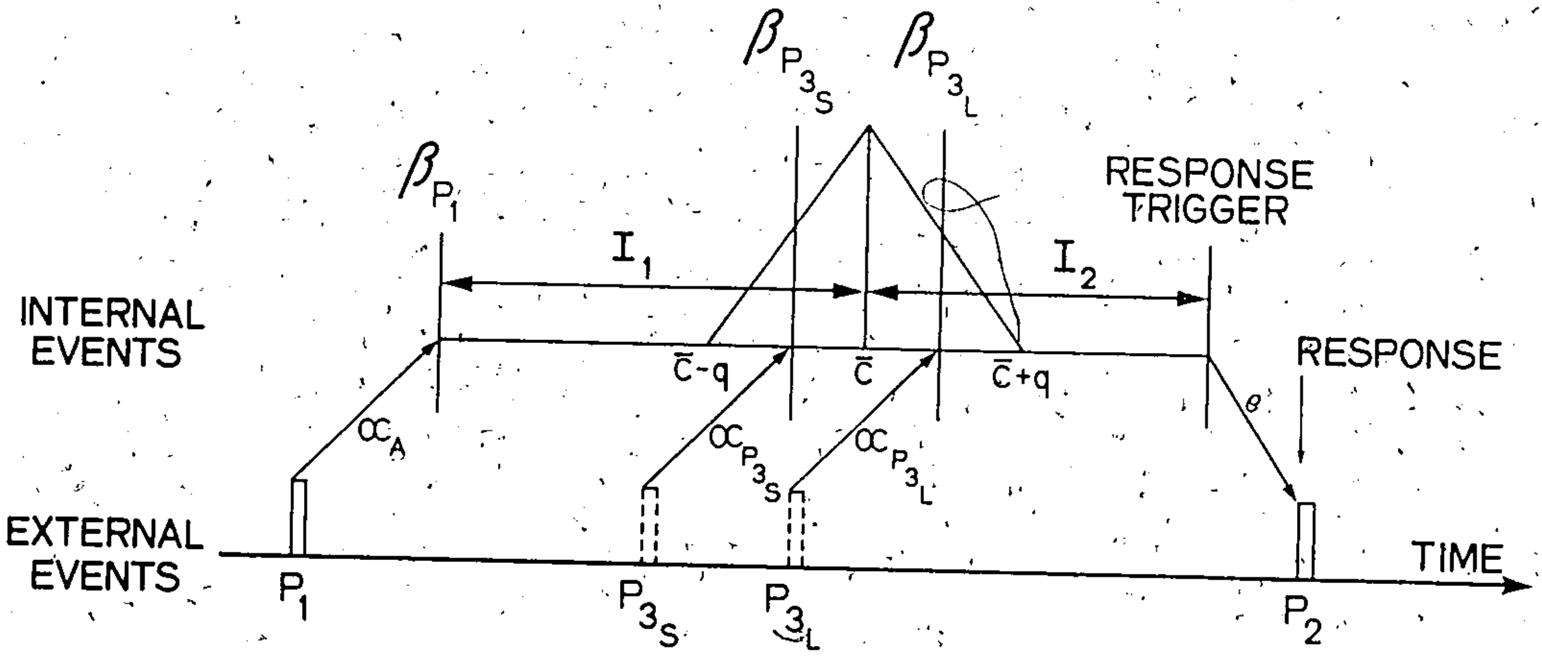
Evidence has been presented that the afferent latency of the auditory marker stimulus is without significant variance. In addition, we know that a deterministic timer can be used to time the response latency in a response-stimulus synchronization task. If this exact time interval could be added directly to the afferent latency, as shown in Figure 2, there would be a point, labelled C in that Figure, that is invariant with respect to P_1 although it is temporally distant from it.

If this is the case, and if the above assumptions are valid, C could serve as a deterministic criterion point about which "virtually perfect" duration discrimination is possible. Synchronization performance would look like that previously found in response-stimulus synchronization research, while duration discrimination performance would be error-free, when the central arrival times of the stimuli ending the duration discrimination stimuli are centred about C. Alternatively, if the quantal steps are inseparable from the interval d so that C is triangularly distributed rather than invariant, the use of the same internal interval to perform both synchronization and duration discrimination would lead to the same estimates of variability from both the synchronization and duration discrimination results, when the duration discrimination stimuli span $\overline{C}$.

Sequential Model

The procedures used in the experiments to be described were designed to enable Ss to use the deterministic synchronization timer to perform duration discrimination. However, it is conceivable that Ss will use some mechanism other than that described above to perform the dual synchronization - duration discrimination task. One possible alternative to the above-described mechanism is that the two tasks could be performed sequentially. Such a hypothetical sequential mechanism is illustrated in Figure 4. When P_1, the initial marker stimulus, is presented, S begins to time an interval, the end of which serves as a criterion in the duration discrimination task. The distribution of end-points, C, of this interval, I_1, is triangular. As in Kristofferson's (1977) real-time criterion model of duration discrimination, the duration discrimination response is determined by which event occurs

Figure 4. Sequential model of internal events in dual synchronization-duration discrimination task. α: afferent latency of marker stimulus; β; central arrival time of marker stimulus; I: internally-timed interval; C: triangularly distributed duration discrimination criterion (I_1 ends and I_2 begins at C); q: duration of quantal timing step; e: efferent latency of motor response; P_1, P_2, P_3: auditory stimuli marking presented durations. Only one P_3 stimulus can be presented on each trial.


$\beta_{P_{3_S}}$
$\beta_{P_{3_L}}$
β_{P_1}
RESPONSE TRIGGER
I_1
I_2
INTERNAL EVENTS
$\bar{c}-q$
$\bar{c}$
$\bar{c}+q$
RESPONSE
α_A
$\alpha_{P_{3_S}}$
$\alpha_{P_{3_L}}$
θ
EXTERNAL EVENTS
TIME
P_1
P_{3_S}
P_{3_L}
P_2

first, C or β_{P_3}. When C occurs before β_{P_3}, S judges that the P_1-P_3 interval is "long". When β_{P_3} precedes C, S calls the P_1-P_3 interval "short". This duration discrimination response is withheld until after the synchronization response has been made. A second interval, I_2, is then timed from the duration discrimination event. That is, I_2 is begun at time C or β_{P_3}, whichever occurs first. Thus, the event that determines the discrimination response also triggers I_2. I_2 terminates with the synchronization response trigger. In Figure 4, the synchronization response trigger is shown as a point for simplicity but it should be noted that this response trigger may also be triangularly distributed (Kristofferson, 1976; Michaels, 1977). This model states that Ss perform the two tasks in sequence, using the real-time criterion mechanism to perform the discrimination task, then timing a deterministic synchronization interval from the discrimination event. The sequential model, as illustrated in Figure 4, does not predict perfect duration discrimination performance. However, when P_3 is sufficiently close to P_2, I_2 is no longer required and S must time only a single interval, beginning at β_{P_1}. If this interval were deterministic, its end-point could possibly be used as a criterion to perform perfect duration discrimination. Thus, Ss could perform the two tasks sequentially when the mid-point of the set of duration discrimination stimuli is near the centre of the P_1-P_2 interval, but when P_3 is close to P_2, the deterministic synchronization timer could be used to perform perfect duration discrimination, as described above.

When $I_2=0$, the internal events could become as illustrated in Figure 2, where only one invariant internal time interval is produced. In Figure 2, C is deterministic and the two quantal steps are shown to be separate from the end-point of d. Since the duration of d can be changed without changing the variance of the distribution of synchronization responses, it is reasonable to assume that the triangular variability, which would arise from the convolution of two independent quantal steps, does not arise from the generation of d. In addition, as mentioned above, the prediction of perfect duration discrimination in the present dual task situation requires not only that no variance arise before C (as in Figure 2), but also that the quantal steps can be separated from the internal interval so that C can be used as a deterministic duration discrimination criterion.

Previous studies of duration discrimination have found that the criterion is triangularly distributed (Kristofferson, 1977, 1980) and this is the way C is depicted in Figure 4. If C remains triangularly distributed when $I_2 = 0$, the internal events would be as illustrated in Figure 3, rather than Figure 2. This would result if the quantal steps cannot be separated from the deterministic interval and, in this case, the same triangularly distributed time point would serve as both duration discrimination criterion and synchronization response trigger. However, it may be that when the only internal interval produced is that used for the synchronization response, C can be invariant with respect to P_1, and can be used to perform duration discrimination.

The sequential model makes specific predictions about the distribution of synchronization responses when $I_2 > q$ and S must produce two consecutive intervals. On trials when no P_3 is presented, the synchronization interval I_2 will always be triggered by C. The synchronization response latency distribution will be the convolution of the triangular distribution of C with the response trigger distribution and the distribution of the efferent response mechanism. When P_{3S} ("short") is presented, the distribution of C will be censored at $\beta_{P_{3S}}$ (Kendall & Stuart, 1973). That is, if I_2 is not triggered by C before $\beta_{P_{3S}}$, it is triggered by $\beta_{P_{3S}}$. The synchronization response distribution will contain this censored distribution of C, convoluted with the response trigger and efferent latency distributions. When P_{3L} ("long") is presented, the probability that I_2 will be triggered by C is larger than when P_{3S} is presented. The distribution of C is censored later, and this larger portion of C is included in the synchronization response distribution. In this case, the synchronization response distribution will have a larger mean, and will be more variable, than when P_{3S} is presented. The synchronization response distribution will be latest and most variable when no P3 is presented, since I2 will always be triggered by C and the entire C distribution will be part of the synchronization response chain.

In the sequential model, the event that triggers I_2 (C or β_{P_3}) also determines the discrimination response. Therefore, synchronization response distributions will not only depend on P_3, as just described, but for a given P_1-P_3 interval, synchronization responses will be related to the discrimination response. For example, when P_{3S} ("short") is presented and C occurs before $\beta_{P_{3S}}$, discrimination responses will be "long" and I_2 will be triggered by C. When $\beta_{P_{3S}}$ occurs first, discrimination responses will be "short" and I_2 will be triggered by $\beta_{P_{3S}}$. When the discrimination response is "short", synchronization responses will be later and less variable than when the discrimination response is "long", since synchronization responses on "short" trials are timed from BP_S. This point is invariant and occurs after the part of the distribution of C which triggers I when the discrimination response is "long" (refer to Figure 4). Because the sequential model of the dual task events makes such specific predictions about the relationship of synchronization response distributions to duration discrimination responses, it should be clear whether or not Ss are using this timing strategy to perform the dual task.

Two Independent Mechanisms

Another possible way of performing the dual synchronization - duration discrimination task would be to have two parallel and independent mechanisms, one producing the synchronization interval while the other monitors the interval to be discriminated. Although the decision process would have to be different from that described by Eisler (1975, 1981a,b), his notion of two simultaneously operating temporal sensory registers could be applied to such a model. A recent experiment (Curtis & Rule, 1977) has shown that two concurrently presented durations are not treated in the same way as when they are presented successively. Ss were required to judge the total duration of, average duration of, or difference between two temporal intervals. The results conformed to a linear model of time perception when the durations were presented sequentially but when the two durations were presented simultaneously they were not combined linearly. Eisler (1981b) stated that his two sensory registers can not monitor two different durations that start simultaneously and, indeed, Curtis and Rule's results seem to provide evidence that two concurrent temporal intervals are not processed independently. Curtis and Rule's stimulus intervals ranged from 0.5 to 10 sec., and so were larger than those used in the present study.

We do know that two different short durations can be stored and reproduced in a temporal production task without interference when the two intervals are not concurrent. Saslow (1974) had Ss respond within a narrow temporal payoff band. That is, Ss were reinforced if their response latency fell within a specified range. Two different required response latencies were randomly intermixed within a session and a warning signal informed S which interval he was to produce on each trial. In this situation, there was no increase in response latency variance over that which was found when only one response latency was required within a session. In the present dual task situation, it is possible that Ss could use independent mechanisms to concurrently perform the duration discrimination and response-stimulus synchronization tasks. If this were the case, the performance on each task would look like that found in previous experiments where each task was performed alone. Also, if the mechanisms used to perform the two tasks were completely independent, the synchronization response latency variance and the psychometric variance of the duration discrimination task would not be related to one another.

Use of Entire P_1-P_3-P_2 Stimulus Pattern

In the present dual synchronization - duration discrimination task, Ss do not make their duration discrimination response as soon as P_3 is presented, but this response is withheld until after the synchronization response has been made. The previously-discussed mechanisms for performing the dual task assume that duration discrimination will be based on the duration of the P_1-P_3 interval. However, the present paradigm makes it possible for Ss to use the P_3-P_2 interval to perform the duration discrimination task. In order to locate B_{P_3} very close to C, the end-point of the deterministic internal interval illustrated in Figure 2, stimulus P_3 might be much closer to P_2 than it is to P_1. Thus, Ss may be able to discriminate the temporal location of P_3 more accurately by attending to the P_3-P_2 interval rather than the P_1-P_3 interval. Alternatively, the three auditory stimuli could interact in a complex way, producing a state which is discriminable for different P_1-P_3 intervals. A condition in which P_2 does not occur when P_3 is presented is included in the present experiments to test for the possible use of these strategies to perform the duration discrimination task.

Other Considerations

The present experiments were designed to maximize the possibility that Ss will use a single internally-generated time interval to perform both response-stimulus synchronization and duration discrimination. However, it has been suggested that the two concurrent tasks could be performed by two parallel and independent mechanisms, or that the duration discrimination could be performed by observing the overall pattern of the three presented stimuli while the synchronization interval is being timed. That is, Ss might not use the same timer to perform the two tasks. A concurrent memory task is sometimes used to show the development of automaticity in a letter detection task where a lack of interaction between the two tasks indicates that the latter has become automatic (Logan, 1979). If different timing mechanisms were used to perform each part of the dual synchronization—duration discrimination task, and if one or both of these processes were to become automatized, performance on the two parts would be independent. Indeed, Kristofferson (1977) has suggested that stable internal time intervals may be the duration of stored chains of automatic processes like those proposed by Shiffrin & Schneider (1977). These processes are established after a great deal of practice and, once they are learned, they are executed in the same way, without requiring attention, each time they are initiated. If response-stimulus synchronization were to become automatized in this way, attention would be free to concentrate on duration discrimination and the two tasks could be performed by different mechanisms, only one of which requires attention by the subject. Of course, it has not been shown that attention is necessary to perform duration discrimination, and this task might also become automatic. Consistent mapping of stimuli and responses from trial to trial has been shown to lead to the development of automaticity in visual and auditory letter detection tasks (Logan, 1979; Schneider & Fisk, 1982; Poltrock et al., 1982). As recent research on automaticity has generally used letter stimuli, generalizations to timing behaviour might not be completely justified. However, in both the response-stimulus synchronization and duration discrimination tasks used here, the consistent mapping requirement is met. In synchronization, the required timed response is exactly the same on every trial. In duration discrimination, the "short" stimulus always requires a "short" response and the "long" stimulus always requires a "long" response. Moreover, these conditions remain consistent from session to session throughout most of the experiments. Thus, since this requirement for automaticity has been met, the relationship between performances on the two parts of the dual task may provide some indication of whether one or both becomes automatic.

The present experiments were designed to see whether the apparently deterministic response-stimulus synchronization timer can be used to perform duration discrimination, possibly with unprecedented accuracy. Even if this goal is not attained, the experiments will show whether the two tasks can be performed concurrently without disruption and what the effect of each task is on the other when the two are performed together. We will also see whether, in the dual task situation, each task displays the same characteristics that have previously been found. The results will shed light on the hypothesized S-R chain of events in response-stimulus synchronization. Specifically, is Figure 2 an accurate representation of the internal events? More generally, the experiments will provide new data relevant to the question of the existence of a single "time sense". That is, are different types of timing tasks, performed separately or concurrently, accomplished by the same timing mechanisms?

Previously Obtained Performance

In order to see whether performance of response-stimulus synchronization and duration discrimination in the dual task situation is comparable to that found previously when either task was performed alone, a brief summary of earlier findings is required. Only two studies have looked at single-interval response-stimulus synchronization in well-practised subjects (Hopkins & Kristofferson, 1980; Kristofferson, 1976). Table 1 shows the approximate synchronization

Table 1: Response-stimulus Synchronization - Results of previous investigators.

EXPERIMENT	S	REQUIRED LATENCY (msec.)	APPROXIMATE S^2 (msec.^{2})
Kristofferson (1976)	AK	300 - 550	150
	GH	170 - 410	110
Hopkins & Kristofferson (1980)	GH	450	50
	GT	310	55
	CH	310	72
	MW	360	115

response variances found by these authors for the range of response latencies of interest here. Mean response latencies were always within a few msec. of the required latency.

There are several studies of duration discrimination that have used base durations similar to those studied here, but only three used empty intervals marked by brief auditory stimuli, and well-practised Ss (Divenyi & Danner, 1977; Getty, 1975; Kristofferson, 1980). Table 2 presents the duration discrimination results of these studies, in terms of "q", as closely as could be determined from the published data. The calculation of q is based on Kristofferson's (1967a,b) quantal theory of central timing and it represents the measure, in msec., of half the base of a hypothetical triangular distribution of the duration discrimination criterion (see Figure 3). The variance of a triangular distribution with a base of 2q msec. is related to q in the following way:

$$\sigma_c^2 = \frac{q^2}{6}$$

Thus, q is directly proportional to the psychometric standard deviation in duration discrimination.

The present experiments were designed to see whether the apparently deterministic response-stimulus synchronization timer can be used to perform duration discrimination, possibly with unprecedented accuracy. Even if this goal is not attained, the experiments will show whether the two tasks can be performed concurrently without disruption and what the effect of each task is on the other when the two are performed together. We will also see whether, in the dual task situation, each task displays the same characteristics that have previously been found. The results will shed light on the hypothesized

Table 2: Duration discrimination - results of previous investigators.

EXPERIMENT	S	BASE DURATION (msec.)	APPROXIMATE q (msec.)
Divenyi & Danner (1977)	1	320	27.6
	2	320	32.7
Getty (1975)	DG	200	25.84
	TW	200	36.83
Kristofferson (1980)	AK	200	24.7
	AK	250	26.2

S-R chain of events in response-stimulus synchronization. Specifically, is Figure 2 an accurate representation of the internal events? More generally, the experiments will provide new data relevant to the question of the existence of a single "time sense". That is, are different types of timing tasks, performed separately or concurrently, accomplished by the same timing mechanism?

General Method

Subjects and Apparatus

Subjects were graduate students in the McMaster psychology department. The experiments were conducted using two male subjects and one female subject (the author). All Ss were aware of all experimental conditions.

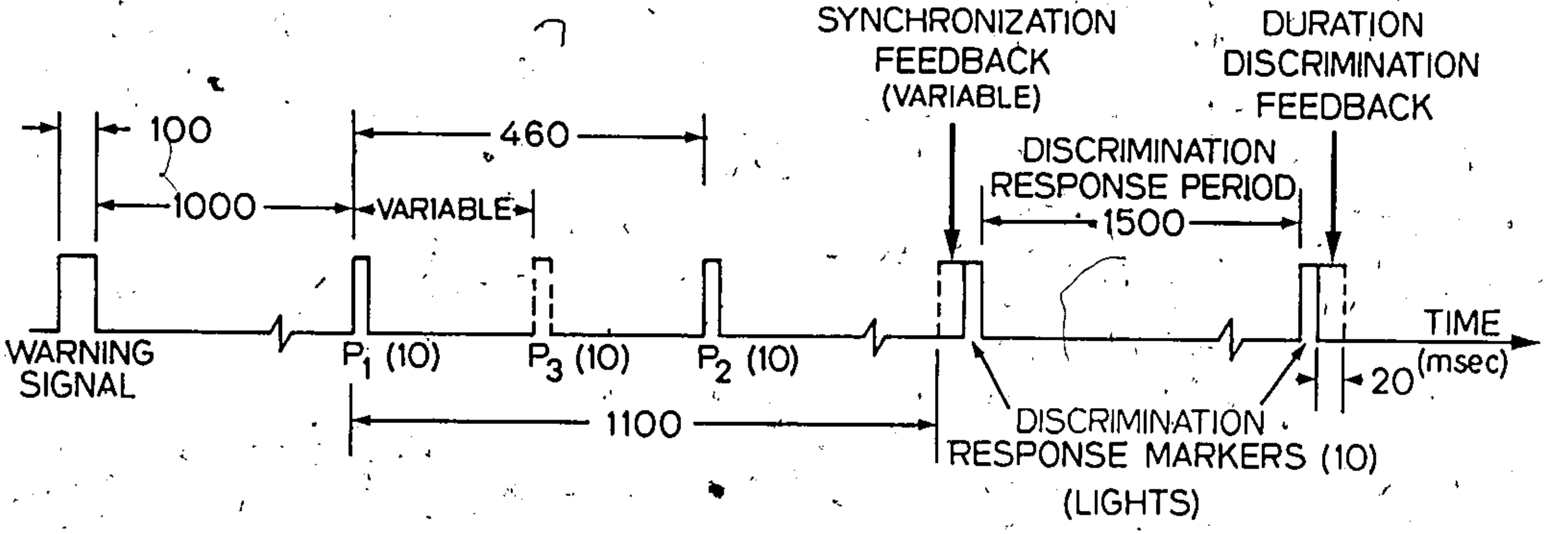
Ss sat in a dimly-illuminated, sound-attenuated chamber. The warning signal on each trial was a noisy, low-pitched sound emitted by a speaker in the chamber. The auditory stimuli were presented binaurally through headphones. They were sinusoidal tones of 2,000 Hz gated at zero-crossing with a rise-decay time of 2.5 msec. and an intensity of 68 dB relative to .0002 dynes/cm.^{2} when on continuously. The visual signal was an easily-detectable yellow-green light-emitting diode, 5 mm. in diameter, located approximately 70 cm. in front of S. The response apparatus, which rested on a table top in front of S, was a flat metal box measuring 43 x 25 x 5 cm. from which protruded a row of six plastic response buttons, each 1.5 cm. in diameter and 0.5 cm. high. S rested his arms on the table and his hands on the response box with his index finger poised over or resting lightly on the response button. Synchronization responses were made with the right hand by depressing the button at one end of the row. Duration discrimination responses were made with the left hand by depressing one of the two middle buttons, one labelled "short" and the other labelled "long". The presentation of stimuli and the recording of responses were under the control of a PDP-8/e computer.

Procedure

The sequence of events on each trial is shown in Figure 5. One second after an auditory warning signal, the synchronization interval, marked by P_1 and P_2, was presented. P_1 and P_2 were auditory stimuli, each 10 msec. in duration. The P_1-P_2 interval, defined as the time between the onsets of these two stimuli, was 460 msec. throughout most of the experiments. Conditions under which this value was changed are described below. A third tone, P_3, physically identical to P_1 and P_2, could be presented during the P_1-P_2 interval. The P_1-P_3 interval could take on different durations from trial to trial. During sessions when P_3 was used, the possible values of the P_1-P_3 interval, and a no-P_3 condition, when P_3 was omitted, were all equally likely to occur on each trial. P_3 never occurred more than once on a trial.

S was required to press the synchronization response button in synchrony with the onset of P_2 on every trial. Response latencies (measured from P_1 onset) were recorded to the nearest msec. Feedback on synchronization performance was provided 1,100 msec. after the onset of P_1. If the response occurred before P_2 (early), the feedback was a 10,000 Hz tone, the duration of which was the difference between the times of the P_2 onset and the response. If the response was late, the frequency of the feedback tone was 2,000 Hz and its duration was the time of the synchronization error. If the computer recorded a response latency of 460 msec. (perfect synchrony), no synchronization feedback tone was presented. Although this delayed feedback was always provided, it should be noted that Ss received immediate feedback on the accuracy of their synchronization response through the conjunction of P_2 with the sensory effect of their response, including the sound of the response

Figure 5. Events on each trial throughout the experiments. P_1, P_2, P_3: 2,000 Hz tones.


SYNCHRONIZATION FEEDBACK (VARIABLE)
DURATION DISCRIMINATION FEEDBACK
100
460
1000
VARIABLE
DISCRIMINATION RESPONSE PERIOD
1500
WARNING SIGNAL
P_1 (10)
P_3 (10)
P_2 (10)
TIME
(msec)
20
1100
DISCRIMINATION RESPONSE MARKERS (10) (LIGHTS)

button and kinesthetic feedback from the button-press. Indeed, the relation between P_2 and the sensory effect of the synchronization response was the only trial-to-trial feedback used by Kristofferson in his 1976 study of response-stimulus synchronization. Hopkins and Kristofferson (1980) concluded that delayed feedback is useful during acquisition of accurate response-stimulus synchronization but when performance is well established, it can be omitted with no detrimental effect on performance. In the present study, it was thought that retaining the delayed feedback about synchronization accuracy would help Ss to maintain stable synchronization performance throughout the various experimental manipulations. In order to maintain a constant time between the synchronization interval and the delayed feedback, the discrimination response period followed the synchronization feedback when the duration discrimination task was added.

Synchronization feedback was followed immediately by the discrimination response period, the duration of which was 1500 msec. The beginning and end of the discrimination response period were each marked by a 10 msec. light flash. When a P_3 duration discrimination stimulus was presented, the discrimination response period was followed by a 20 msec. tone burst, the frequency of which indicated the duration of the P_1-P_3 interval on that trial. If the discrimination stimulus had been "short", the frequency of the tone was 10,000 Hz; if the interval was "long", the tone was 2,000 Hz. All Ss could easily discriminate these two feedback tones from one another. The next trial began 1,000 msec. later.

A daily experimental session consisted of four blocks of 100 trials each, separated by 30 sec. rest periods. Sessions lasted about

40 min. Duration discrimination responses were never required during the first block of a session. In the first block, Ss synchronized with P_2 on every trial. P_3 was presented randomly on half the trials in block 1, always in the position that was the midpoint of the possible P_1-P_3 duration values that would be used in the remaining three blocks. This duration will be referred to as the P_1-P_3 midpoint (P_1-P_3 MP). The different procedure in the first block was provided to allow Ss to stabilize their synchronization performance and become familiar with the P_1-P_3 MP each day before the addition of the duration discrimination task in the remaining three blocks. The results from the first block of each daily session were excluded from the data analysis. Also, Ss occasionally reported that their finger had "slipped", producing an unintentional and extremely aberrant synchronization response. Such responses, which occurred rarely, were excluded from the data analysis.

Data Analysis

Duration discrimination results will be reported in terms of "q". This is the measure, in msec., of half the base of a hypothetical triangular distribution of the duration discrimination criterion, C (see Figure 3). Calculation of q uses the proportion of errors made when each value of P_1-P_3 is presented, assuming a triangular distribution of C. Kristofferson (1977, 1980) has reported duration discrimination results in terms of q estimates. Although the q measure was originally derived from Kristofferson's (1967a,b) quantal theory of central timing, it is used here as a descriptive measure of duration discrimination performance, without necessarily implying a specific quantal discrimination mechanism. The smaller is the estimate of q, the better is the discrimination performance.

The variance of a triangular distribution with a base of 2q msec. is related to q in the following way:

$$\sigma_c^2 = \frac{q^2}{6}$$

Thus, the measure q is a direct measure of the psychometric standard deviation of duration discrimination performance. The mean, $\overline{C}$, of the hypothetical triangular criterion distribution will also be reported for the duration discrimination results. Details of the calculation of q and $\overline{C}$ are given in Appendix 3.

Training and Baseline Performance

Method

Ss began training by performing only the synchronization task - no P_3 stimuli were presented. The P_1-P_2 interval was 460 msec. for all Ss. After at least 20 sessions under this condition, P_3 was added. Initially, P_3 occurred 240 msec. following P_1 randomly on half the trials, and no P_3 was presented on the remaining trials. Only the synchronization response was required. The P_1-P_2 interval remained at 460 msec. These conditions were the same throughout all four blocks of each session. Ss ran at least 50 sessions under this condition before the discrimination task was added.

When Ss were performing at a stable level in the synchronization task, the duration discrimination task was added. The experimental condition described here will subsequently be referred to as the "baseline" condition. The P_1-P_2 interval remained at 460 msec. During the first block of trials in each session, the P_1-P_3 interval was 240 msec. (the P_1-P_3 MP) randomly on half the trials and no P_3 was presented on the remaining trials. Only the synchronization response was required. The next three blocks of trials consisted of the dual synchronization - duration discrimination task. No P_3 was presented on one third of the trials. On one third of the trials the P_1-P_3 interval was less than 240 msec., and on one third of the trials the P_1-P_3 interval was greater than 240 msec. The three types of trials were randomly intermixed. On trials when P_3 had occurred, S was required to respond "short" if the P_1-P_3 interval had been less than 240 msec. and "long" if P_1-P_3 was greater than 240 msec., after he had made the synchronization response. The possible P_1-P_3 durations were initially 235 and 245 msec. for all Ss. These were adjusted because of the difficulty of the discrimination. The final P_1-P_3 values for the three Ss were: JB - 230 & 250 msec.; GTH - 232 & 248 msec.; CK - 235 & 245 msec. The difference between the two possible values of the P_1-P_3 duration is referred to as ΔD. The possible values of the P_1-P_3 duration were always symmetrical about the P_1-P_3 MP. The number of sessions run by each subject in each of the training conditions is presented in Table 3. Subject JB had run many sessions under different conditions in pilot studies before those sessions listed in Table 3.

Results and Discussion

During synchronization training, the mean synchronization response latency quickly came to within a few msec. of perfect synchrony (460 msec.) and remained there. Synchronization variance decreased with practice for all Ss. Performance on the synchronization task during training and baseline sessions is shown in Figures 6, 7, and 8 for subjects JB, GTH, and CK, respectively. Subject JB had run many sessions under different conditions in pilot studies before those shown in Figure 6. The values shown in Figures 6, 7, and 8 are the overall means and variances, calculated by pooling together all responses in blocks 2, 3, and 4 of each experimental session. For all Ss, synchronization variance increased when a P_3 stimulus was first introduced into the P_1-P_2 interval, but the variance decreased with continued practice. When the discrimination task was added, synchronization variance continued to decrease, for all Ss. The

Table 3: Number of sessions run by each subject in training and baseline conditions.

	SUBJECT		
CONDITION	JB	GTH	CK
SYNC. ONLY $P_1-P_2 = 460$	29	23	32
SYNC. ONLY $P_1-P_2 = 460$ $P_3 = 240$	86	78	53
SYNC.-DUR. DISC.			
$\Delta D = 10$	9	1	19
$\Delta D = 30$	2		
$\Delta D = 20$	25	5	
$\Delta D = 16$		7	

Figure 6. Synchronization performance during training and baseline sessions, Subject JB. P_1-P_2 = 460 msec. Filled circles: overall performance; open circles: no P_3; open squares: P_3 = 240 msec.; filled triangles: "short" P_3; open triangles: "long" P_3. Asterisks denote groups of less than five sessions.

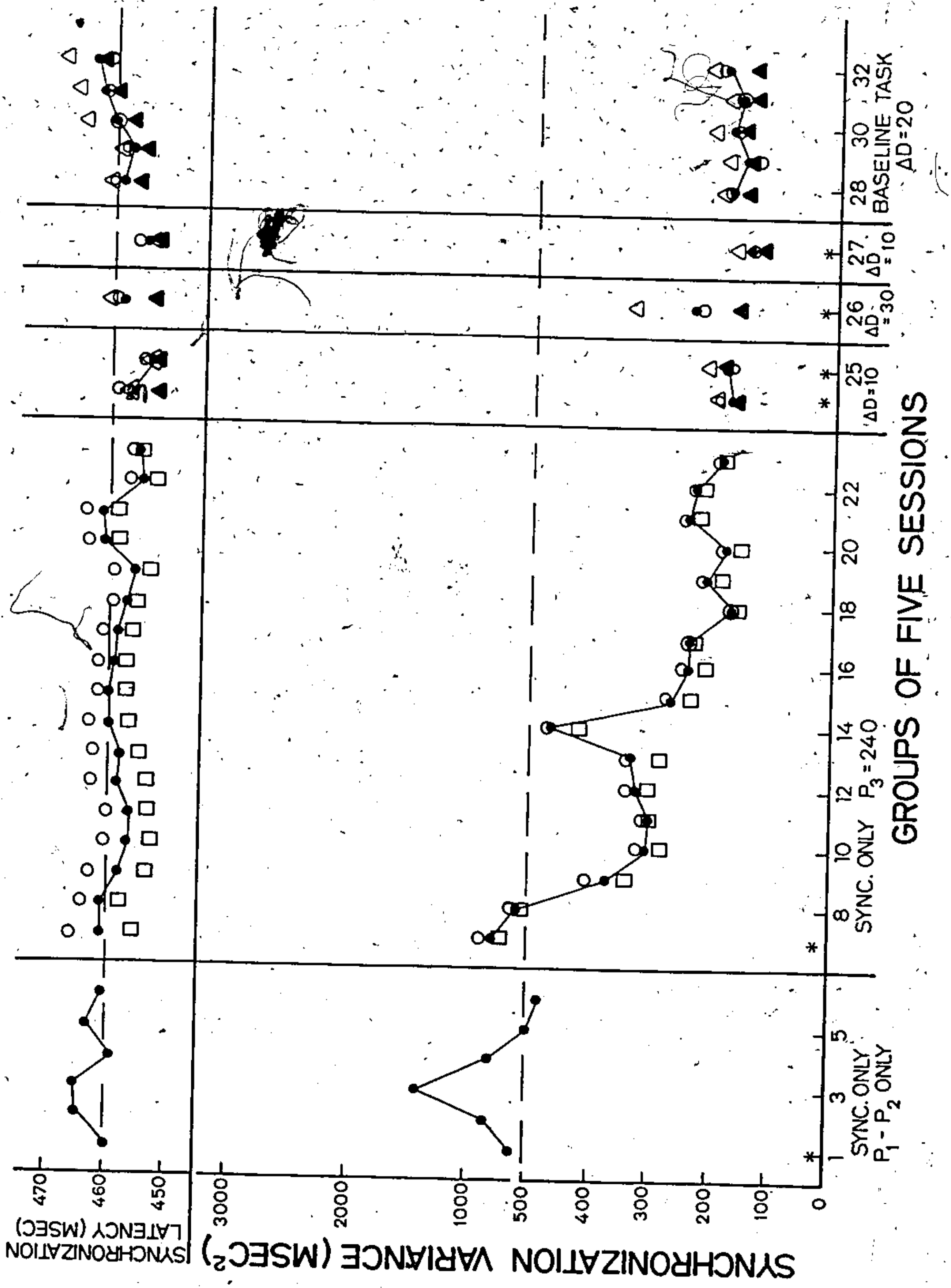

SYNCHRONIZATION LATENCY (MSEC)
470
460
450
SYNCHRONIZATION VARIANCE (MSEC^2)
3000
2000
1000
500
400
300
200
100
0
1
3
5
SYNC. ONLY
$P_1 - P_2$ ONLY
8
10
12
14
16
18
20
22
SYNC. ONLY P_3 = 240
25
ΔD=10
26
ΔD =30
27
ΔD =10
28
30
32
BASELINE TASK
ΔD=20
*
GROUPS OF FIVE SESSIONS

Figure 7. Synchronization performance during training and baseline sessions, Subject GTH. P_1–P_2 = 460 msec. Filled circles: overall performance; open circles: no P_3; open squares: P_3 = 240 msec.; filled triangles: "short" P_3; open triangles: "long" P_3. Asterisks denote groups of less than five sessions.

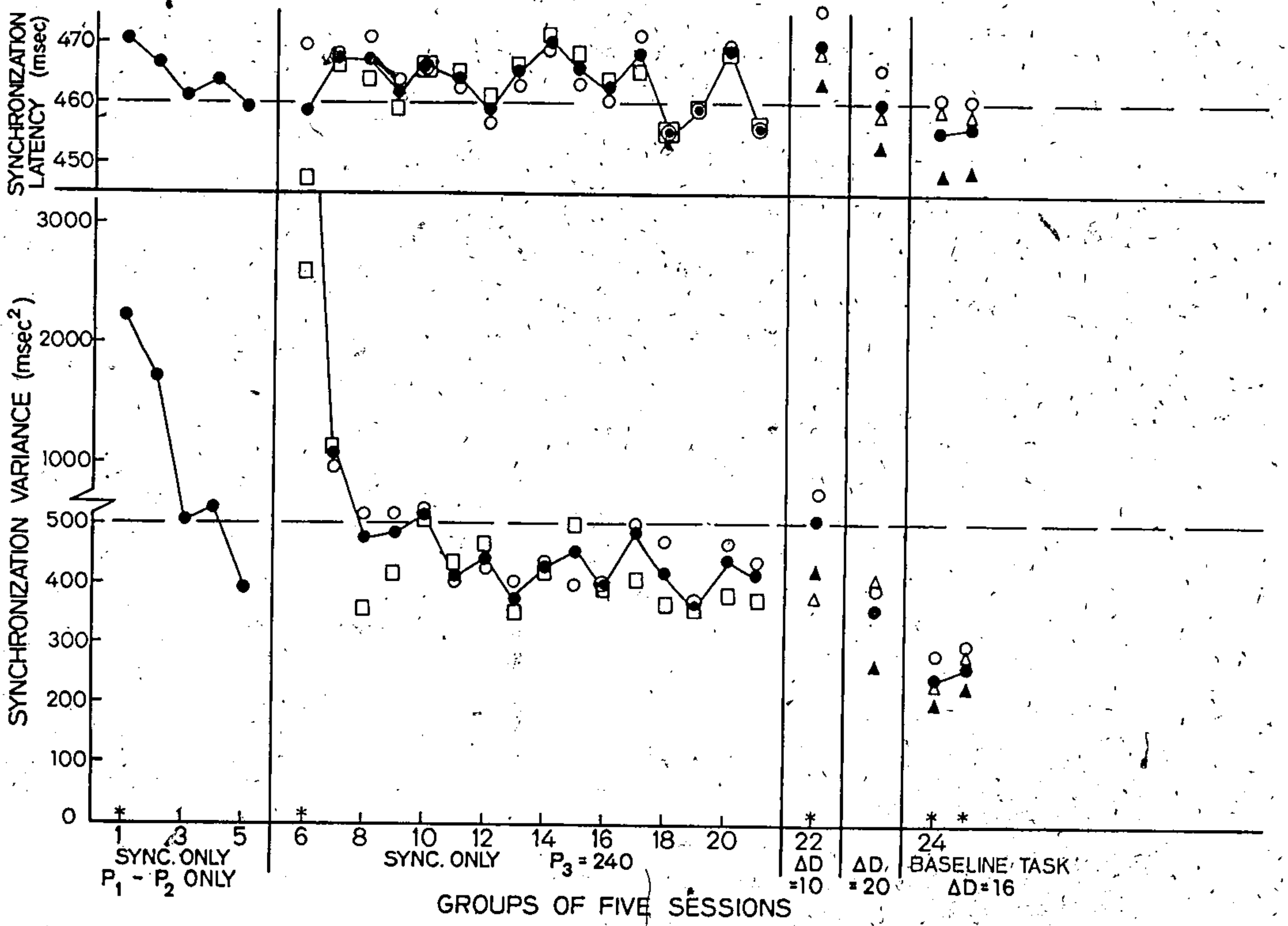
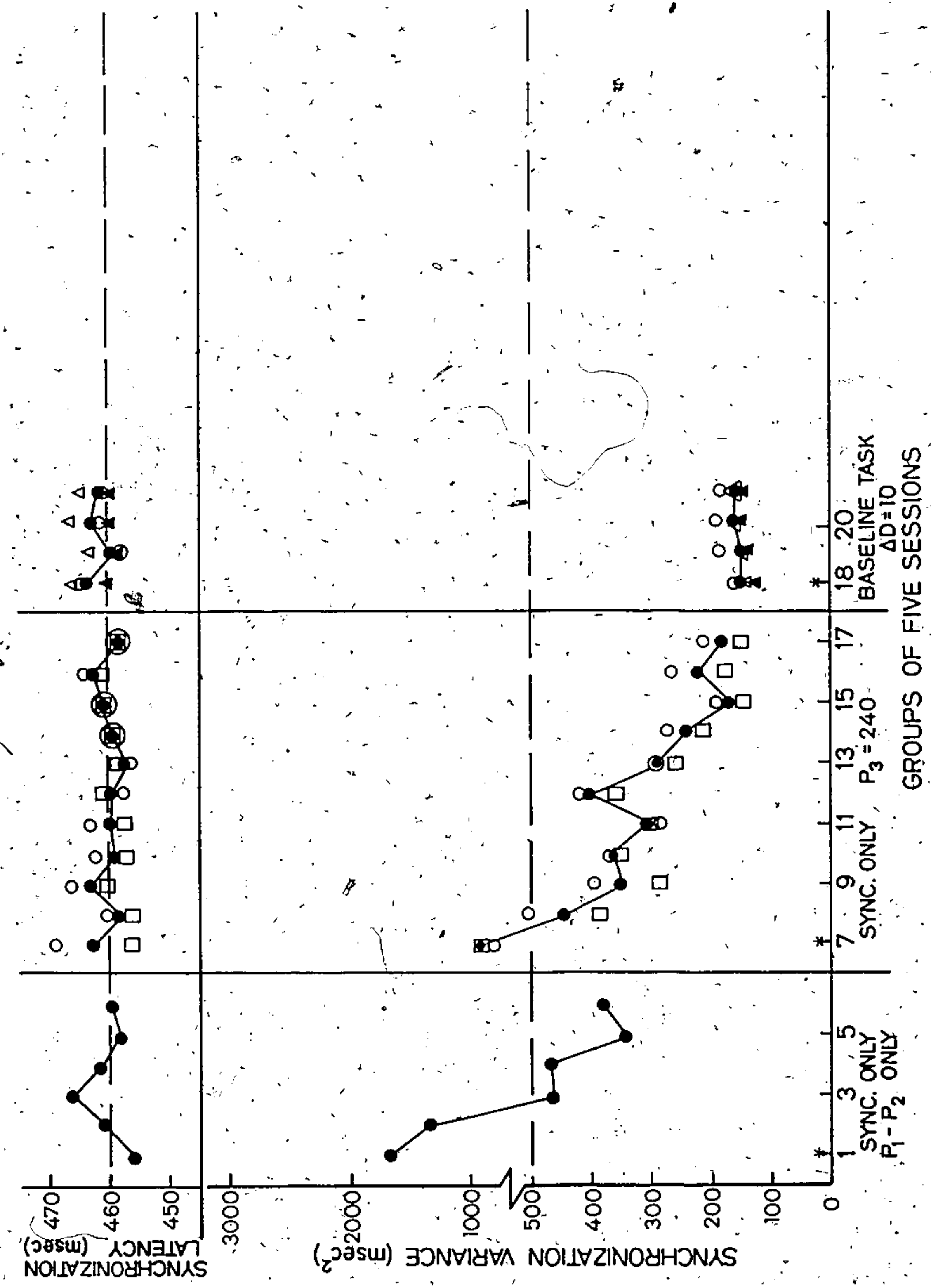

SYNCHRONIZATION LATENCY (msec)
470
460
450
SYNCHRONIZATION VARIANCE (msec^2)
3000
2000
1000
500
400
300
200
100
0
1
3
5
6
8
10
12
14
16
18
20
22
24
*
SYNC. ONLY
$P_1 - P_2$ ONLY
SYNC. ONLY
$P_3 = 240$
ΔD =10
ΔD =20
BASELINE TASK
ΔD=16
GROUPS OF FIVE SESSIONS

Figure 8. Synchronization performance during training and baseline sessions, Subject CK. P_1-P_2 = 460 msec. Filled circles: overall performance; open circles: no P_3; open squares: P_3 = 240 msec.; filled triangles: "short" P_3; open triangles: "long" P_3. Asterisks denote groups of less than five sessions.

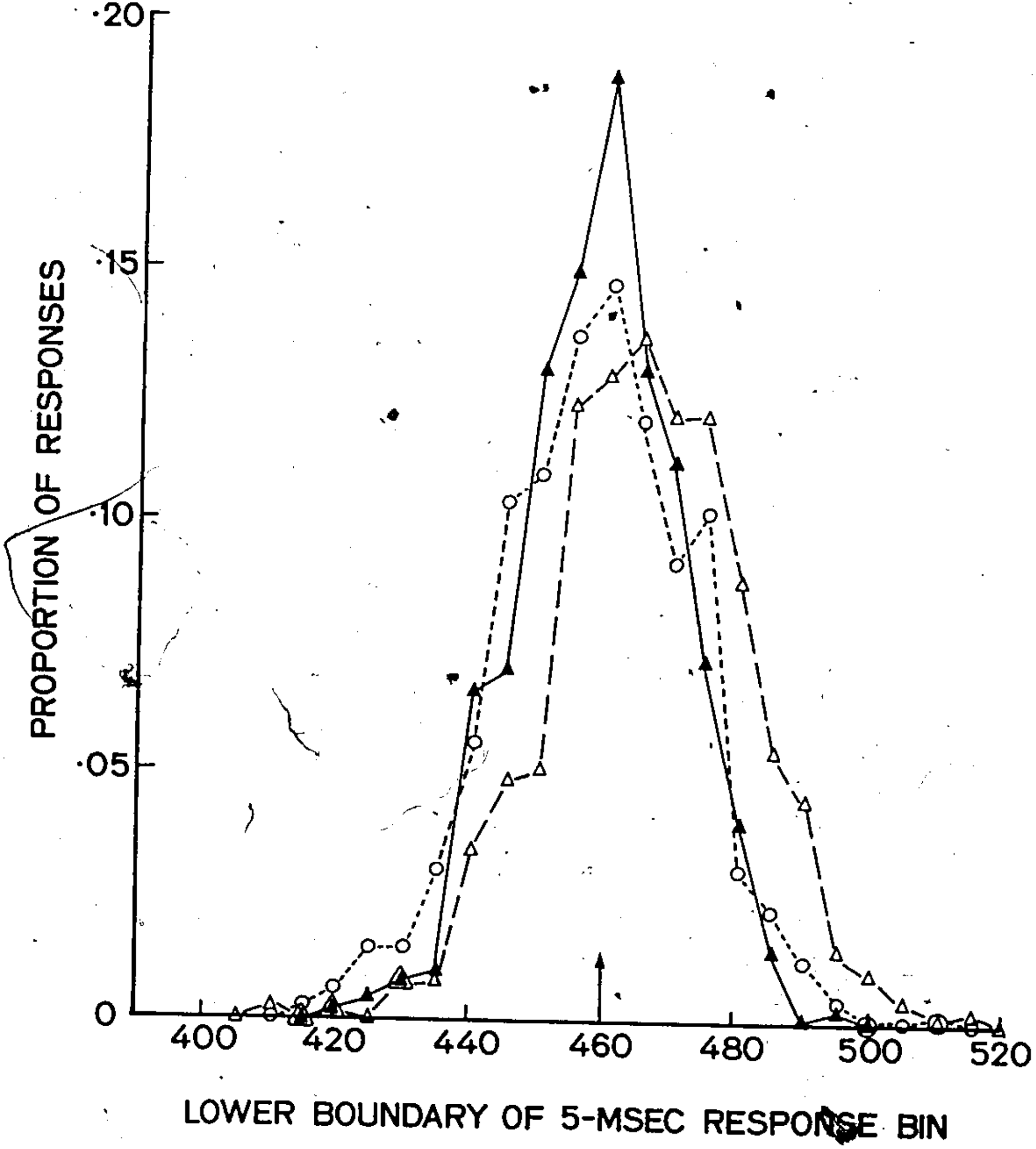

SYNCHRONIZATION LATENCY (msec)
470
460
450
SYNCHRONIZATION VARIANCE (msec²)
3000
2000
1000
500
400
300
200
100
0
1
3
5
SYNC. ONLY
P1 - P2 ONLY
7
9
11
13
15
17
SYNC. ONLY P3 = 240
18
20
BASELINE TASK
ΔD=10
GROUPS OF FIVE SESSIONS
*
*
*

baseline synchronization performance shown in Figures 6, 7, and 8 is that immediately following the training sessions, before the other experimental manipulations. One feature of the data in Figures 6, 7, and 8 is the difference in synchronization performance for the different values of the P_1-P_3 interval in the baseline condition. In most sessions, the mean synchronization latency was shortest, and the synchronization variance was lowest, when the shorter P_1-P_3 interval was presented. For subject JB, synchronization responses were longest and most variable when the longer P_1-P_3 interval was presented, while GTH made the longest and most variable synchronization responses on trials when no P_3 was presented. CK's synchronization responses were longest when the longer P_1-P_3 interval was presented, and were most variable when no P_3 was presented.

Synchronization response distributions were symmetrical and fully-bounded, like those of previous studies (Hopkins & Kristofferson, 1980; Kristofferson, 1976). The synchronization variances in the baseline condition are similar to those reported by Kristofferson (1976) for synchronization alone but they are not as low as those found by Hopkins and Kristofferson (1980) (see Table 1), using a refined response procedure. Figure 9 shows typical synchronization response latency distributions for JB, averaged over the last five sessions under baseline conditions. The variance is smallest when the short P_1-P_3 interval is presented, next largest when no P_3 is presented, and largest on the trials when the long P_1-P_3 interval is presented. The mean synchronization latency is about the same when the short P_1-P_3 interval and no P_3 are presented; it is longer than this when the long P_1-P_3 interval is presented.

Figure 9. Synchronization response latency distributions, Subject JB. Responses are taken from the last five baseline sessions preceding Experiment 1. P_1-P_2 = 460 msec. Filled triangles: P_1-P_3 = 230 msec., $\overline{X}$ = 461 msec., S^2 = 138 msec.^{2}, N = 499; open triangles: P_1-P_3 = 250 msec., $\overline{X}$ = 468 msec., S^2 = 218 msec.^{2}, N = 498; open circles: no P_3, $\overline{X}$ = 460 msec., S^2 = 201 msec.^{2}, N = 495; overall: $\overline{X}$ = 463 msec., S^2 = 199 msec.^{2}, N = 1493.

54a



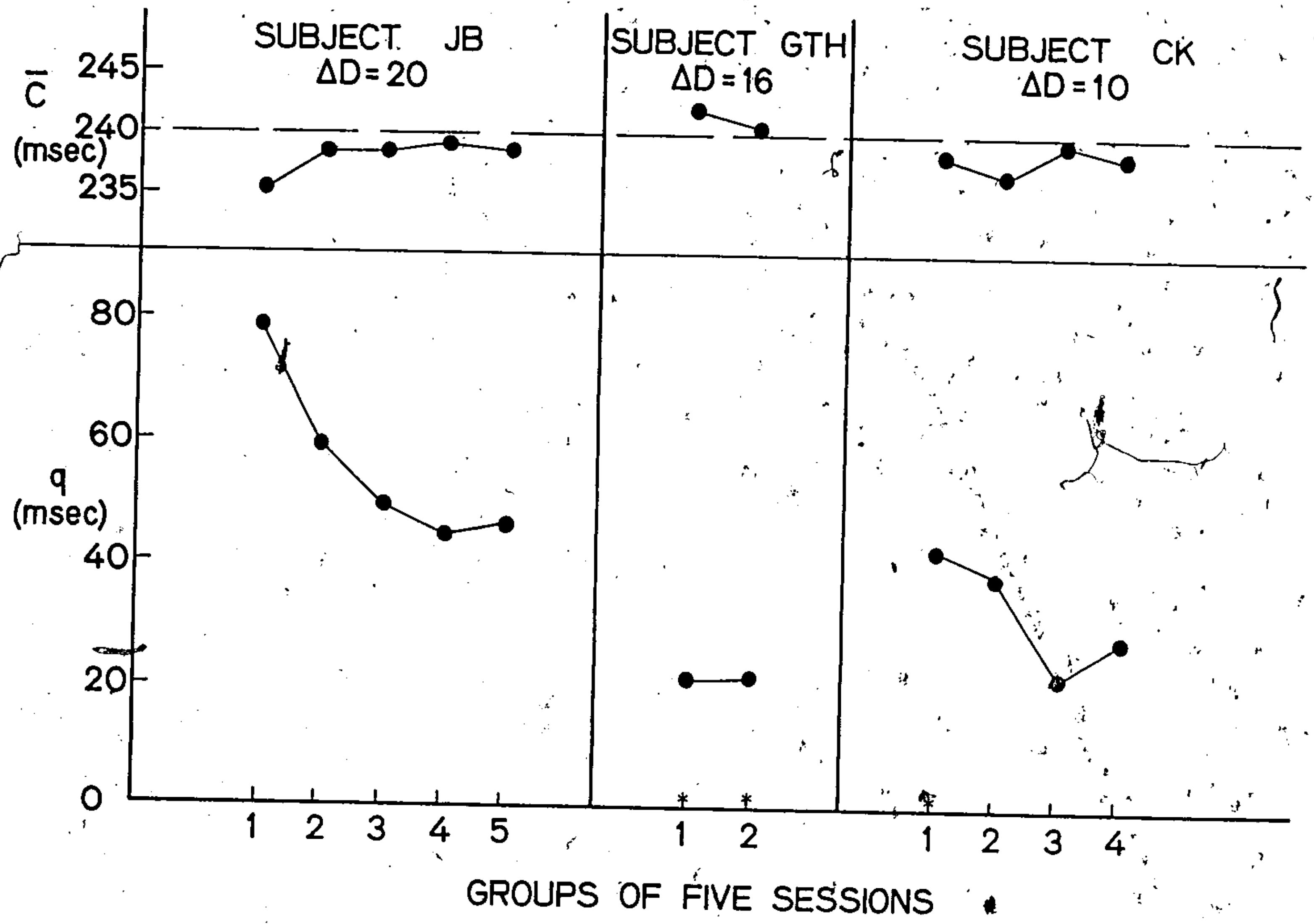
PROPORTION OF RESPONSES
·20
·15
·10
·05
0
400
420
440
460
480
500
520
LOWER BOUNDARY OF 5-MSEC RESPONSE BIN

Discrimination performance for the baseline task in the sessions preceding Experiment 1 is shown in Figure 10 for all three Ss. The $\overline{C}$ value is the estimate of the mean of a hypothetical triangular distribution of the duration discrimination criterion and q is the estimate of half the base of the triangle, as described above. The q estimates for JB and CK were reduced during baseline training while those of GTH reached a relatively low level very quickly. Before Experiment 1 was begun, discrimination performance was comparable to that found by other investigators using similar base durations (Allan & Kristofferson, 1974a; Divenyi & Danner, 1977; Getty, 1975; Kristofferson, 1980) (see Table 2) and the estimate of $\overline{C}$ was very near 240 msec. (the P_1-P_3 MP) for all Ss.

Baseline performance on the dual synchronization - duration discrimination task showed clearly that Ss are quite capable of performing the two tasks concurrently. Both tasks were performed at a level comparable to that found in previous studies of the individual tasks, as described above. When the duration discrimination task was introduced, synchronization variances were decreased. However, although the presence of the discrimination task was certainly not disruptive to synchronization performance, synchronization means and variances were dependent on the P_1-P_3 interval to a small extent, as described above. Thus, it has been demonstrated that both components of the dual synchronization - duration discrimination task can be performed very adequately.

The baseline performance data contain some evidence that the response-stimulus synchronization task and the duration discrimination task are not being performed by the same mechanism. Specifically, the

Figure 10. Discrimination performance during baseline task preceding Experiment 1. P_1-P_3 MP = 240 msec. Asterisks denote groups of less than five sessions.


SUBJECT JB
ΔD = 20
SUBJECT GTH
ΔD = 16
SUBJECT CK
ΔD = 10
C̄
(msec)
245
240
235
q
(msec)
80
60
40
20
0
1
2
3
4
5
1
2
1
2
3
4
GROUPS OF FIVE SESSIONS

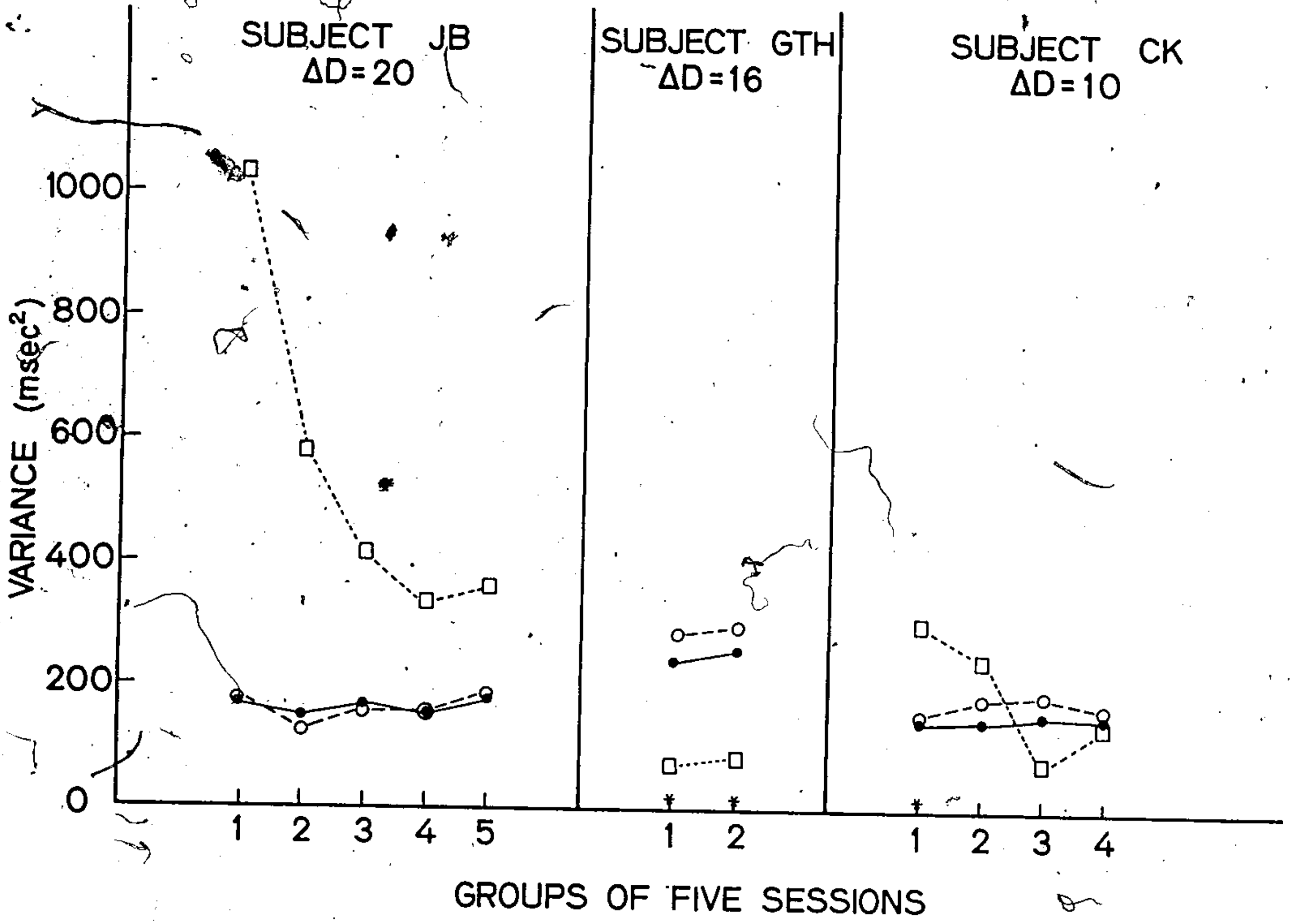
psychometric variance in the duration discrimination task was not related to the variance of the synchronization response distributions. The variance of a triangular distribution with a base of 2q msec. (the hypothetical distribution of C) is dependent upon q in the following way:

$$\sigma^2 = \frac{q^2}{6}$$

If the duration discrimination criterion formed part of the synchronization chain of events, as illustrated in the sequential model in Figure 4, the psychometric variance would be less than or equal to the synchronization variance. Figure 11 shows both the psychometric variance for the duration discrimination and the synchronization variance for the baseline sessions for all three Ss. For JB, the psychometric variance is consistently higher than the synchronization variance. Also, her psychometric variance was reduced by practice during the sessions shown in Figure 11, while the synchronization response variance remained constant. CK's psychometric variance is similar to his synchronization variance but changes in his discrimination performance are not reflected in the synchronization variance, which remains fairly constant. The psychometric variance is lower than the synchronization variance for GTH, the only S to show this pattern. Thus, at this stage in the experiments, there is no evidence that the duration discrimination criterion forms part of the synchronization chain of events, or that the variation in performance on the two tasks arises from the same source. Indeed, the fact that the psychometric variance for duration discrimination and the synchronization response variance were unrelated in the baseline

Figure 11. Synchronization response latency variance and duration discrimination psychometric variance during baseline task preceding Experiment 1. P_1-P_2 = 460 msec. P_1-P_3 MP = 240 msec. Filled circles: overall synchronization performance; open circles: no P_3; open squares: psychometric variance. Asterisks denote groups of less than five sessions.

58a


SUBJECT JB
ΔD=20
SUBJECT GTH
ΔD=16
SUBJECT CK
ΔD=10
VARIANCE (msec²)
1000
800
600
400
200
0
1
2
3
4
5
1
2
1
2
3
4
GROUPS OF FIVE SESSIONS

training sessions suggests that the two concurrent tasks are not performed by the same timing mechanism.

It should be noted that during the baseline sessions just described, the duration of the P_1-P_3 MP (240 msec.) made it unlikely that Ss could use the end-point of d (Figure 2) to perform the duration discrimination, although the dual task might have been performed by a sequential mechanism like that illustrated in Figure 4. The purpose of the first experiment was to change the duration of d or P_1-P_3 MP so that the two might become the same, allowing Ss to use the end-point of d as a criterion to perform the duration discrimination.

Experiment 1: Search for Perfect Discrimination

After the baseline training sessions described above, an attempt was made to align the P_1-P_3 MP with the end-point of d, the internal time interval generated in order to perform the synchronization task (illustrated in Figure 2). It was thought that, if this possibly invariant time point could be used as a criterion to perform the duration discrimination, very accurate (possibly even perfect) duration discrimination performance might be found. Three different experimental manipulations were used in this attempt: A) the P_1-P_2 interval was held constant while the P_1-P_3 MP was gradually increased; B) the P_1-P_3 MP was held constant while the P_1-P_2 interval was gradually decreased; C) with the P_1-P_3 MP near the end-point of d (as closely as could be determined), Δ, the difference between the two possible values of P_1-P_3, was made very large and then gradually decreased.

Experiment 1A: P_1-P_2 = 460 msec.; P_1-P_3 MP gradually increased.

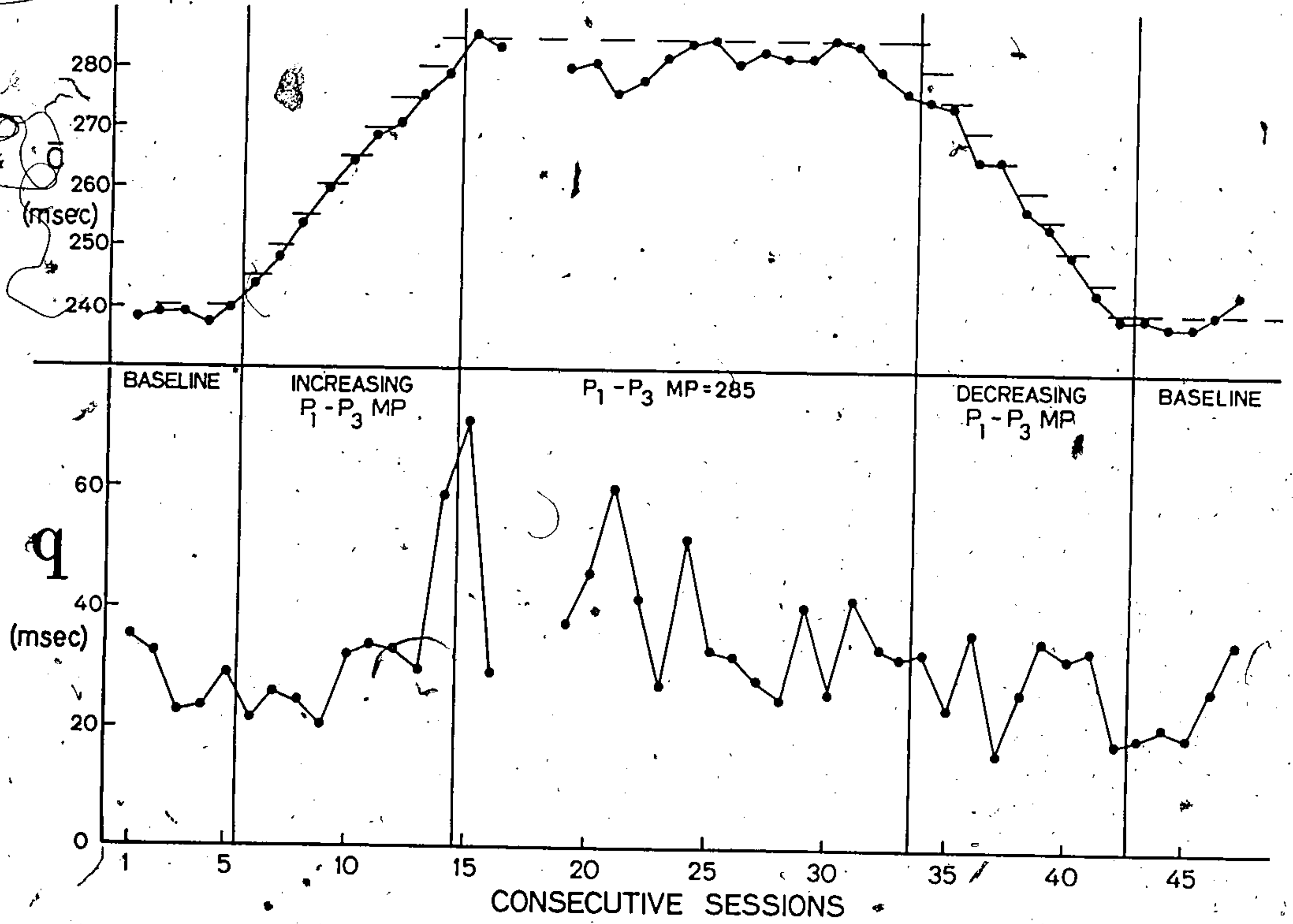
Method

The P_1-P_2 synchronization interval was 460 msec. throughout. During each succeeding session, the P_1-P_3 MP, midpoint of the duration discrimination stimuli, was increased by 5 msec. The P_1-P_3 MP was presented on one half of the trials during block 1, when only synchronization responses were required. In the remaining three blocks, P_1-P_3 could take on two possible values, centred about the P_1-P_3 MP with a Δ of 10 msec. The P_1-P_3 MP remained constant throughout each session. No P_3 was presented on one third of the trials, and each of the two values of P_1-P_3 was presented on one third of the trials. Both synchronization and duration discrimination responses were required on each trial, as in the baseline condition. The P_1-P_3 MP was increased from 240 msec. to 285 msec. in nine sessions in steps of 5 msec./session. Due to disruption of the discrimination performance, the P_1-P_3 MP was held constant at 285 msec. for 19 additional sessions. The P_1-P_3 MP was then decreased in nine more 5 msec. steps to 240 msec. Subject CK served in this experiment.

Results

Figure 12 shows the estimates of q and $\overline{C}$ from the discrimination performance in Experiment 1A. As the P_1-P_3 MP increased, the estimate of $\overline{C}$ gradually lagged behind the P_1-P_3 MP. Estimates of q showed some increase as the P_1-P_3 MP increased until, when the P_1-P_3 MP was 285 msec., discrimination was severely disrupted. At this point it was decided to run several sessions with the P_1-P_3 MP constant at 285 msec. Previous studies of duration discrimination have shown that several sessions of practice are required to reduce the psychometric variance after each change in base duration (Allan & Kristofferson, 1974a; Kristofferson, 1980). The two sessions for which no data are shown in Figure 12 are those for which q and $\overline{C}$ could not be estimated because the discrimination performance was at or below chance. After a total of 20 sessions with a P_1-P_3 MP of 285 msec., CK's discrimination performance had still not returned to its pre-Experiment 1A baseline level. There was much variability in q estimates between sessions and some individual sessions gave estimates of q that were comparable to those obtained in

Figure 12. Estimates of q and $\overline{C}$ for consecutive sessions in Experiment 1A. Subject CK.



280
270
260
250
240
$\bar{q}$
(msec)
BASELINE
INCREASING $P_1 - P_3$ MP
$P_1 - P_3$ MP = 285
DECREASING $P_1 - P_3$ MP
BASELINE
60
40
20
0
q
(msec)
1
5
10
15
20
25
30
35
40
45
CONSECUTIVE SESSIONS

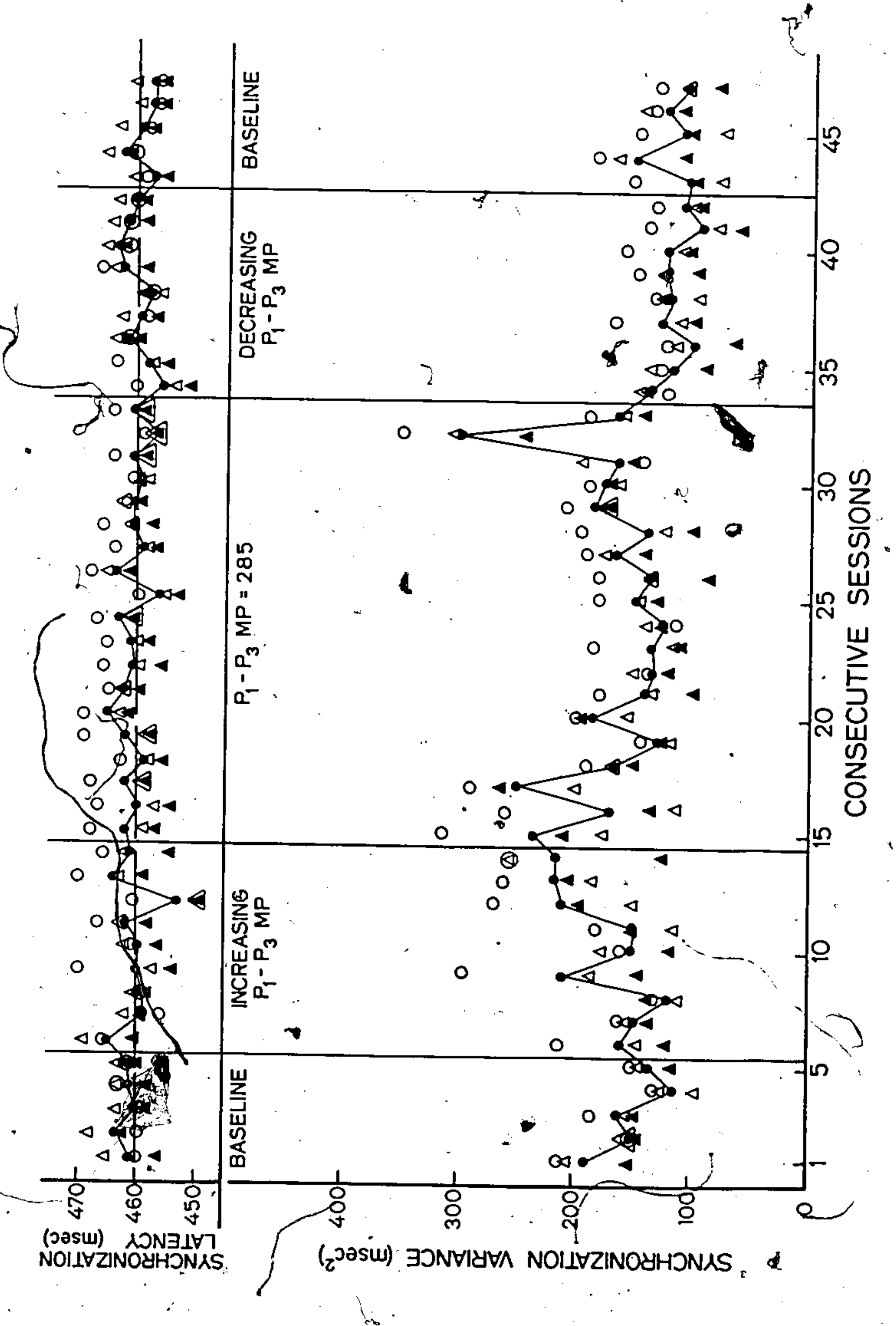
the baseline sessions. However, the average q estimate for the last five sessions during which P_1-P_3 MP = 285 msec., was 34.86 msec. compared to an average q estimate of 27.65 msec. for the last five baseline sessions before Experiment 1A began. In addition, the q estimates did not show a downward trend for the last ten sessions for which P_1-P_3 MP = 285 msec. and estimates of $\overline{C}$ were less than the P_1-P_3 MP in many sessions.

Since increasing the P_1-P_3 MP was so disruptive to performance, this manipulation was discontinued and the P_1-P_3 MP was returned to the baseline value of 240 msec. Estimates of q remained variable while the P_1-P_3 MP was gradually decreased. In the five baseline sessions ending Experiment 1A (sessions 43 to 47 in Figure 12), the average q estimate was 23.03 msec., lower than that for the baseline sessions preceding Experiment 1A (sessions 1 to 5 in Figure 12).

Synchronization performance for CK in Experiment 1A is shown in Figure 13. There was an increase in synchronization variance while the P_1-P_3 MP was being increased. When the P_1-P_3 MP was constant, overall synchronization performance generally returned to pre-Experiment 1A levels, except for one or two more variable sessions. In the five baseline sessions after Experiment 1A, the average overall synchronization variance was 130 msec.^{2}, lower than the 150 msec.^{2} found in the five sessions before P_1-P_3 MP was increased. The overall mean synchronization latency was within a few msec. of 460 msec. throughout Experiment 1A.

In most sessions during this experiment, synchronization responses were shortest and least variable when the shorter P_1-P_3 value was presented. During pre-Experiment 1A baseline sessions, and in the

Figure 13. Synchronization performance in Experiment 1A. Subject CK. Filled circles: overall synchronization performance; open circles: no P_3; filled triangles: "short" P_3; open triangles: long P_3.


SYNCHRONIZATION LATENCY (msec)
470
460
450
SYNCHRONIZATION VARIANCE (msec²)
400
300
200
100
0
BASELINE
INCREASING P₁ - P₃ MP
P₁ - P₃ MP = 285
DECREASING P₁ - P₃ MP
BASELINE
CONSECUTIVE SESSIONS
1
5
10
15
20
25
30
35
40
45

baseline sessions ending Experiment 1A, synchronization responses were longest when the longer P_1-P_3 value was presented and were most variable in either this condition or when no P_3 was presented. This pattern of synchronization latencies and variances was affected by the change in P_1-P_3 MP. As P_1-P_3 MP increased, the synchronization latency on "no P_3" trials increased, so that these trials produced the longest latency when P_1-P_3 MP = 285. This difference in synchronization latency between the three types of trials decreased with practice with P_1-P_3 MP = 285. Similarly, synchronization variance on "no P_3" trials increased more than did the variance on trials when P_3 was present as P_1-P_3 MP increased. When P_1-P_3 MP = 285, synchronization variances were almost always largest when no P_3 was presented, and the differences between the variances on the three trial types was larger than it had been in the baseline condition, although overall synchronization variances were comparable. Thus, with an increase in P_1-P_3 MP, the synchronization responses on the trials when no P_3 was presented showed a larger increase in mean and variance than did those on trials when the two values of P_1-P_3 were presented.

It is possible that, if P_1-P_3 MP had continued to increase, a point would have been found where the end of the deterministic internal synchronization timing interval (d) could be used to perform the duration discrimination, resulting in greatly improved performance. However, because the changes that were made in P_1-P_3 MP were so disruptive to duration discrimination performance, this manipulation was discontinued and P_1-P_3 MP was returned to the baseline level of 240 msec.

Experiment 1B: P_1-P_3 MP = 240 msec.; P_1-P_2 gradually decreased.

Method

The P_1-P_3 MP, the midpoint of the possible P_1-P_3 durations, was 240 msec. throughout this experiment. The value of ΔD was also constant throughout: 20 msec. for JB and 16 msec. for GTH. The P_1-P_2 synchronization interval, which had previously always been 460 msec., was decreased by 5 msec. during each succeeding experimental session. The P_1-P_2 interval remained constant throughout each session. For JB, P_1-P_2 was decreased from 460 msec. to 290 msec. in 36 sessions and then was increased to 335 msec. in six sessions. For GTH, P_1-P_2 was decreased from 460 msec. to 360 msec. in 22 sessions and then was returned to 460 msec. in 20 sessions. On a few occasions, two sessions were run at a particular value of P_1-P_2. When P_1-P_2 was decreasing, changes in P_1-P_2 between sessions were always 5 msec. However, when P_1-P_2 was increasing, some of the steps between successive sessions were 10 msec. The exact sequence of conditions is clear in Figures 14-17, which show the results of this experiment. During block 1 of each session, P_1-P_3 = 240 msec. on one half of the trials and no P_3 was presented on the remaining trials. Only the synchronization response was required. During the remaining three blocks, no P_3 was presented on one third of the trials, and each of the two P_1-P_3 values were presented on one third of the trials. Both synchronization and duration discrimination responses were required on each trial, as in the baseline condition.

Results

Estimates of q and $\overline{C}$ as a function of P_1-P_2 interval are shown in Figure 14 for GTH and in Figure 15 for JB. GTH's q estimates were stable and were little affected by changing P_1-P_2 until P_2 was close to P_3. Discrimination was disrupted when P_2 approached P_3 and was quickly restored when P_1-P_2 was increased. Estimates of $\overline{C}$ for the sessions shown in Figure 14 were never more than 5 msec. from the P_1-P_3 MP (240 msec.). Estimates of $\overline{C}$ did not vary systematically with changes in P_1-P_2. In Figure 15, it can be seen that JB's discrimination performance improved as the P_1-P_2 interval was decreased. However, as P_2 approached within 100 msec. of P_1-P_3 MP, discrimination performance deteriorated. Performance improved again when P_1-P_2 was increased. The estimates of $\overline{C}$ for JB also showed no systematic variation with changes in P_1-P_2.

No value of P_1-P_2 was found at which discrimination performance was markedly superior to that at other P_1-P_2 values. Michaels (1977) showed that the central arrival time of a countermanding stimulus is near the mean of the hypothesized distribution of response triggers in a synchronization task when the countermanding stimulus occurs slightly less than 120 msec. before the recorded synchronization response. In Experiment 1B, the P_3-P_2 interval became 120 msec. or less for both Ss. At the shortest P_1-P_2 intervals, it is unlikely that the midpoint of the central arrival times of the P_3 stimuli were occurring before the end-point of d, the internal synchronization timing interval. It had been hypothesized that the end-point of d could be used as a criterion to produce "virtually perfect" duration discrimination. In Experiment

Figure 14. Estimates of q and $\overline{C}$ as a function of P_1-P_2 interval in Experiment 1B. Subject GTH. Filled circles: decreasing P_1-P_2; open circles: increasing P_1-P_2. Asterisks denote values which are the average of two sessions at one value of P_1-P_2. Circled asterisks apply to increasing P_1-P_2.

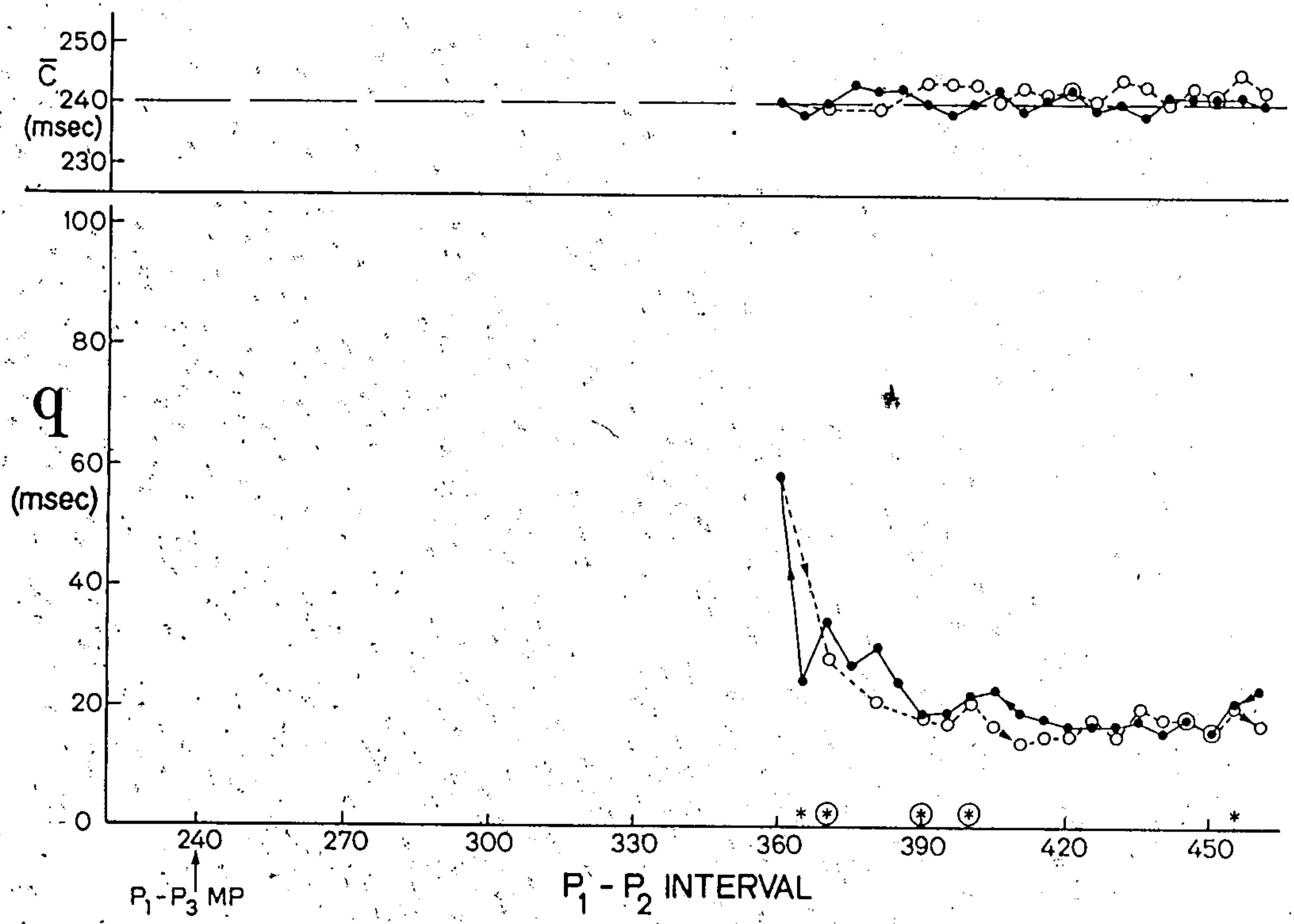
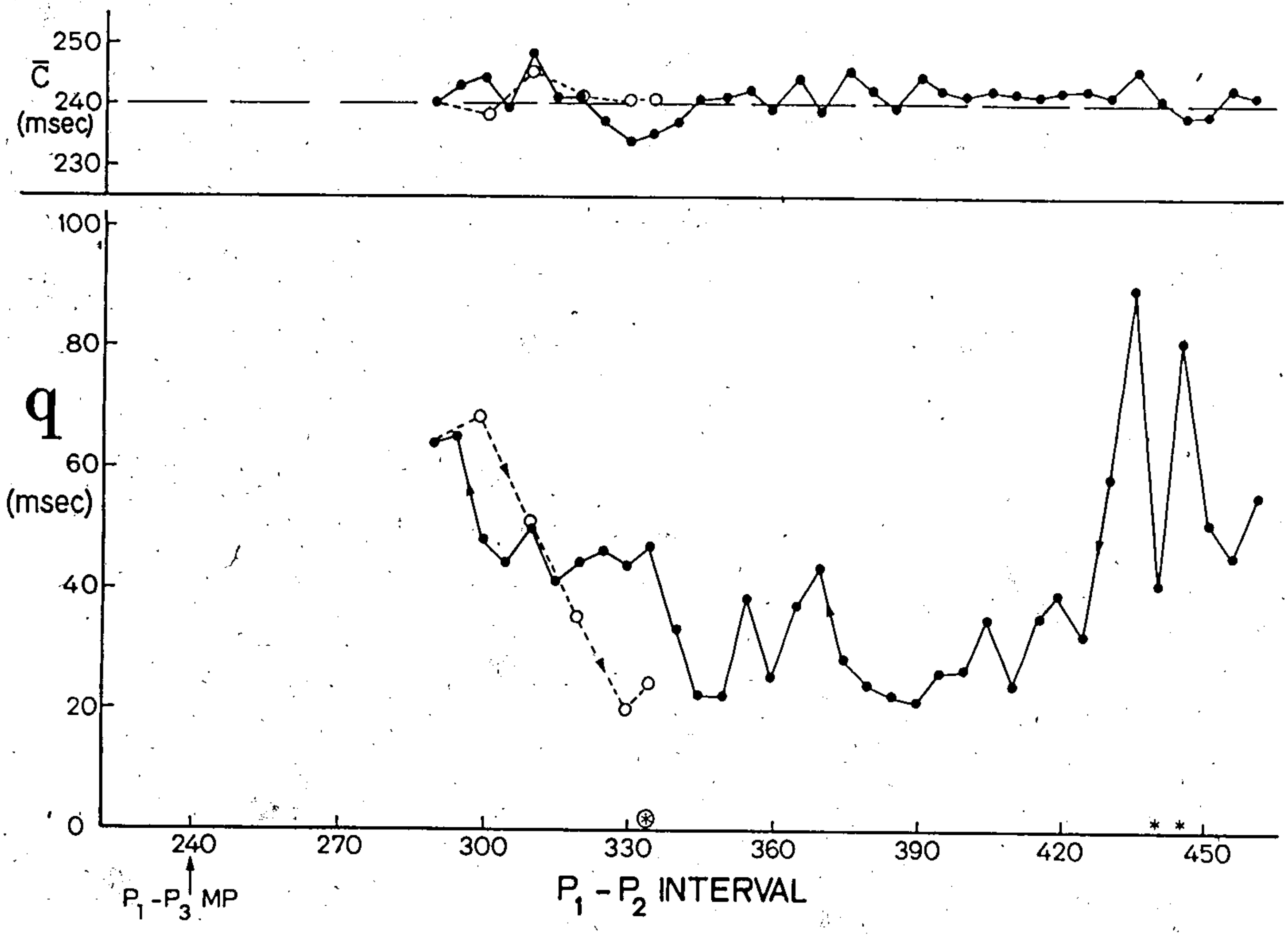

250
$\bar{C}$
240
(msec)
230
100
80
q
60
(msec)
40
20
0
240
270
300
330
360
390
420
450
P_1-P_3 MP
P_1-P_2 INTERVAL
*
⊛
⊛
⊛
*

Figure 15. Estimates of q and $\overline{C}$ as a function of P_1-P_2 interval in Experiment 1B. Subject JB. Filled circles: decreasing P_1-P_2; open circles: increasing P_1-P_2. Asterisks denote values which are the average of two sessions at one value of P_1-P_2. Circled asterisks apply to increasing P_1-P_2.



$\bar{C}$
(msec)
250
240
230
q
(msec)
100
80
60
40
20
0
240
270
300
330
360
390
420
450
$P_1 - P_3$ MP
$P_1 - P_2$ INTERVAL
* *

1B, d was shortened enough that its end-point probably came very near to the duration discrimination criterion. However, no dramatic improvement in duration discrimination performance was observed.

It is interesting to note that, as P_1-P_2 was decreased, the P_3-P_2 interval became much shorter than the P_1-P_3 interval and Ss could have used the P_3-P_2 interval as a basis for the duration discrimination. However, there is no evidence that Ss used this strategy in this experiment. Another experimental manipulation, to be described later, specifically tested for the use of this strategy.

Synchronization performance as a function of P_1-P_2 interval is shown in Figure 16 for GTH and in Figure 17 for JB. Although there is a very slight trend toward an increase in variance as P_1-P_2 decreased for both Ss, synchronization variance was relatively unaffected by changes in P_1-P_2. This confirms previous findings that the synchronization interval can be changed without disrupting performance and that the synchronization variance is independent of mean synchronization latency for this range of synchronization latencies (Hopkins and Kristofferson, 1980; Kristofferson, 1976). The mean response latency closely followed P_2 as it changed.

During Experiment 1B, JB thought that the duration discrimination task felt easiest when the P_1-P_2 interval was 340 msec. In fact, it was after P_1-P_2 decreased below this value that her discrimination performance worsened. However, the estimate of q when P_1-P_2 = 340 msec. was not lower than at some other values of P_1-P_2. When P_1-P_2 is 340 msec., the P_1-P_3 MP is 100 msec. before P_2. This value is near to that by which a countermanding stimulus must precede P_2 to prevent half of the responses in a synchronization task (Michaels,

Figure 16. Synchronization performance as a function of P_1-P_2 in Experiment 1B. Subject GTH. i: decreasing P_1-P_2; ii: increasing P_1-P_2. Filled circles: overall synchronization performance; open circles: no P_3; filled triangles: P_3 = 232 msec.; open triangles: P_3 = 248 msec. Asterisks denote values which are the average of two sessions at one value of P_1-P_2..

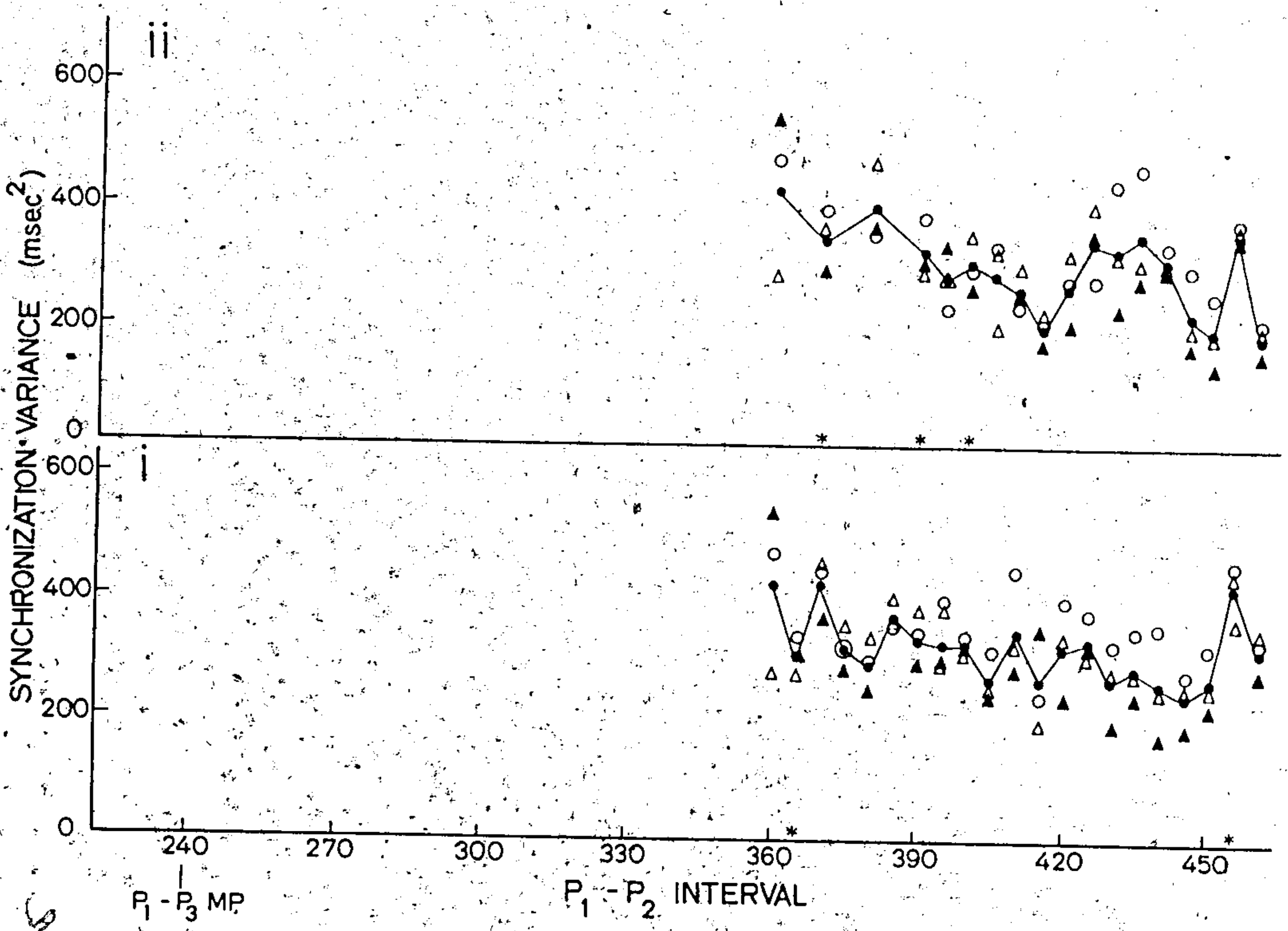
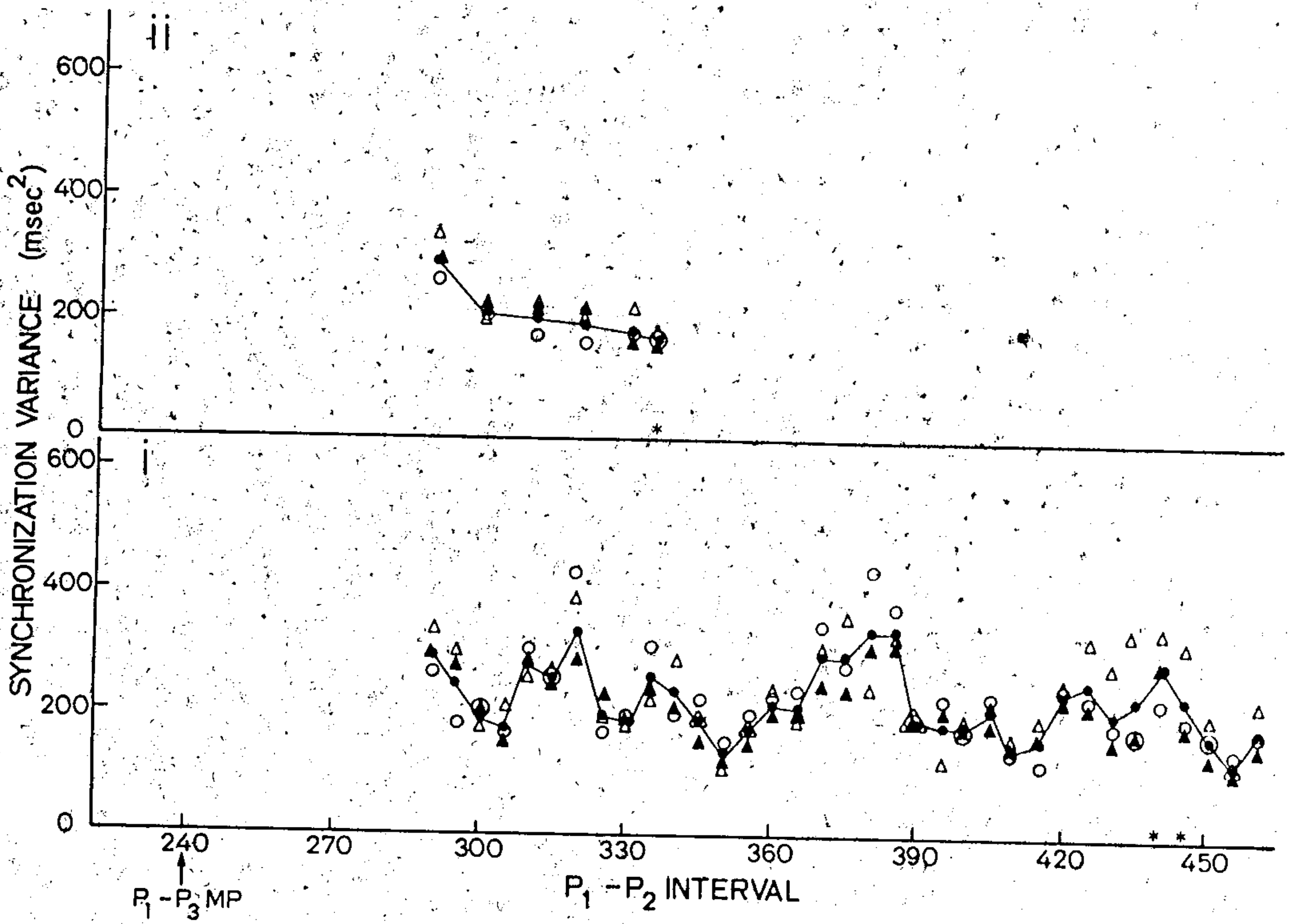

ii
i
SYNCHRONIZATION • VARIANCE (msec^2)
600
400
200
0
240
270
300
330
360
390
420
450
$P_1 - P_3$ MP
$P_1 - P_2$ INTERVAL

Figure 17. Synchronization performance as a function of P_1-P_2 in Experiment 1B. Subject JB. i: decreasing P_1-P_2; ii: increasing P_1-P_2. Filled circles: overall synchronization performance; open circles: no P_3; filled triangles: P_3 = 230 msec.; open triangles: P_3 = 250 msec. Asterisks denote values which are the average of two sessions at one value of P_1-P_2.


ii
i
SYNCHRONIZATION VARIANCE (msec^2)
600
400
200
0
240
270
300
330
360
390
420
450
$P_1 - P_3$ MP
$P_1 - P_2$ INTERVAL

1977). Thus, when P_1-P_2 = 340 msec., the end-point of d, the internal time interval produced to perform the synchronization task, could be very near $\overline{C}$, the mean duration discrimination criterion. If this were the case, it might be possible to improve duration discrimination performance by first making the discrimination very easy and then gradually "closing in on" $\overline{C}$ and the end-point of d. This was the aim of Experiment 1C.

Experiment 1C: decreasing ΔD.

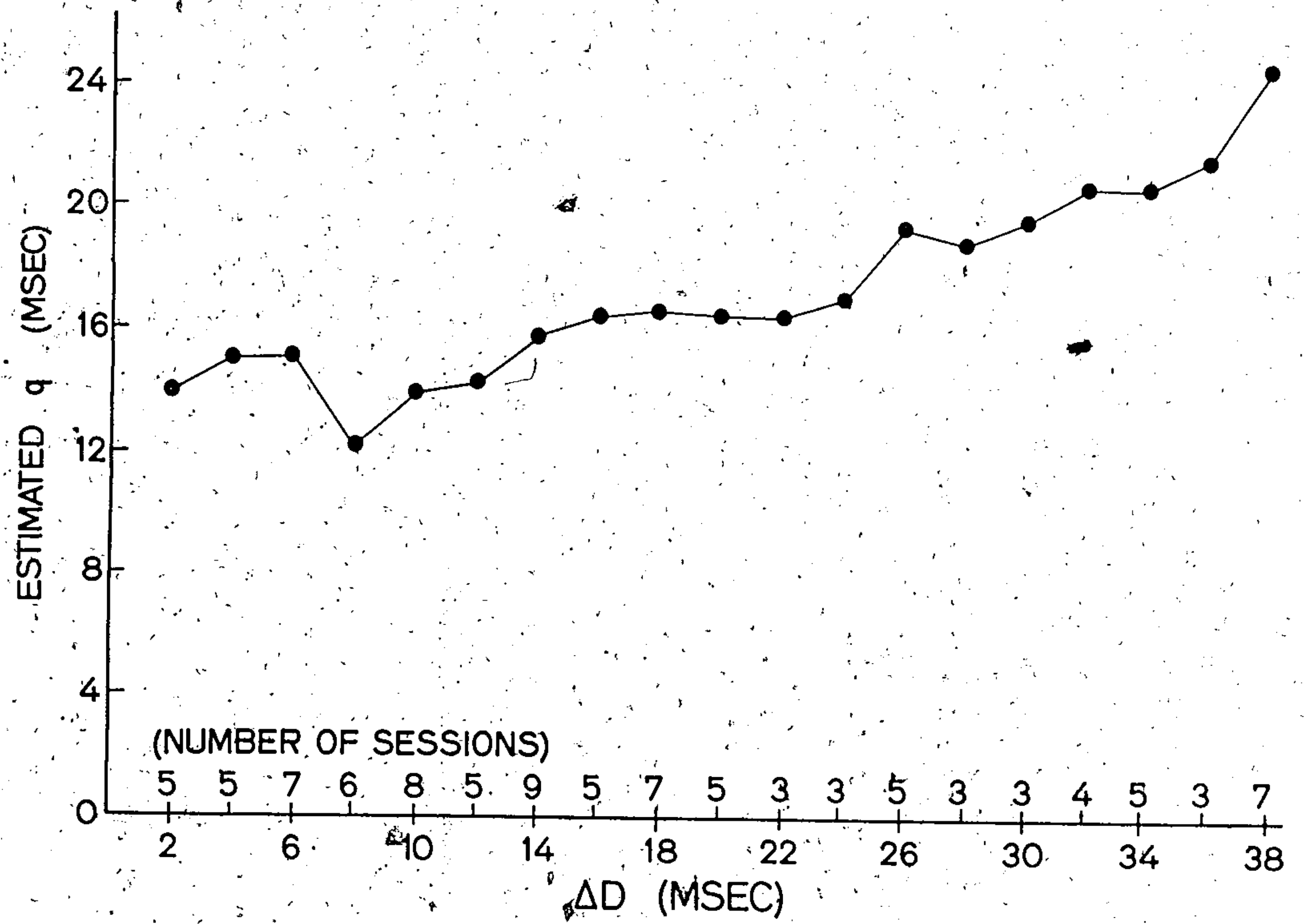
Method

Throughout this experiment, P_1-P_2 = 340 msec. and P_1-P_3 MP = 240 msec. The difference between the two possible values of P_1-P_3 in each session, ΔD, was initially 40 msec. That is, the two possible P_1-P_3 durations were 220 and 260 msec. After several sessions with one value of ΔD, this value was decreased by 2 msec. in each successive group of sessions until a ΔD value of 2 msec. was reached. For each value of ΔD, between three and nine sessions were run before ΔD was decreased by another 2 msec. The exact number of sessions run with each value of ΔD is shown in Figure 18, which shows the discrimination results for this experiment. ΔD was always constant throughout each session. A total of 106 sessions were run in this experiment. During block 1 of each session, P_1-P_3 = 240 msec. on one half of the trials and no P_3 was presented on the remaining trials. Only the synchronization response was required. During the remaining three blocks, no P_3 was presented on one third of the trials, and each of the two possible P_1-P_3 values was presented on one third of the trials. Both synchronization and duration discrimination responses were required on each trial, as in the baseline condition. Subject JB served in this experiment.

Results

Figure 18 shows estimates of q as a function of ΔD. Although the results are plotted against an increasing ΔD, it should be noted that, in the experiment, ΔD was successively decreased. That is, the temporal order of sessions is from right to left in Figure 18. No data are presented for $\Delta D = 40$ as, in this condition, no errors were made when $P_1-P_3 = 260$ msec ("long" response), so q could not be estimated. The q estimates in Figure 18 were calculated by combining the data across sessions at each ΔD value. That is, the errors from each session were added together and a single q value was calculated. Where the number of sessions run was greater than five, the data shown are from only the last five sessions run at that value of ΔD. It can be seen in Figure 18 that perfect discrimination ($q = 0$) was not achieved. If the discrimination criterion (C) were triangularly distributed, with a range of 2q msec., estimates of q would be constant for all values of ΔD within the range of C. In Figure 18, we can see that, although q is relatively constant for ΔD less than 24 msec., q does increase with ΔD at the larger ΔD values. If q were constant with a value of about 15 msec. (the average of the q estimates for ΔD less than 24 msec.), the q estimates should be constant for values of ΔD less than 30 msec. (the hypothetical range of C), which they are not. Since the values of ΔD were tested in consecutive descending order, the finding that q was an increasing function of ΔD could be due to practice. An alternative explanation of the finding that q increases with ΔD is that the duration discrimination stimulus is not processed on every trial. Estimates of q can be calculated when there is only one error for each value of P_1-P_3. When ΔD is large and P_3 falls outside the range of C, an estimate of q will result if S makes a few errors by accidentally pressing the wrong

Figure 18. Estimated q as a function of ΔD in Experiment IC. Subject JB. P_1-P_2 = 340 msec.; P_1-P_3 MP = 240 msec.


ESTIMATED q (MSEC)
0
4
8
12
16
20
24
(NUMBER OF SESSIONS)
5
5
7
6
8
5
9
5
7
5
3
3
5
3
3
4
5
3
7
2
6
10
14
18
22
26
30
34
38
ΔD (MSEC)

duration discrimination response button. If there were a constant small number of such errors, q estimates would increase as ΔD increases. Indeed, for $\Delta D > 26$ msec., JB never made more than five errors in any one session for any value of P_1-P_3. Each value of P_1-P_3 was presented on approximately 100 trials in each session. Thus, the increasing q at large values of ΔD would result if the P_1-P_3 stimulus was not processed on a small number of trials. That is, on some trials, errors occur which are not due to the duration discrimination mechanism (Allan & Kristofferson, 1974a). During this experiment, estimates of $\overline{C}$ were never more than 3 msec. from P_1-P_3 MP (240 msec.).

Figure 19 shows synchronization performance for JB during this experiment. The values shown in Figure 19 are averaged over the sessions run at each value of ΔD, using only the last five sessions when more than five sessions were run. Like Figure 18, the order in which sessions were run proceeds from right to left in Figure 19. Overall synchronization variance decreased during the course of the experiment, as ΔD was decreased. Overall mean latency was usually within 1 or 2 msec. of perfect synchrony (340 msec.). Figure 19 also shows clearly that synchronization responses were earliest and least variable when the shorter P_1-P_3 interval was presented, and responses were latest and most variable on the trials on which no P_3 was presented. The differences between the synchronization means and variances on the three types of trials (short P_1-P_3, long P_1-P_3, and no P_3) decreased as ΔD decreased. Figures 20 and 21 show the distributions of synchronization response latencies for the sessions where $\Delta D = 32$ msec. and $\Delta D = 4$ msec., respectively. The differences between the means and variances of the distributions for "long" and "short" P_1-P_3 values are larger when $\Delta D = 32$ msec. than when $\Delta D = 4$ msec. In both figures, the leading edges of

Figure 19. Synchronization performance as a function of ΔD in Experiment 1C. Subject JB. Filled circles: overall performance; open circles: no P_3; filled triangles: "short" P_3; open triangles: "long" P_3. P_1-P_2 = 340 msec.

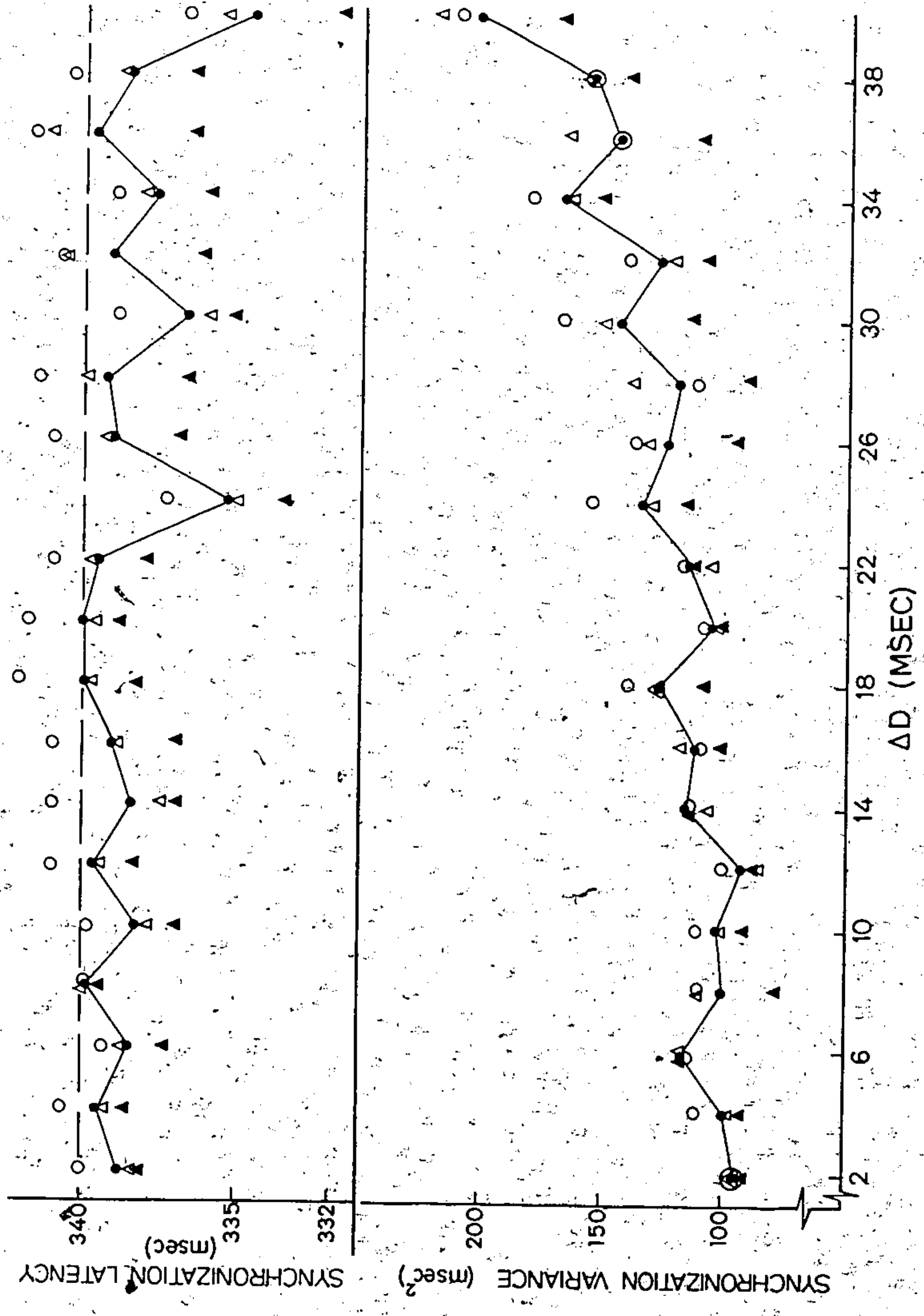

SYNCHRONIZATION LATENCY
(msec)
340
335
332
SYNCHRONIZATION VARIANCE
(msec²)
200
150
100
2
6
10
14
18
22
26
30
34
38
ΔD (MSEC)

Figure 20. Synchronization response latency distributions for $\Delta D = 32$ msec. in Experiment 1C. Subject JB. $P_1 - P_2 = 340$ msec. Filled triangles: $P_1 - P_3 = 224$ msec., $\overline{X} = 336$ msec., $S^2 = 108$ msec.^{2}, $N = 399$; open triangles: $P_1 - P_3 = 256$ msec., $\overline{X} = 341$ msec., $S^2 = 123$ msec.^{2}, $N = 402$; open circles: no P_3, $\overline{X} = 341$ msec., $S^2 = 141$ msec.^{2}, $N = 397$; overall: $\overline{X} = 339$ msec., $S^2 = 128$ msec.^{2}, $N = 1198$.

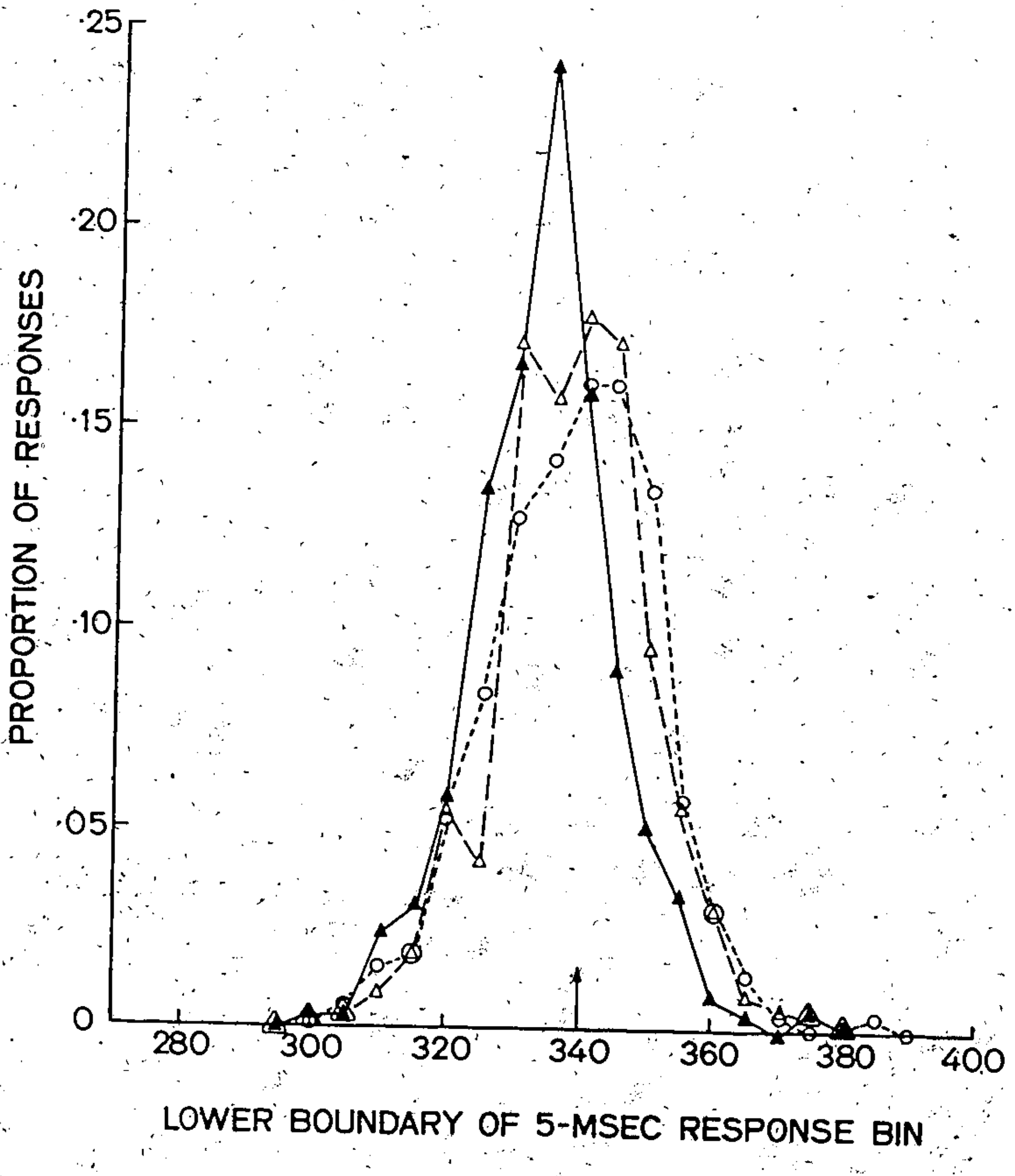
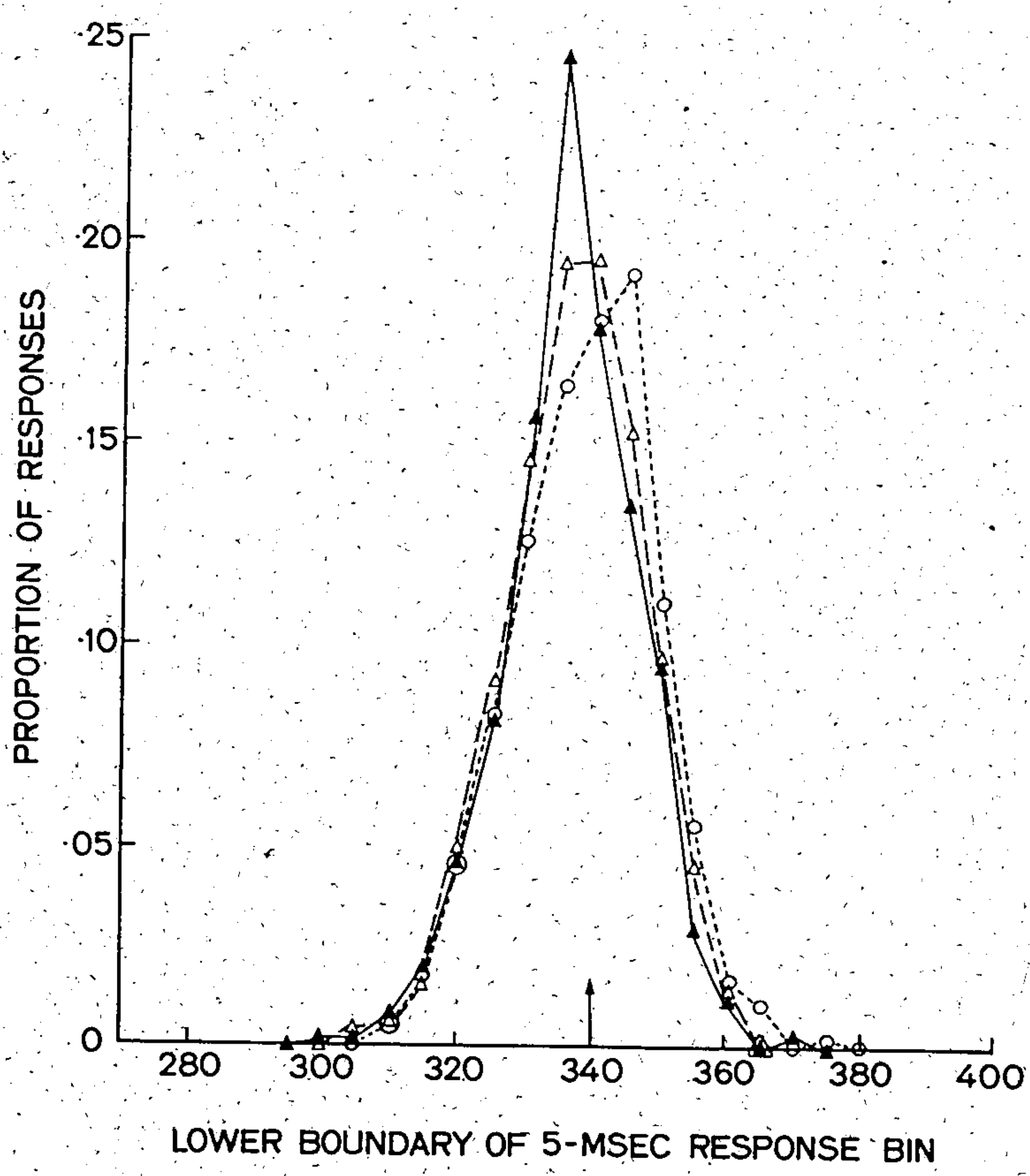

·25
·20
·15
·10
·05
0
PROPORTION OF RESPONSES
280
300
320
340
360
380
400
LOWER BOUNDARY OF 5-MSEC RESPONSE BIN

Figure 21. Synchronization response latency distributions for $\Delta D = 4$ msec. in Experiment 1C. Subject JB. $P_1-P_2 = 340$ msec. Filled triangles: $P_1-P_3 = 238$ msec., $\overline{X} = 338.6$ msec., $S^2 = 93$ msec.^{2}, $N = 503$; open triangles: $P_1-P_3 = 242$ msec., $\overline{X} = 339.2$ msec., $S^2 = 97$ msec.^{2}, $N = 499$; open circles: no P_3, $\overline{X} = 340.6$ msec., $S^2 = 110$ msec.^{2}, $N = 497$; overall: $\overline{X} = 339.5$ msec., $S^2 = 100$ msec.^{2}, $N = 1499$.


PROPORTION OF RESPONSES
.25
.20
.15
.10
.05
0
280
300
320
340
360
380
400
LOWER BOUNDARY OF 5-MSEC RESPONSE BIN

the distributions overlap; increased means and variances are due to a larger proportion of longer responses.

Discussion - Experiment 1

In Experiment 1, "virtually perfect" duration discrimination performance was not achieved. The P_1-P_3 MP must have been very near the end-point of d, the deterministic internal interval produced to perform the synchronization task (refer to Figure 2), in at least some of the experimental sessions. However, no pair of values of P_1-P_3 MP and P_1-P_2 was found for which duration discrimination performance was dramatically better than for other pairs of P_1-P_2 and P_1-P_3 MP values. Thus, Ss were apparently unable to use an invariant end-point of d as a criterion for perfect duration discrimination in the present experimental situation.

There is evidence that a deterministic d interval was set up in Experiment 1. Synchronization response latency distributions had low variance and were triangular in shape, like those previously found in experiments on synchronization alone (Hopkins & Kristofferson, 1980; Kristofferson, 1976). In Experiment 1B, synchronization performance did not suffer when P_1-P_2 was changed between sessions and the synchronization variance was constant throughout the range of P_1-P_2 values used. The synchronization variance was influenced by the P_1-P_3 duration discrimination interval, but it was independent of the P_1-P_2 synchronization interval. The fact that the duration of the synchronization interval can be changed without affecting the variance suggests that an invariant timer forms part of the synchronization chain (Kristofferson, 1976), although the effect of P_3 shows that a single deterministic interval cannot entirely account for the observed behaviour. Because synchronization variance was independent of P_1-P_2 duration, the fact that Ss did not use a deterministic synchronization timer to perform the duration discrimination in Experiment 1 cannot be attributed to a failure to achieve deterministic timing for the synchronization task.

In Experiment 1, there is evidence that a deterministic interval d was generated, but an invariant criterion was not used to perform duration discrimination. Thus, at least one of the assumptions necessary for the use of an invariant C has been violated. The order of events in response-stimulus synchronization may be different from that illustrated in Figure 2, so that C is variable. Alternatively, Figure 2 may accurately represent the order of events, but the variable q components may not be separable from d, or variance may arise in the discrimination of the temporal order of β_{P_3} and C. The results do not allow us to distinguish which of these assumptions was violated.

As a result of Experiment 1, we can also reject the sequential model of performance in the dual synchronization-duration discrimination task. This model, illustrated in Figure 4, hypothesized that the triangularly distributed duration discrimination criterion forms part of the response-stimulus synchronization chain such that a second time interval, ending with the synchronization response trigger, is timed from C, the duration discrimination criterion. This model makes specific predictions about the relationship of discrimination performance to synchronization response variance, which were not supported in Experiment 1. The sequential model predicts that the psychometric variance found in the duration discrimination task will always be smaller than the synchronization variance. In Experiment 1, psychometric variance was not correlated with synchronization response variance. When the P_1-P_3 MP was moved in Experiment 1A, and when P_2 was moved in Experiment 1B, discrimination performance could be severely disrupted without affecting the synchronization variance. In Experiment 1C, both the psychometric variance for duration discrimination and the synchronization response variance decreased as ΔD was decreased. In addition, synchronization response latency distributions were latest and most variable on trials when no P_3 was presented and were shortest and least variable on trials when the "short" P_1-P_3 interval was presented, as the sequential model predicts. However, the fact that, in Experiments 1A and 1B, discrimination performance can show large fluctuations in variance without an accompanying change in synchronization performance, requires the conclusion that the timing mechanisms used to perform response-stimulus synchronization and duration discrimination are not entirely the same, at least in the present experimental situation. The independence of variance seen in the two tasks would certainly be evident if two separate timers were operating. However, the present results would be compatible with the use of a single timer, with changes in duration discrimination performance resulting from changes in the proportion of trials on which the stimuli are processed, or changes in the response selection mechanism.

The mechanisms used to perform response-stimulus synchronization and duration discrimination can operate concurrently in the present dual task situation. Duration discrimination performance in Experiment 1 was as good as, if not better than, that previously reported by other investigators using similar base durations (Divenyi & Danner, 1977;

Getty, 1975; Kristofferson, 1980; see Table 2). In addition, synchronization response variances were comparable to those previously reported (Hopkins & Kristofferson, 1980; Kristofferson, 1976; see Table 1). The results also confirmed previous findings (Hopkins & Kristofferson, 1980; Kristofferson, 1976; 1980) that a change in base duration is disruptive to duration discrimination performance while mean synchronization latency can be changed by small amounts, usually with no effect on performance.

Response-stimulus synchronization and duration discrimination may not be timed by the same mechanism when the two tasks are performed concurrently. In addition, both are performed adequately in the dual task situation. However, in the present experimental paradigm, the two tasks are not independent. Duration discrimination performance is disrupted when P_2 is very close to P_1-P_3 MP. In addition, synchronization responses are affected by the value of P_1-P_3, the duration discrimination interval, as is shown clearly in Figures 20 and 21, although this effect of P_3 on the internal synchronization interval did not influence its deterministic property.

Although Ss apparently did not use the end-point of d as a duration discrimination criterion in the present study, we cannot reject the hypothesis that duration discrimination is performed by generating a deterministic internal interval. If an invariant internal criterion were generated, duration discrimination would involve a temporal order discrimination between the criterion and the time of occurrence of the stimulus marking the end of the duration discrimination interval. Thus, perfect duration discrimination would not result unless the temporal order discrimination could be performed perfectly. An onset asynchrony of only a few milliseconds is required to discriminate correctly the order of presentation of two brief tones that differ in frequency (Efron, 1973; Patterson & Green, 1970). However, judging the temporal order of two stimuli in different modalities (auditory and visual) requires a larger time difference between the stimuli (Allan, 1975). If all the psychometric variance in duration discrimination in Experiment 1 were attributed to an order discrimination mechanism, the temporal order discrimination performance is usually much better than that for bimodal stimuli but not quite as good as that for tones of different frequency. For example, in Experiment 1B, when P_1-P_2 > 390 msec., the estimate of q for subject GTH averaged about 17 msec. with a ΔD of 16 msec. (see Figure 14). If we assume that a deterministic internal criterion is located midway between the two possible values of P_1-P_3, GTH's performance would mean that he was correctly discriminating the order of two events (β_{P_3} and the criterion), 8 msec. apart, 86% of the time. There is some subjective evidence from Experiment 1 that indicates that C may function like a stimulus. Both JB and GTH began to "hear" the criterion on trials when no P_3 was presented. JB experienced a distinct auditory sensation at the time when P_3 was expected, and GTH sometimes reported difficulty in deciding whether or not P_3 had occurred, although he rarely made a duration discrimination response when no P_3 had been presented. Indeed, Ss often reported that the subjective duration discrimination task involved discriminating between two qualitatively different sensory experiences, each associated with a particular P_1-P_3 value, rather than deciding on the duration of P_1-P_3. This is similar to the phenomenological report of Ss discriminating the order of two brief tones (Patterson & Green, 1970). The two different orders produce sensations that can be qualitatively discriminated rather than a perception of one tone having occurred before the other. Therefore, although Experiment 1 showed that the duration discrimination task does not form part of the synchronization S-R chain, we cannot reject the hypothesis that Ss performed the duration discrimination by producing a deterministic internal interval. The psychometric variance could arise from the temporal order decision mechanism rather than from a timing mechanism. Of course, the design of the dual task in the present experiment does not prevent Ss from using an interval measure strategy, or some complex aspect of the overall P_1-P_3-P_2 stimulus pattern, to perform the duration discrimination.

In the present experimental paradigm, the variance in the duration discrimination task could arise from a criterion distribution, or from variation due to the discrimination of the temporal order of β_{P_3} and an invariant criterion. However, the real-time criterion theory of duration discrimination (Kristofferson, 1977) assumes that β, the central arrival time of the stimulus ending the discrimination interval, and C are perfectly discriminated, and this theory fits Kristofferson's data very well. Kristofferson used speeded duration discrimination responding, which may result in the use of a duration discrimination strategy different from that used in the dual task situation, where duration discrimination responses are delayed. However, because of the success of the real-time criterion theory of duration discrimination, it is probably more reasonable to attribute the present duration discrimination variance to a variation in C, although there is not yet sufficient evidence to entirely reject the hypothesis that duration discrimination could be performed by the production of an invariant internal criterion.

Experiment 2: Variable ΔD

In Experiment 1, "virtually perfect" duration discrimination performance was not achieved. However, the simultaneous performance of both response-stimulus synchronization and duration discrimination tasks did show that the two tasks are probably not performed by the same timing mechanism. In addition, the interpolation of the duration discrimination task had systematic effects on synchronization response latency distributions. In order to study further the effect of the value of P_1-P_3 on synchronization, and to examine the form of the distribution of the duration discrimination criterion, an experiment was conducted in which ΔD covered a wider range of values than had previously been studied, and took on more than one value within each experimental session.

Method

Subjects JB and GTH served in this experiment. The synchronization intervals throughout the experiment were: $P_1-P_2 = 340$ msec. for JB and $P_1-P_2 = 460$ msec. for GTH. For duration discrimination, the P_1-P_3 MP was always 240 msec. for both Ss. There were 21 possible values of ΔD, ranging from 2 to 42 msec. in steps of 2 msec. These were divided into three groups of seven values each: small - 2 to 14 msec.; medium - 16 to 28 msec.; large - 30 to 42 msec. During each session, three values of ΔD were used, one selected from each of these groups. Thus, on any trial, P_1-P_3 could take on one of six possible values. Each of the six values was equally likely to occur. In addition, no P_3 was presented on one-seventh of the trials. Ss ran a total of 35 sessions in the experiment, so that they were exposed to each ΔD value in five sessions. Each time a particular ΔD value was used, it was combined with different values of ΔD from the other two groups, as often as possible.

As in the previous experiments, no duration discrimination was required in block 1 of each session. P_3 occurred at the P_1-P_3 MP (240 msec.) on half of the trials and did not occur on the remaining trials. Ss were required to respond in synchrony with P_2 on every trial. In the remaining three blocks of each session, synchronization responses were made on every trial and duration discrimination responses were required whenever a P_3 stimulus was presented.

Results: Duration Discrimination

The probability of a "long" duration discrimination response, as a function of the P_1-P_3 interval, is shown in Figures 22 and 23 for subjects JB and GTH respectively. For both subjects, a monotonically increasing S-shaped function was obtained. The best-fitting cumulative triangular functions were determined for both sets of data. If the entire psychometric variance were due to a triangularly distributed criterion, there would be no discrimination errors for the extreme values of P_1-P_3. However, it was assumed that the duration discrimination stimulus is not processed on some proportion of the trials (Allan & Kristofferson, 1974b). That is, because of momentary inattention on some trials, S does not use the triangularly distributed criterion to determine whether the presented stimulus is "short" or "long." The proportion of trials processed by the theoretical

Figure 22. Probability of a "long" duration discrimination response as a function of P_1-P_3 interval in Experiment 2. Subject JB. Filled circles: data, approx. 214 trials per point; continuous line: best-fitting cumulative triangular function, corrected for non-processing. $K = 0.985$; $B = 0.62$; $q = 15.5$ msec.; $\overline{C} = 239.36$ msec.

Triangular distribution function:

$$P(\text{"Long"}) = \begin{cases} 0.0093 & P_1-P_3 < 223.86 \\ \dfrac{0.985(P_1-P_3)^2 - 441.00(P_1-P_3)}{480.5} + 102.74 & 223.86 \le P_1-P_3 \le 239.36 \\ \dfrac{502.07(P_1-P_3) - 0.985(P_1-P_3)^2}{480.5} - 132.18 & 239.36 < P_1-P_3 \le 254.86 \\ 0.9943 & P_1-P_3 > 254.86 \end{cases}$$

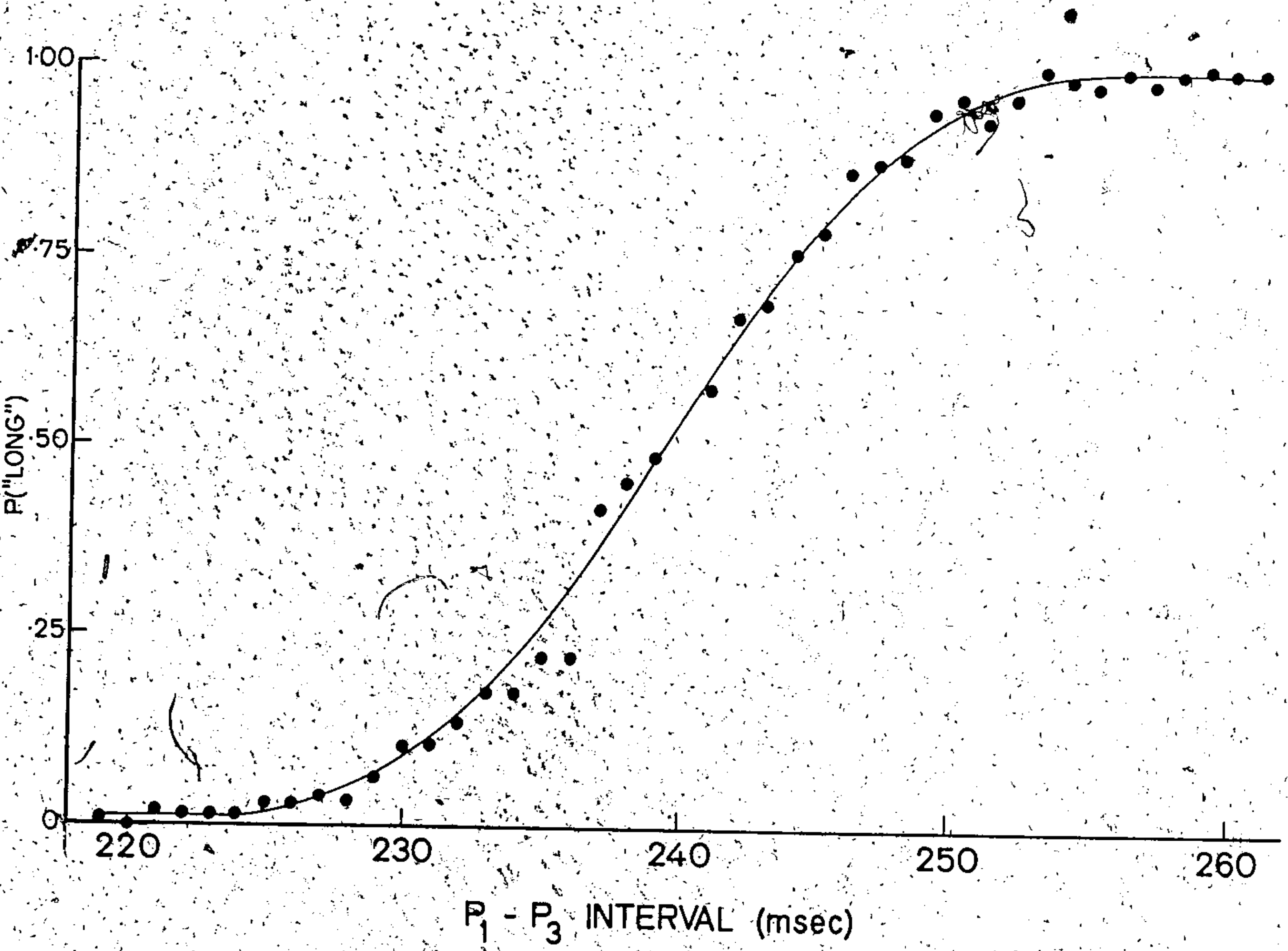
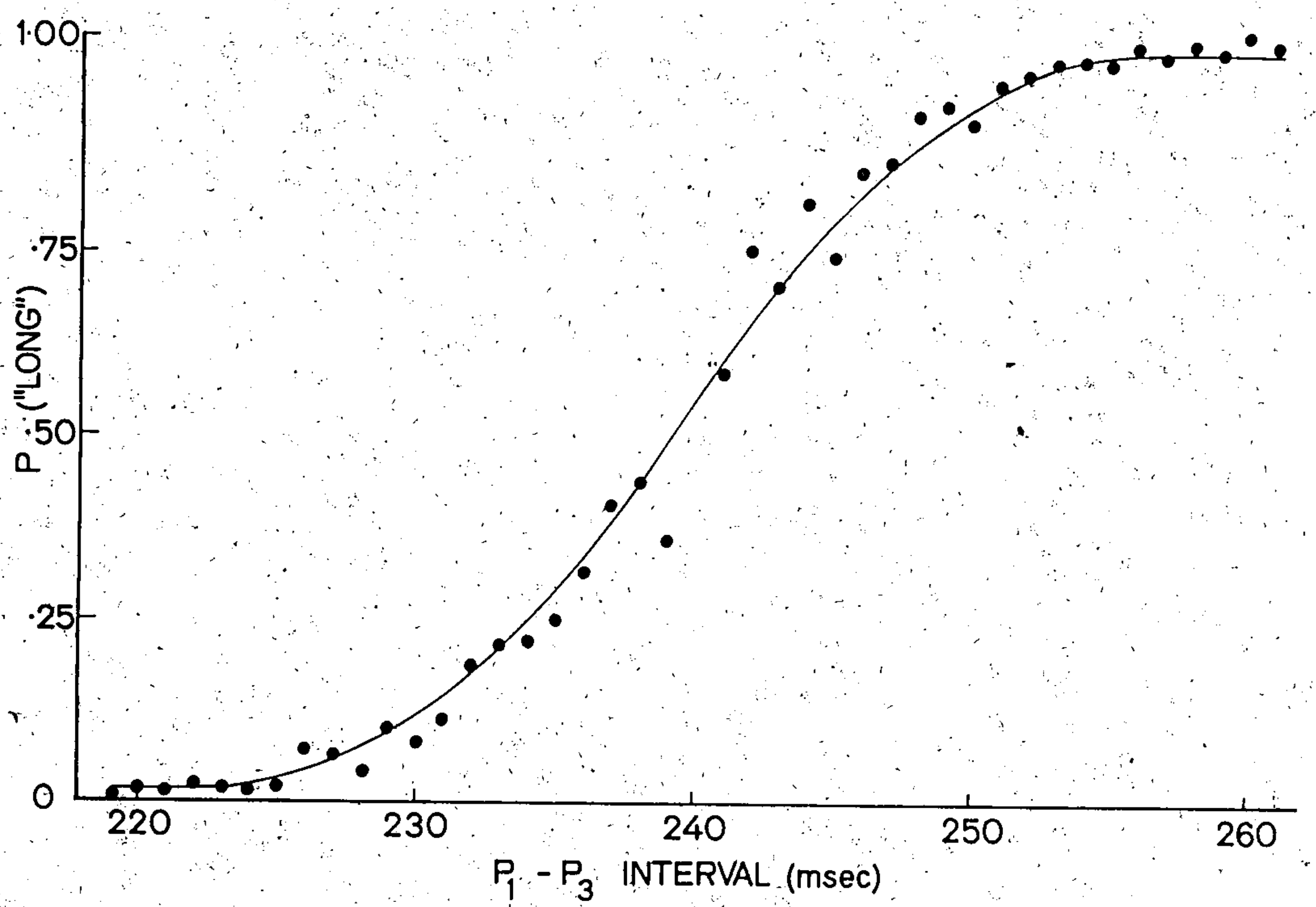

1.00
.75
.50
.25
0
P("LONG")
220
230
240
250
260
$P_1 - P_3$ INTERVAL (msec)

Figure 23. Probability of a "long" duration discrimination response as a function of P_1-P_3 interval in Experiment 2. Subject GTH. Filled circles: data, approx. 214 trials per point; continuous line: best-fitting cumulative triangular function, corrected for non-processing. $K = 0.960$; $B = 0.49$; $q = 17.1$ msec.; $\overline{C} = 239.57$ msec.

Triangular distribution function:

$$P(\text{"Long"}) = \left\{ \begin{array}{l|r} 0.0196 & P_1-P_3 < 222.47 \\[1em] \dfrac{0.96(P_1-P_3)^2 - 427.14(P_1-P_3)}{584.82} + 81.26 & 222.47 < P_1-P_3 < 239.57 \\[1em] \dfrac{492.81(P_1-P_3) - 0.96(P_1-P_3)^2}{584.82} - 107.20 & 239.57 < P_1-P_3 < 256.67 \\[1em] 0.9796 & P_1-P_3 > 256.67 \end{array} \right.$$


1·00
·75
·50
·25
0
P ("LONG")
220
230
240
250
260
P_1 - P_3 INTERVAL (msec)

triangular criterion is labelled K in Figures 22 and 23. The probability of making a "long" discrimination response on a trial on which the stimulus was not processed is labelled B. The q estimates (half the base of the best-fitting triangle) are 15.5 msec. and 17.1 msec. for JB and GTH respectively. The cumulative triangular distributions provide good fits to the data. However, JB's data were also fit with a normal distribution which fit almost as well as the triangular distribution. Details of this analysis are given in Appendix B. Thus, these duration discrimination data are consistent with a triangular distribution of the criterion, although they do not require this assumption.

The duration discrimination data of Figures 22 and 23 are presented in a different form in Figures 24 and 25. These Figures show q estimates as a function of ΔD in Experiment 2 for subjects JB and GTH respectively. The q estimates were obtained from the number of errors made at each value of P_1-P_3, assuming the stimulus is processed by the duration discrimination mechanism on every trial. As in Experiment 1C, the estimates of q are not constant across all values of ΔD. Estimates of q are an increasing function of ΔD, except for the smallest ΔD values for JB. In fact, the data in Figure 24 are almost exactly the same as those in Figure 18 (except for the three smallest values of ΔD), which represent JB's performance in Experiment 1C. In that experiment, JB was exposed to the ΔD values consecutively, from the largest to the smallest, and it was thought that the decreasing q estimates could be due to practice. However, as was noted in the discussion of Experiment 1C, non-processing of the duration discrimination stimulus on only a few trials would result in uncorrected q estimates that increase with ΔD,

Figure 24. Estimated q as a function of ΔD in Experiment 2. Subject JB. P_1-P_2 = 340 msec.; P_1-P_3 MP = 240 msec.

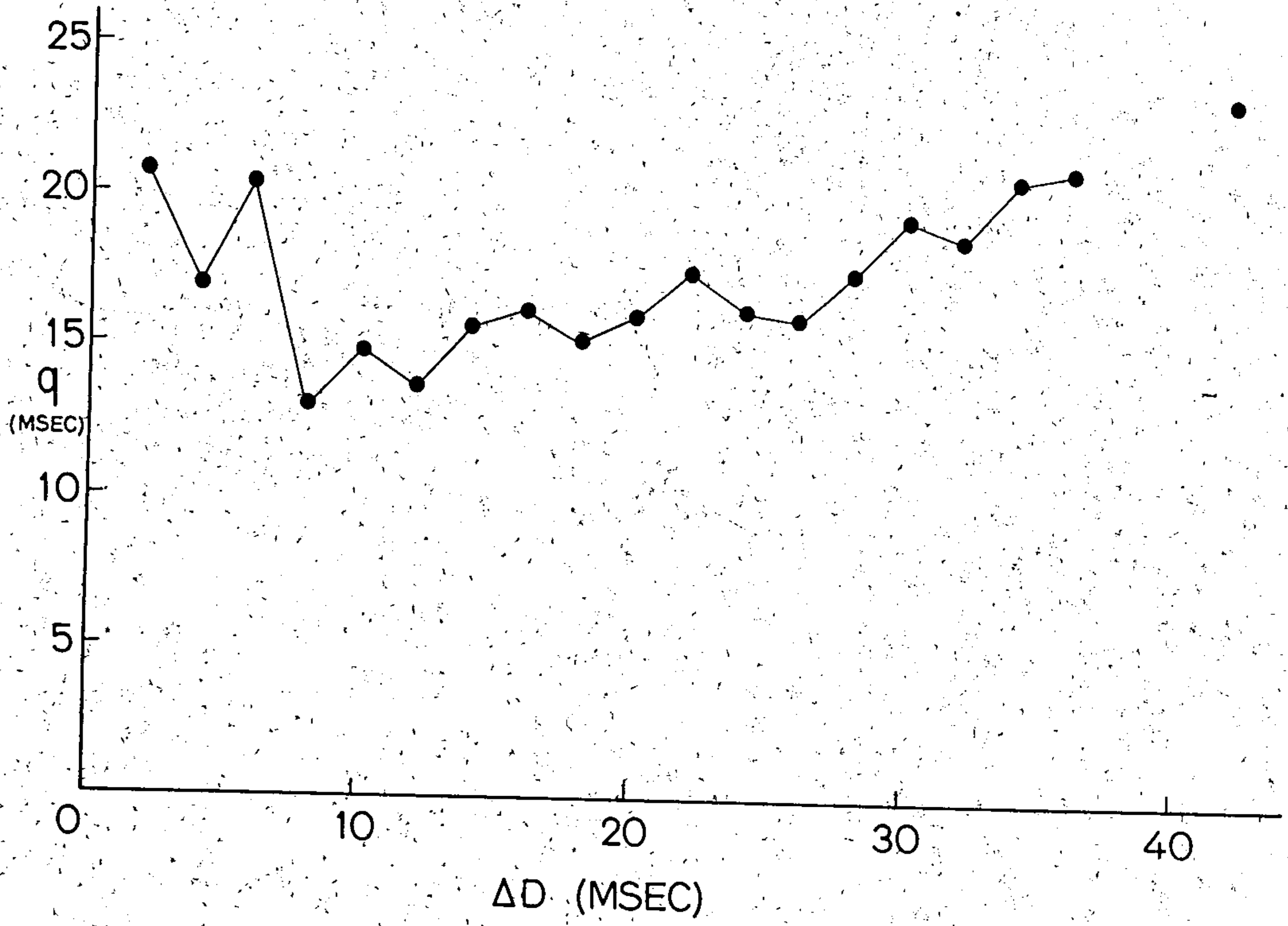
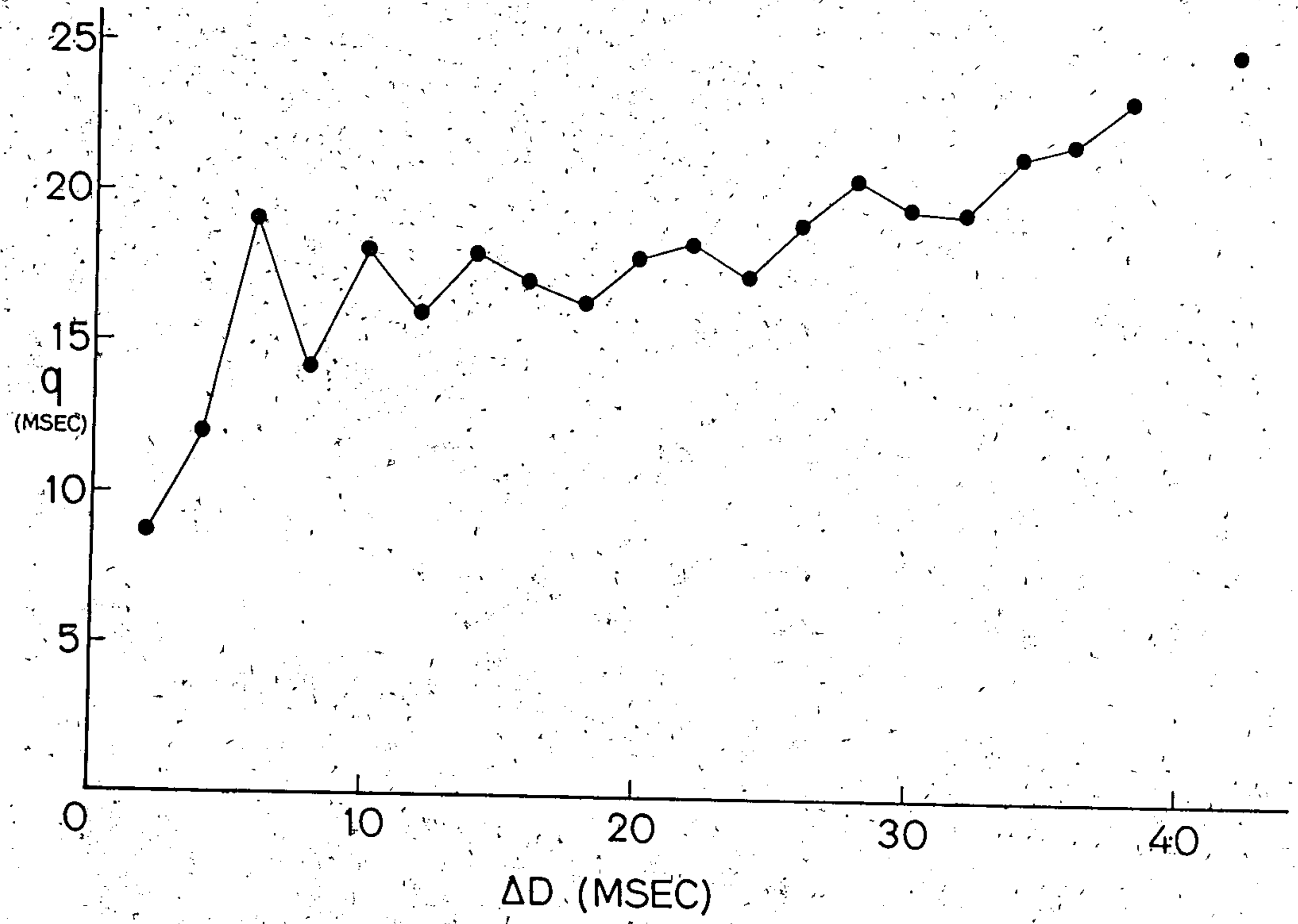

25
20
15
10
5
0
q
(MSEC)
10
20
30
40
ΔD (MSEC)

Figure 25. Estimated q as a function of ΔD in Experiment 2. Subject GTH. P_1-P_2 = 460 msec.; P_1-P_3 MP = 240 msec.


25
20
15
10
5
0
q
(MSEC)
10
20
30
40
ΔD (MSEC)

for large values of ΔD when P_3 would be outside the range of the distribution of C. The data of Figure 24 were collected about a year after the beginning of Experiment 1C, demonstrating very stable duration discrimination performance. GTH's data (Figure 23) show the same form as those of JB, except for the smallest ΔD values, where GTH's q estimates were very low. Thus, it appears that a triangularly distributed criterion, accompanied by the assumption that stimuli are not processed on a small proportion of the trials, provides a reasonable description of duration discrimination performance in the present dual task.

Results: Synchronization

The mean latency and variance of the synchronization responses, as a function of P_1-P_3 interval, are shown in Figures 26 and 27 for subjects JB and GTH respectively. Both mean and variance are increasing functions of the P_1-P_3 interval for both Ss, although the data, especially the variances, are quite variable. In fact, for JB, the synchronization variance when P_1-P_3 = 261 msec. is actually lower than when P_1-P_3 = 219 msec. Each point in Figures 26 and 27 represents performance on approximately 214 experimental trials. The data of Figures 26 and 27 are represented differently in Figures 28 and 29. In Figures 28 and 29, the mean latency and variance of the synchronization responses are shown as a function of ΔD for JB and GTH, respectively. In these Figures, which fold in half the functions shown in Figures 26 and 27, the synchronization performance for both the short and long P_1-P_3 values, for each value of ΔD, is shown. In addition, the means and variances of the synchronization responses on the trials on which no P_3

Figure 26. Synchronization performance as a function of P_1-P_3 interval in Experiment 2. Subject JB. P_1-P_2 = 340 msec. Approx. 214 trials per point.

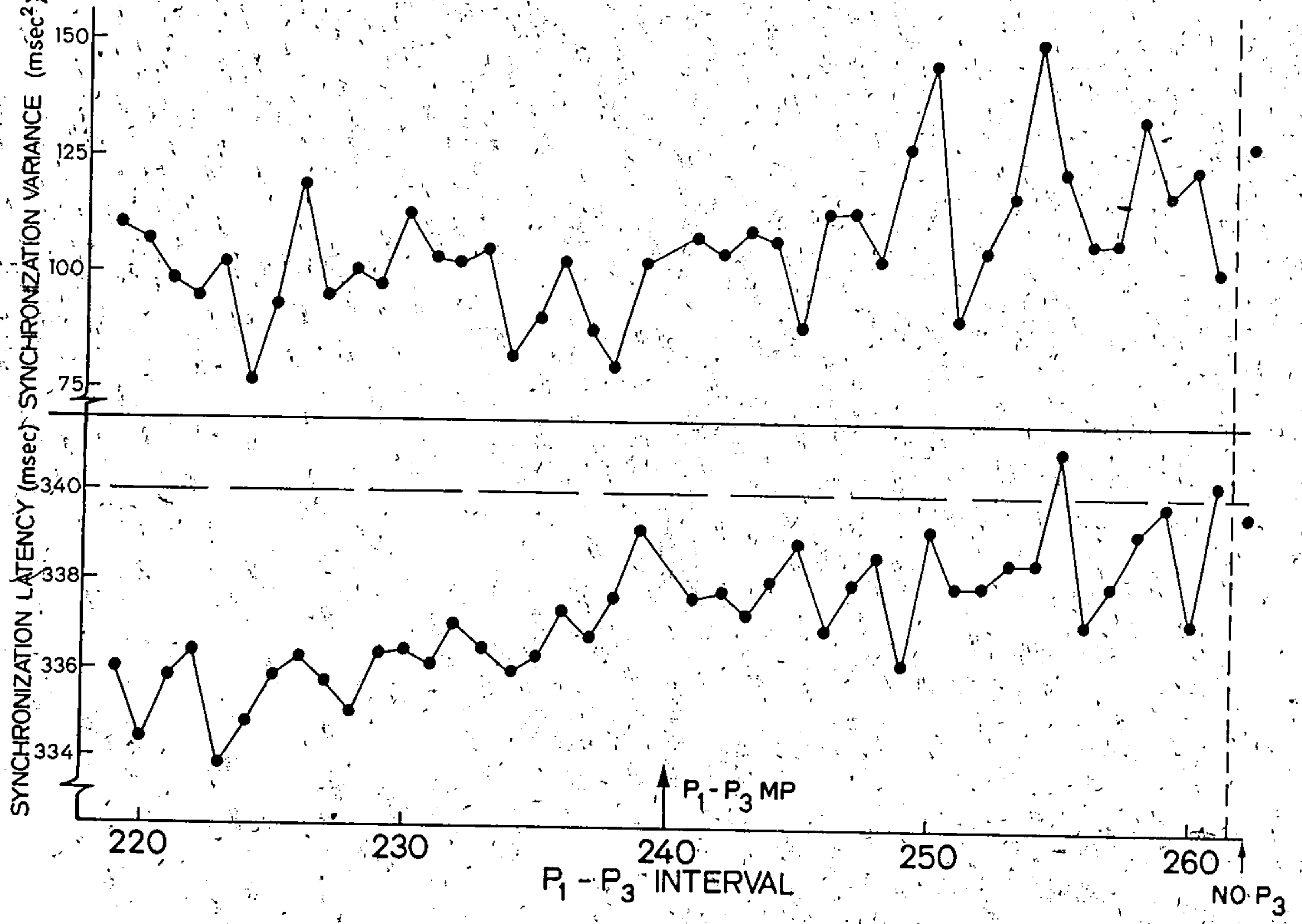

SYNCHRONIZATION VARIANCE (msec^2)
150
125
100
75
SYNCHRONIZATION LATENCY (msec)
340
338
336
334
$P_1 - P_3$ MP
NO P_3
220
230
240
250
260
$P_1 - P_3$ INTERVAL

Figure 27. Synchronization performance as a function of P_1-P_3 interval in Experiment 2. Subject GTH. $P_1-P_2 = 460$ msec. Approx. 214 trials per point.

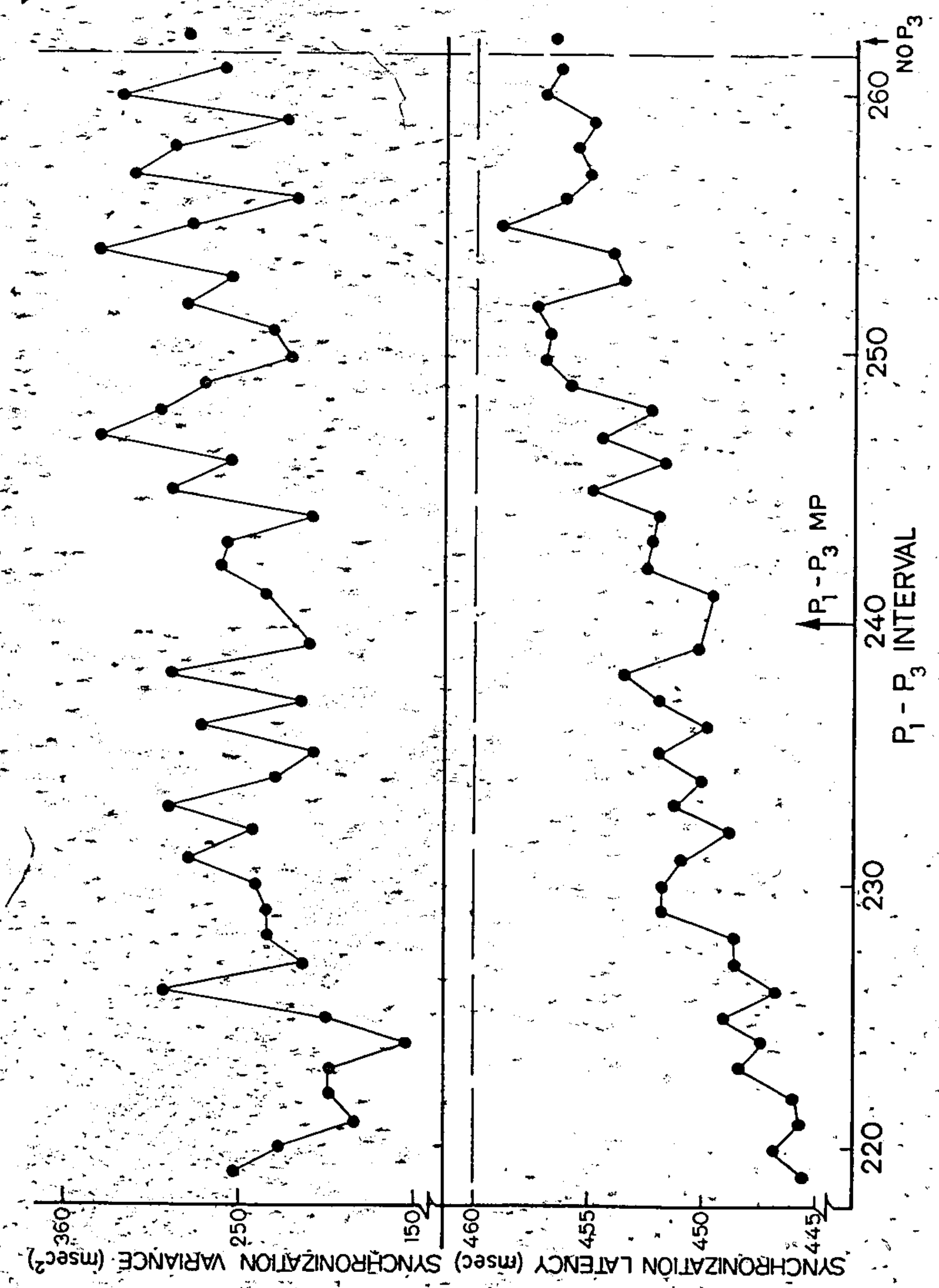

SYNCHRONIZATION LATENCY (msec)
SYNCHRONIZATION VARIANCE (msec²)
360
250
150
460
455
450
445
220
230
240
250
260
P1 - P3 INTERVAL
P1 - P3 MP
NO P3

Figure 28. Synchronization performance as a function of ΔD in Experiment 2. Subject JB. P_1-P_2 = 340 msec.; P_1-P_3 MP = 240 msec. Filled triangles: "short" P_1-P_3; open triangles: "long" P_1-P_3; open circles: no P_3.

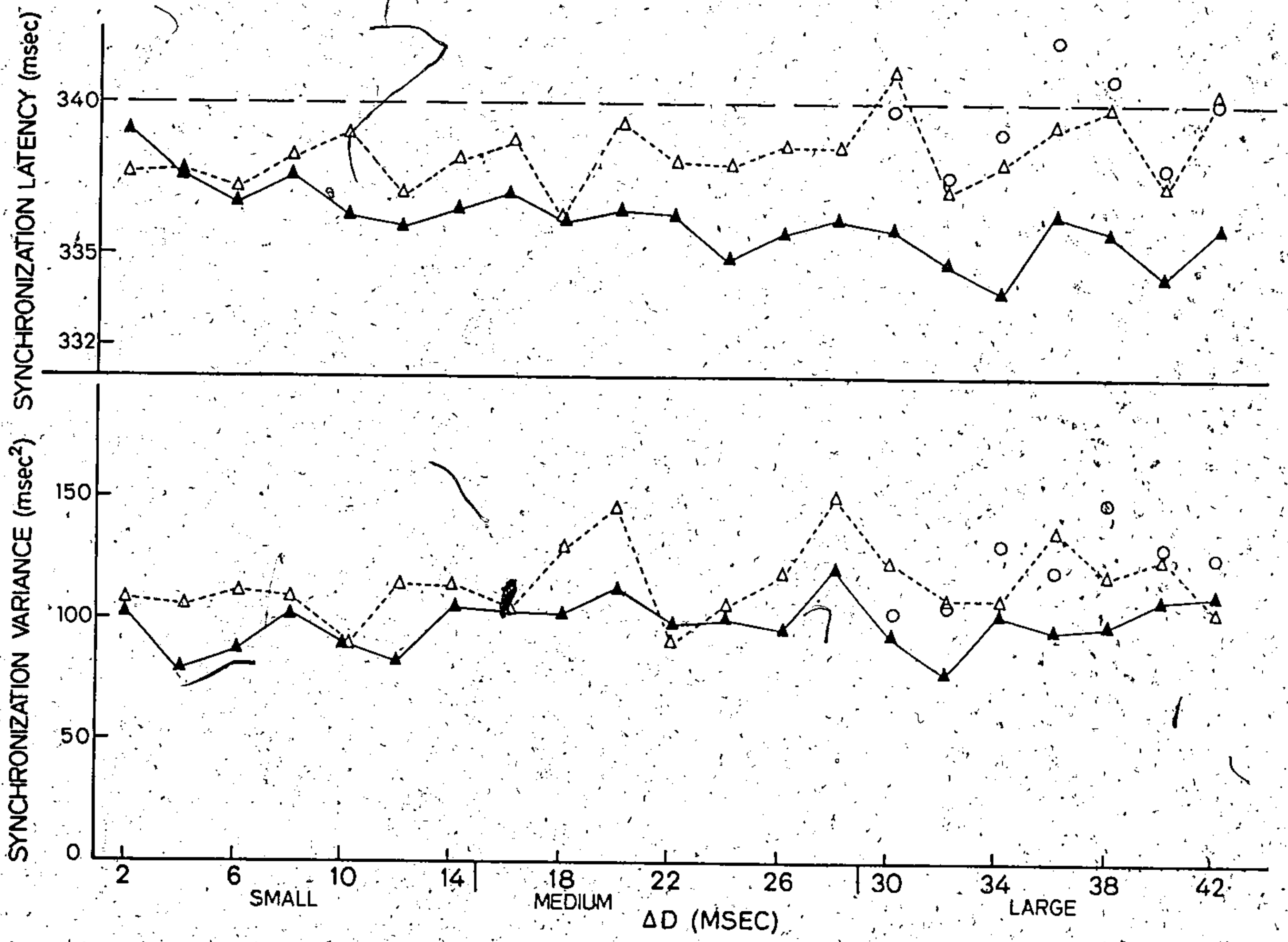
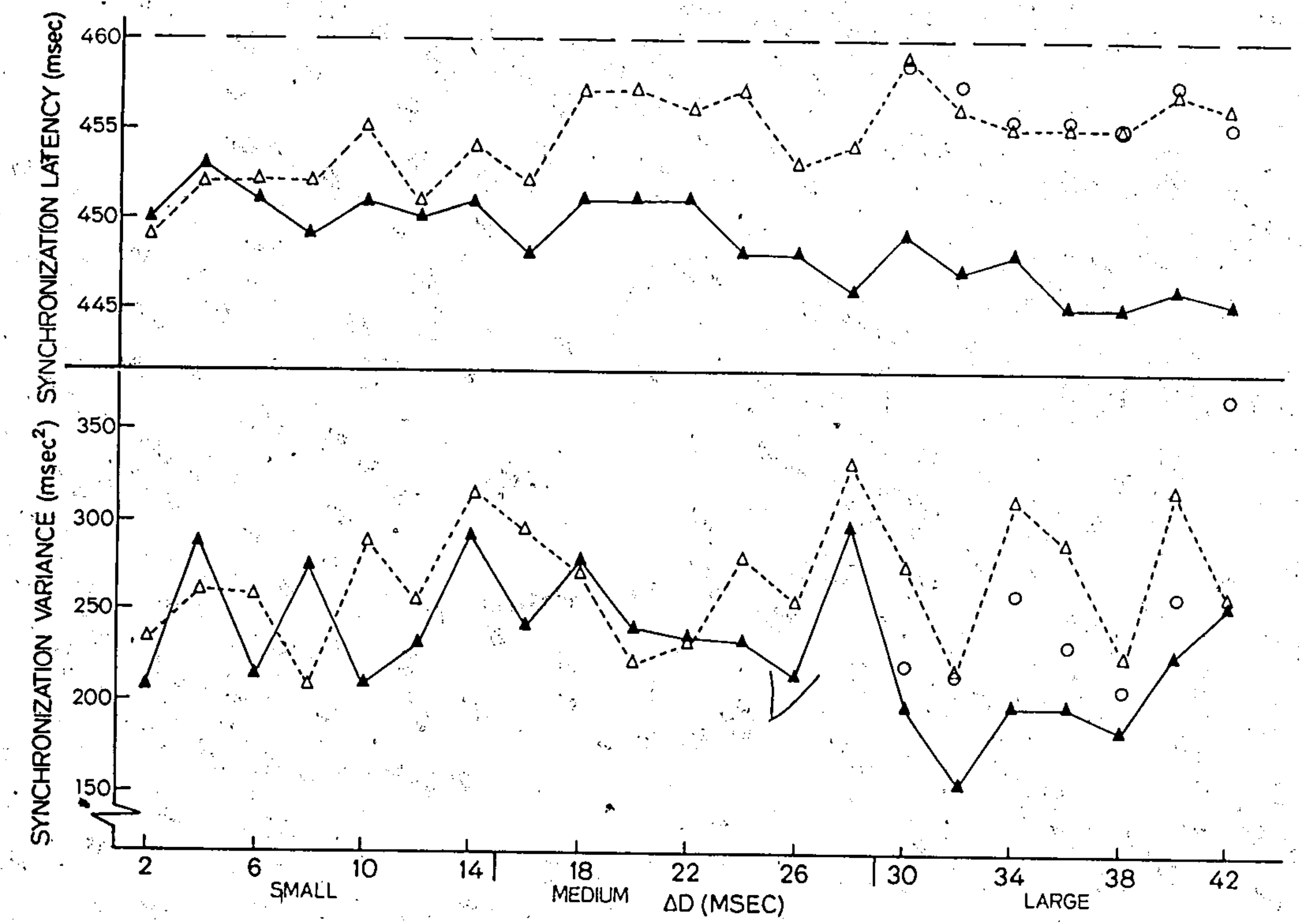

SYNCHRONIZATION LATENCY (msec)
340
335
332
SYNCHRONIZATION VARIANCE (msec²)
150
100
50
0
2
6
10
14
18
22
26
30
34
38
42
SMALL
MEDIUM
LARGE
ΔD (MSEC)

Figure 29. Synchronization performance as a function of ΔD in Experiment 2. Subject GTH. P_1-P_2 = 460 msec.; P_1-P_3 MP = 240 msec. Filled triangles: "short" P_1-P_3; open triangles: "long" P_1-P_3; open circles: no P_3.


SYNCHRONIZATION LATENCY (msec)
460
455
450
445
SYNCHRONIZATION VARIANCE (msec^2)
350
300
250
200
150
2
6
10
14
18
22
26
30
34
38
42
SMALL
MEDIUM
LARGE
ΔD (MSEC)

was presented are shown as a function of the largest ΔD value that was presented in each session. For each value of ΔD, the mean and variance of the synchronization responses are almost always larger for the longer P_1-P_3 value than for the shorter P_1-P_3 and the difference between the two means and variances increases as ΔD increases. The synchronization responses on the trials on which no P_3 was presented are very similar to those for the longer P_1-P_3 interval for each of the large values of ΔD.

Discussion

In Experiment 1, the hypothesis that the duration discrimination criterion formed a part of the S-R chain in response-stimulus synchronization in the dual task was rejected because duration discrimination performance could be severely disrupted while synchronization performance was little affected. In Experiment 2, the sequential model is contradicted by the fact that the differences between the synchronization response distributions for the long and short P_1-P_3 values, at each value of ΔD, are not as large as would be expected if the discrimination criterion were part of the synchronization chain. If a triangular duration discrimination criterion distribution with a range of 2q formed part of the synchronization chain of events, as illustrated in Figure 4, its effects should be clearly evident when β_{P_3} falls outside the range of C. For large values of ΔD the synchronization response latency distributions for each pair of P_1-P_3 values should differ in mean by the time between $\beta_{P_3 S}$ and $\overline{C}$, and in variance by the variance of C. That is, the entire distribution of C would be included in the distribution of synchronization responses when P_1-P_3 is "long", and no part of the distribution of C would be included when P_1-P_3 is "short". The overall q estimates in Experiment 2 were 15.5 and 17.1 msec. for subjects JB and GTH, respectively. Triangular distributions with bases of 31 and 34.2 msec. would have variances of 40.04 and 48.74 msec.^{2}, respectively. For JB, when $\Delta D > 31$ msec., the difference between the variances of the synchronization response latency distributions when longer and shorter P_1-P_3 values are presented, should be 40 msec.^{2} In Figure 28, it can be seen that only one difference (for $\Delta D = 36$ msec.) is this large. For GTH (see Figure 29), there are four values of $\Delta D > 34$ msec. For two of these (36 and 40 msec.), the difference in variance between the two synchronization response latency distributions is about 100 msec.^{2}, and for the other two values, the difference is much smaller than the 49 msec.^{2} predicted by the sequential model of the dual synchronization–duration discrimination task.

The exact time of β_{P_3} is unknown, but if the afferent latency of an auditory stimulus is deterministic, β_{P_3S} should be 4 msec. earlier when $\Delta D = 42$ msec. (short P_1-P_3 = 219 msec.) than when $\Delta D = 34$ msec (short P_1-P_3 = 223 msec.). Thus, the difference in the mean synchronization response latencies for the two values of P_1-P_3 at each value of ΔD should increase by 4 msec., as ΔD increases from 34 to 42 msec., if the sequential model holds. Responses on trials when the shorter P_1-P_3 value is presented would become 4 msec. earlier as ΔD increases , while those on trials when the longer P_1-P_3 value is presented (I_2 initiated by C; refer to Figure 4) would have constant latency, for these values of ΔD. In Figure 28, it is clear that the differences between the mean synchronization response latencies for longer and shorter P_1-P_3 values do not change as ΔD increases from 34 to 42 msec. In fact, the total differences between the two latencies are never larger than about 5 msec. for subject JB. For GTH, as ΔD increased from 36 to 42 msec, the difference between the two synchronization response latencies increased by 1 msec. in Fig. 29, but this is due to an increase in synchronization latency on "long" P_1-P_3 trials, rather than a decrease in latency on "short" P_1-P_3 trials. The results of Experiment 2 are consistent with those of Experiment 1 in that they do not conform to the quantitative predictions of the sequential model of the dual synchronization-duration discrimination task.

In almost all of the results described so far, the synchronization response latency distribution has been shorter and less variable on trials when the "short" P_1-P_3 is presented than on trials when the "long" P_1-P_3 is presented, for a given value of ΔD. The sequential model, depicted in Figure 4, has been rejected as the basis of this finding. Another possible hypothesis which could account for the dependence of synchronization responses on P_1-P_3 duration is that the effect is due to the filled-duration illusion. This illusion refers to the fact that a short interval which contains discrete stimulus events is judged longer than an empty interval of the same duration (Adams, 1977, 1978; Buffardi, 1971; Thomas & Brown, 1974). In addition, an interval containing stimulus events near its beginning is judged longer than an interval containing stimulus events near its end (Adams, 1978; Buffardi, 1971). In the present dual synchronization-duration discrimination task, the synchronization task requires S to time an interval that sometimes contains an intervening stimulus event

(P_3). If the filled-duration illusion were in effect, S would perceive that more time had gone by on trials on which P_3 occurred and would thus make his synchronization response earlier. The earlier P_3 occurred, the earlier would be the synchronization response. Although this explanation has some appeal, there are difficulties in applying it to the present results. The differences in possible P_3 locations in the present experiment are small compared to the differences between "early" and "late" intervening stimuli that have been used to study the filled-duration illusion (Adams, 1978; Buffardi, 1971). In comparison to those experiments, all of the present P_3 locations are in the middle of the P_1-P_2 interval. In addition, there is little evidence that the variability of a perceived interval is affected by the placement of the intervening stimulus (Adams, 1977, 1978; Thomas & Brown, 1974). Thus, although the filled-duration illusion might be invoked to explain the effects of P_3 location on mean synchronization latency, it would not predict the variance effects found in the present experiments. Indeed, if attention were momentarily diverted to take note of an intervening stimulus, it might be expected that the synchronization variance would be increased on trials when P_3 was presented, relative to that on trials when no P_3 was presented. However, in the present experiments, synchronization response distributions on trials when no P_3 was presented were almost always more variable than those of trials on which P_3 was presented.

The Observation Window Model

Previous research has shown that a deterministic time interval can be inserted into the S-R chain in a response-stimulus synchronization task (Kristofferson, 1976). The synchronization response latency variances are constant when the mean latency is anywhere in the range from 170 to 550 msec. In addition, Ss can change the mean latency of their synchronization responses by a small amount between sessions with little or no effect on the response variance.

In duration discrimination, it has generally been found that the psychometric variance is an increasing function of base duration (Abel, 1972 a,b; Allan et al., 1971; Creelman, 1962; Divenyi & Danner, 1977; Getty, 1975), although this variance can be constant for a restricted range of base durations (Kristofferson, 1980). Changing the base duration in a duration discrimination task between sessions results in an increase in the psychometric variance, which gradually decreases after many sessions of practice (Allan & Kristofferson, 1974 b; Kristofferson, 1980).

The present research has confirmed these characteristics of both the synchronization and duration discrimination tasks, when the two are performed concurrently. In Experiment 1, a small range of duration discrimination base durations was used, but changing the base duration between sessions disrupted discrimination performance. The mean synchronization latency could be changed with little effect on response variance. The interpolation of a duration discrimination task within the synchronization interval does not affect this property of the synchronization timer.

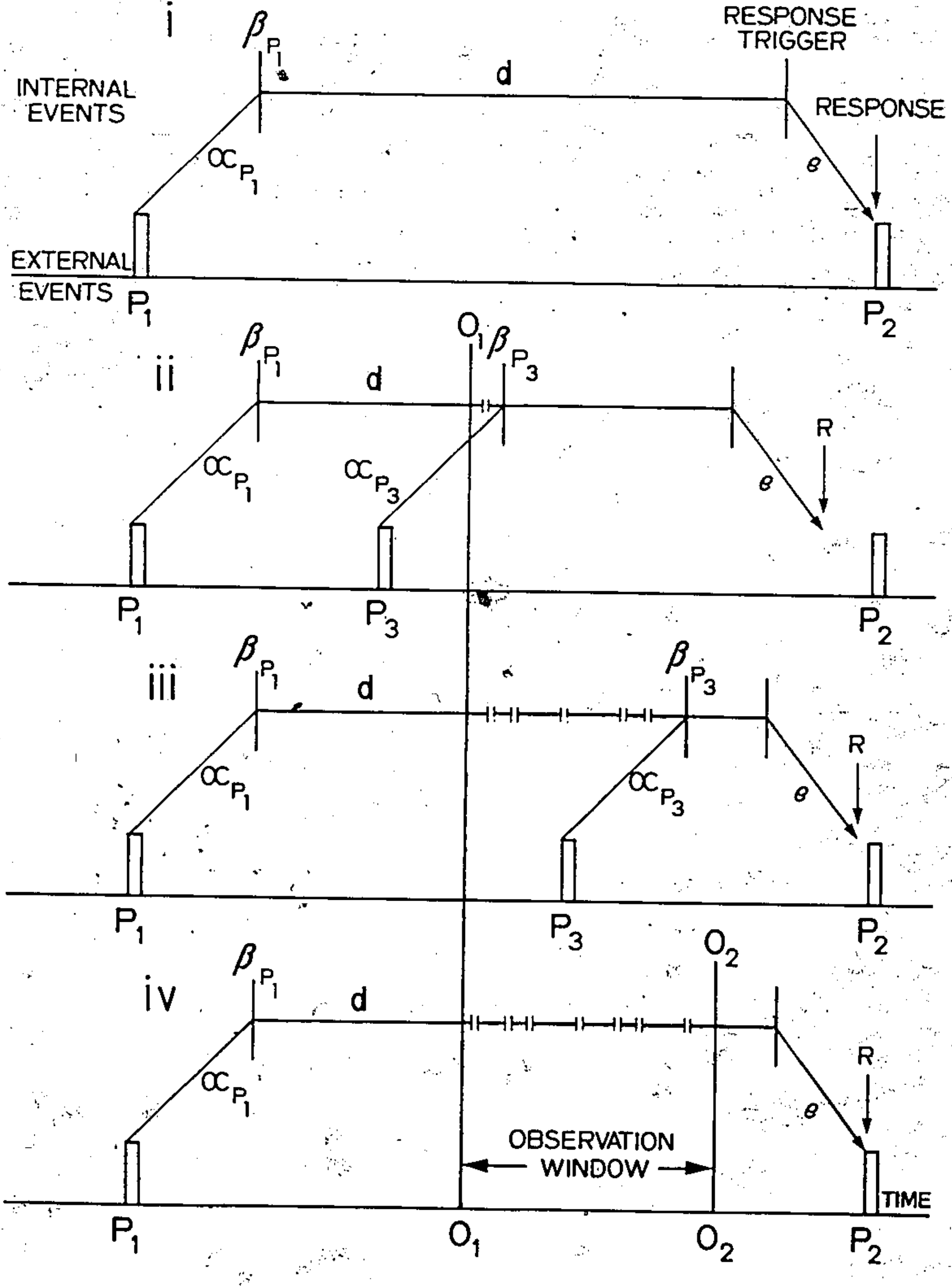
In both Experiments 1 and 2, the interpolation of the duration discrimination stimuli within the synchronization interval had systematic effects on synchronization responses in the dual task situation. On trials on which the P_1-P_3 interval was "short" the mean latency and variance of the synchronization response distributions were lower than on trials when the P_1-P_3 interval was "long". The differences between the synchronization response distributions were larger when the range of possible P_1-P_3 values was larger. Trials on which no P_3 was presented had synchronization response latency means and variances similar to, or larger than, those of trials on which the "long" P_1-P_3 interval was presented. Despite this dependence on the value of P_1-P_3, synchronization variance was independent of P_1-P_2 duration, showing that at least one timing component of the synchronization S-R chain is deterministic - the latency can be increased without an increase in variance.

The above-described effects of the discrimination stimuli within the synchronization interval would result if the timing of the deterministic synchronization interval were intermittently disrupted when the presentation of a discrimination stimulus is expected. So many attentional and processing resources are used in looking for and deciding the time of occurrence of P_3 that the timing of the synchronization interval occasionally stops. It is resumed almost immediately. Each tiny discontinuity would increase the total elapsed time from P_1 to the synchronization response, but the breaks are ignored by S in producing the synchronization interval. S looks for P_3 during an "observation window" whose size and location is determined by the range and midpoint of the possible P_1-P_3 intervals. Once a P_3 stimulus has been observed, the timing of the synchronization interval is completed without further interruption. The observation window represents a period of uncertainty during which S is awaiting the stimulus marking the end of the P_1-P_3 interval. The model is illustrated in Figure 30. Figure 30 i shows the chain of events in a response-stimulus synchronization task. This illustration is like that of Figure 2, except that the two quantal steps have been omitted for simplicity. The remainder of Figure 30 shows what happens when a duration discrimination task is inserted into the synchronization interval. The size and placement of the observation window are determined by experience with the set of possible P_3 locations. A specific mechanism for the production of the deterministic synchronization interval is not proposed here. The only assumption made about the production of this interval is that it can be resumed accurately after very brief interruptions.

On any trial in the dual task situation, S begins producing d when P_1 is observed. At time O_1, the beginning of the observation window, S begins to look for P_3. The P_1-O_1 interval is deterministic. The observation window begins after a fixed amount of d has been timed. During the observation window, when S is prepared to observe the time of P_3, there are very brief discontinuities in d. After each break, the production of d is resumed where it left off. If P_3 is observed, no further interruptions occur and the remainder of d is timed out. The total length of the deterministic interval d is always the same. If P_3 does not occur, no more breaks in d occur after O_2, the end of the

Figure 30. Observation Window Model of performance in the dual synchronization-duration discrimination task. (i) synchronization task only; (ii) "short" P_1-P_3 interval; (iii) "long" P_1-P_3 interval; (iv) no P_3. α: afferent latency of marker stimulus; β: central arrival time of marker stimulus; d: internally-timed deterministic interval; e: efferent latency of motor responses; P_1, P_2, and P_3: auditory stimuli; O_1 and O_2: beginning and end, respectively, of observation window.

105a


i
β_{P_1}
d
RESPONSE TRIGGER
INTERNAL EVENTS
RESPONSE
α_{P_1}
θ
EXTERNAL EVENTS
P_1
P_2
ii
β_{P_1}
d
O_1
β_{P_3}
R
α_{P_1}
α_{P_3}
θ
P_1
P_3
P_2
iii
β_{P_1}
d
β_{P_3}
R
α_{P_1}
α_{P_3}
θ
P_1
P_3
O_2
P_2
iv
β_{P_1}
d
R
α_{P_1}
θ
OBSERVATION WINDOW
TIME
P_1
O_1
O_2
P_2

observation window. O_2 does not occur when P_3 has been presented. When P_3 is not presented, the observation window ends when a fixed amount of d has been timed after O_1. Thus, the real time of the P_1-O_2 interval is variable, being longer on trials when there are more breaks in d. In Figure 30, ii, iii, and iv, the straight line representing the deterministic interval d is the same length in all three cases. However, the synchronization response is latest in case iv because there have been more interruptions in d. Each interruption adds a very small amount of time to the synchronization response latency. The length of d is adjusted through feedback on synchronization performance so that synchronization performance is accurate. In Figures 26 to 29, it can be seen that the mean synchronization latency was most veridical on the trials on which no P_3 is presented and on the trials with the longest P_1-P_3 intervals. This suggests that, in adjusting the duration of d, Ss give more weight to synchronization feedback on trials on which no P_3 is presented. As can be seen in Figure 30, the observed distribution of synchronization response latencies will be earliest and least variable when a "short" P_1-P_3 interval is presented and latest and most variable when no P_3 is presented. The amount of d that must be timed after O_1 before the observation window ends is determined by experience with a set of P_1-P_3 intervals. The smallest useful observation window, O_1-O_2, would be timed such that, should no checkpoints occur, O_2 would occur immediately after the latest possible time of β_{P_3}. In this case, the synchronization response distribution on trials on which no P_3 is presented will look like that on the "long" P_1-P_3 trials, as was the case in Experiment 2.

Evidence Supporting the Observation Window Model

In Experiment 1A, when the P_1-P_3 MP was increased, the synchronization response latencies for trials on which no P_3 was presented showed a larger increase in mean and variance than did those for trials on which P_3 was presented (refer to Figure 13). The difference between synchronization responses on "no P_3" trials and on "P_3" trials, decreased as CK had more practice with the new value of the P_1-P_3 MP (285 msec.). Table 4 shows the average statistics for the first and last five sessions for which P_1-P_3 MP = 285 msec. These results are easily understood in terms of the Observation Window Model of the dual task. When the P_1-P_3 MP is increased, O_1 and O_2, the boundaries of the observation window, are increased. The amount by which O_1 may be increased without introducing too many errors is limited by the smallest value of P_1-P_3. However, O_2 may be increased by a large amount without excluding β_{P_3} from the observation window. This is apparently what happened in Experiment 1A. According to the Observation Window Model, d continues uninterrupted once P_3 has been observed. Thus, a large increase in the size of the observation window would have little effect on synchronization responses when P_3 occurs. On trials on which no P_3 is presented, there are discontinuities in d until the end of the observation window (O_2), adding to the mean and variance of the synchronization responses. When the P_1-P_3 MP was increased, the uncertain period, during which CK watched for P_3, increased and filled more of the synchronization interval. As O_2 increased more than O_1, the mean and variance of synchronization responses, on trials on which no P_3 was presented, increased more than did those on discrimination trials. After prolonged practice with a particular P_1-P_3 MP, the observation

Table 4: Synchronization performance by P_1-P_3 interval, Experiment 1A. Subject CK. P_1-P_3 MP = 285 msec.; ΔD = 10 msec.

MEAN SYNCHRONIZATION LATENCY (MSEC.)

P_1-P_3:	280	difference	290	difference	no P_3
FIRST FIVE SESSIONS	456.21	2.82	459.03	7.44	466.47
LAST FIVE SESSIONS	458.79	0.35	459.14	2.71	461.85

MEAN SYNCHRONIZATION VARIANCE (MSEC.^{2})

FIRST FIVE SESSIONS	176.65	6.55	183.20	79.13	262.33
LAST FIVE SESSIONS	176.13	22.39	198.52	18.11	216.63

window became smaller so that it more closely approximated the range of possible P_1-P_3 values. As the observation window shrank, the difference between the distributions of synchronization response latencies on "no P_3" and "P_3" trials was reduced. Table 4 shows that the time by which the average synchronization response on "no P_3" trials exceeded the average on "long" P_3 trials changed from 7.44 msec. to 2.71 msec. after about 15 sessions of practice. The difference in variance between these two distributions changed from 79.13 msec.^{2} to 18.11 msec.^{2} Thus, after practice with P_1-P_3 MP =285 msec., the breaks in d occurring after the later possible time of P_3 added 2.71 msec. and 18.11 msec.^{2} variance to d. The difference between the means of the synchronization response distributions on "long" and "short" P_3 trials was less than 1 msec. in the last five sessions for which P_1-P_3 MP = 285. However, the average difference between the variance of these two distributions actually increased to 22.39 msec.^{2} It can be seen in Figure 13 that this result is mainly due to one session in which an unusually high synchronization variance was produced.

The Observation Window Model is also consistent with the results of Experiment 1C, where ΔD was decreased in consecutive sets of sessions. As ΔD decreased, the difference between the distributions of synchronization response latencies on the three types of trials ("short" P_1-P_3; "long" P_1-P_3; no P_3) decreased. As can be seen in Figures 20 and 21, the leading edges of the distributions overlap; larger means and variances are due to a larger proportion of long responses. When ΔD is large, the observation window is larger than when ΔD is small. Thus, when ΔD is large and the P_1-P_3 interval is "long," the subject spends a relatively long time in a state of uncertainty and a large number of breaks occur in the internal synchronization interval. The distribution of synchronization latencies is later than that for the "short" value of P_1-P_3. In Figure 20, where ΔD = 32 msec., the synchronization responses when P_1-P_3 = 256 msec. are 4.4 msec. longer and 14.58 msec.^{2} more variable than those found when P_1-P_3 = 224 msec. When ΔD is small, the observation window is smaller and there are fewer breaks in d between O_1 and O_{P_3} when P_1-P_3 is "long". Therefore, the difference between synchronization response distributions for the two values of P_1-P_3 is smaller. There are fewer interruptions in d than when ΔD is large. In Figure 21, where ΔD = 4 msec., the synchronization responses when P_1-P_3 = 242 msec. are 0.6 msec. longer and 3.8 msec.^{2} more variable than those found when P_1-P_3 = 238 msec. In these sessions, the observation window is smaller than for the sessions represented in Figure 20. In Figure 21, the leading edges of the distributions are very close together, implying that, when the observation window is very small (ΔD = 4 msec.), there are often no breaks in d. For the sessions represented in Figure 20, ΔD = 34 msec. and the observation window is larger. The leading edges of the synchronization response distributions for trials on which P_1-P_3 is "long" and for trials on which no P_3 is presented, separate more quickly from the leading edge of the synchronization response distribution for trials on which P_1-P_3 is "short". This shows that when the observation window is large, it is less likely that d will be continuous.

Table 5 presents the means and variances of the distributions shown in Figures 20 and 21, and shows the size of the observation window effects. The larger observation window (ΔD = 32 msec.) adds 4.4 msec. and 14.58 msec.^{2} variance to responses when the "long" P_1-P_3 interval is

Table 5: Synchronization performance by P_1-P_3 interval, Experiment 1C. Subject JB.

MEAN SYNCHRONIZATION LATENCY (MSEC.)

	short P_1-P_3	difference	long P_1-P_3	difference	no P_3
ΔD=32	336.16	4.40	340.56	0.16	340.72
ΔD=4	338.60	0.60	339.20	1.40	340.60

MEAN SYNCHRONIZATION VARIANCE (MSEC.^{2})

ΔD=32	108.00	14.58	122.58	18.05	140.63
ΔD=4	93.30	3.80	97.10	12.90	110.00

presented, and a further 0.16 msec. and 18.05 msec.^{2} variance when no P_3 is presented. When ΔD = 4 msec., the observation window is very small and an average of less than 1 msec. and 3.8 msec.^{2} variance is added to d on "long" P_3 trials, relative to "short" P_3 trials. Thus, when the observation window is small, there are few breaks in d and, in fact, it is often continuous.

Comparing across Figures 20 and 21, the mean response latency for P_1-P_3 = 224 msec. is earlier than that for P_1-P_3 = 238 msec., although both are "short" P_1-P_3 intervals. This is consistent with the Observation Window Model. The duration of d is adjusted so that the mean synchronization latency on "no P_3" trials approximates perfect synchrony. When ΔD, and the observation window, are large, the difference between the length of d on "no P_3" trials and on "short" P_1-P_3 trials will be larger than when ΔD is small as there are more discontinuities in d. Since synchronization responses are most veridical when no P_3 is presented, synchronization responses on "short" P_1-P_3 trials will be earlier, relative to P_2, when ΔD is large than will be synchronization responses on "short" P_1-P_3 trials when ΔD is small. The results show not only that synchronization response latency distributions are earlier and less variable when P_1-P_3 is "short" than when P_1-P_3 is "long" or when no P_3 is presented, but that how much earlier and less variable they are is determined by the size of ΔD, the time during which a P_3 stimulus might occur. In addition, Figures 20 and 21 show that synchronization responses on "no P_3" trials are more variable when ΔD is larger than when ΔD is smaller, as is predicted by the Observation Window Model. In both Figures 20 and 21, the synchronization distributions for trials on which no P_3 was presented are slightly later and more variable than those for the "long" P_1-P_3 trials. This is consistent with the Observation Window Model where O_2 occurs a little time after the latest possible P_3 position.

The synchronization results of Experiment 2 also support the Observation Window Model. In Figures 28 and 29, the difference between synchronization response mean and variance for "long" and "short" P_3 decreases as ΔD decreases. This result is consistent with the occurrence of fewer breaks in the synchronization chain when ΔD is smaller. Also, the synchronization response distributions on trials on which no P_3 is presented are very similar to those on the "long" P_3 trials for the large value of ΔD. This would occur if the time of O_2 were near the end of the range of possible P_3 values, which is determined by the largest value of ΔD presented in a session. Table 6 shows the average differences between the synchronization response distributions on "long" and "short" P_3 trials for the largest and smallest values of ΔD in Experiment 2. When ΔD is large, much more time and variance are added by GTH, whose overall variances were higher than those of JB. When ΔD is small, the differences are remarkably similar for the two Ss: responses on "long" P_3 trials are less than 1 msec. longer and about 11 msec.^{2} more variable than those on "short" P_3 trials. These differences are in the same range as those found for JB in Experiment 1C when ΔD = 4 msec. (see Table 5). Thus, a small observation window adds very little time to the average response latency. When the observation window is larger, the amount of time

Table 6: Synchronization performance by P_1-P_3 interval, Experiment 2.

MEAN SYNCHRONIZATION LATENCY (MSEC.)

SUBJECT:	JB			GTH		
P_1-P_3:	short	difference	long	short	difference	long
LARGEST FIVE ΔD VALUES	335.23	3.66	338.89	445.91	9.57	455.48
SMALLEST FIVE ΔD VALUES	337.41	0.47	337.88	451.04	0.79	451.83

MEAN SYNCHRONIZATION VARIANCE (MSEC.^{2})

LARGEST FIVE ΔD VALUES	102.62	14.43	117.05	212.15	66.81	278.96
SMALLEST FIVE ΔD VALUES	92.93	11.01	103.94	238.28	11.41	249.69

added is still less than 10 msec. (Tables 4, 5, & 6). However, the differences in variability between the response distributions are much larger than the differences in mean and are larger than would result from the addition of a uniform distribution of time, with mean equal to the mean differences. The amount of time added to d by the observation window is apparently not uniformly distributed from trial to trial. That is, it may be more likely that either d is continuous or a large number of discontinuities occurs, than it is that a small number of discontinuities occurs. This could indicate that on some trials S waits for P_3 without disrupting d, while on other trials more effort is expended in watching for P_3, resulting in many disruptions in d.

Experimental Results not Consistent with the Model

There are some results of the experiments presented so far that are not consistent with the Observation Window Model. When P_3 was first introduced into the synchronization interval with a single P_1-P_3 interval of 240 msec., Ss CK and JB showed the characteristic pattern right from the start: synchronization response distributions were later and more variable when P_3 was absent than when it was present, even though the P_1-P_3 interval was fixed and only the synchronization response was required. GTH did not produce a consistent pattern of P_3-dependent synchronization distributions until the duration discrimination task was added (refer to Figures 6, 7, and 8). Thus, GTH apparently did not watch for the time of occurrence of P_3 until he needed to do so. In the first sessions of the baseline tasks, all Ss made earliest and least variable synchronization responses when the "short" P_1-P_3 interval was presented. GTH's synchronization responses were longest and most variable, and CK's responses were most variable, when no P_3 was presented. However, JB's responses were longest and most variable, and CK's responses were longest, when the "long" P_1-P_3 interval was presented. The Observation Window Model predicts that synchronization responses on "no P_3" trials will be at least as long and variable as those on trials when the "long" P_1-P_3 interval is presented. It may be that, for some Ss, the presentation of P_3 delays the synchronization response slightly so that responses on "P_3" trials are later, relative to those on "no P_3" trials, than predicted by the Observation Window Model. Later in the experiments, after Ss had had more practice, JB's pattern of synchronization responses changed so that responses were latest and most variable when no P_3 was presented. However, when CK returned to the baseline task after Experiment 1, his synchronization responses were again longest when the "long" P_1-P_3 interval was presented (see Figure 13).

The Observation Window Model does not predict a change in the pattern of synchronization responses when the P_1-P_2 interval is changed in the dual task. In Experiment 1B, the P_1-P_2 interval was shortened by 5 msec. in each successive session. If S were to shorten only the portion of d that occurs after 0_2 (refer to Figure 30), there would be no change in the pattern of synchronization responses. A change would occur when P_2 was close enough to P_3 that the response trigger occurred before 0_2. Synchronization response distributions would still be shortest and least variable when the "short" P_1-P_3 interval was presented, and distributions on trials when the "long" P_1-P_3 interval was presented, and on "no P_3" trials, would be the same. In Experiment 1B, synchronization response distributions did retain their characteristic relationships when the P_1-P_2 interval was first shortened (see Figures 16 and 17). However, as P_2 approached P_3, the consistency of the pattern disappeared. When d becomes short enough that the possible times of occurrence of β_{P_3} are no longer contained within it, the observation window may be deleted from d.

Role of the Observation Window in Duration Discrimination

The insertion of the observation window into the synchronization chain may play some role in the duration discrimination decision. It was shown in Experiment 1 that the duration discrimination and response-stimulus synchronization tasks are probably not carried out by the same timing mechanism. Not only was the deterministic synchronization timer not accessed to perform perfect duration discrimination, but the psychometric variance in the duration discrimination task was independent of the synchronization latency variance. However, the two tasks are <u>not</u> completely independent. A great deal of evidence has been presented that shows the effect of the duration discrimination stimuli on synchronization responses. In addition to this, for a given value of P_1-P_3, synchronization response latencies were related to the duration discrimination response. Figure 31 shows synchronization response latency distributions, separated according to duration discrimination response, for GTH for the five baseline sessions preceding Experiment 1. Figure 32 shows similar distributions for JB from Experiment 1C. The sessions in Figure 32 are the last five sessions for which ΔD = 10 msec. In both Figures, responses are longer and more variable when S responded "long" than when S responded "short," for each value of P_1-P_3. The single exception to this rule in these examples is when P_1-P_3 = 248

Figure 31. Synchronization response latency distributions, according to duration discrimination response, for five sessions preceding Experiment 1. Subject GTH. P_1-P_2 = 460 msec. P_1-P_3 = 232 msec.: filled triangles: "short" resp., $\overline{X}$ = 447 msec., S^2 = 208 msec.^{2}, N = 407; open triangles: "long" resp., $\overline{X}$ = 453 msec., S^2 = 289 msec.^{2}, N = 86. P_1-P_3 = 248 msec.: filled triangles: "short" resp., $\overline{X}$ = 456 msec., S^2 = 270 msec. , N = 108; open triangles: "long" resp., $\overline{X}$ = 458 msec., S^2 = 267 msec.^{2}, N = 383. No P_3: $\overline{X}$ = 461 msec., S^2 = 309 msec.^{2}, N = 490. Overall q estimate = 21.44 msec.

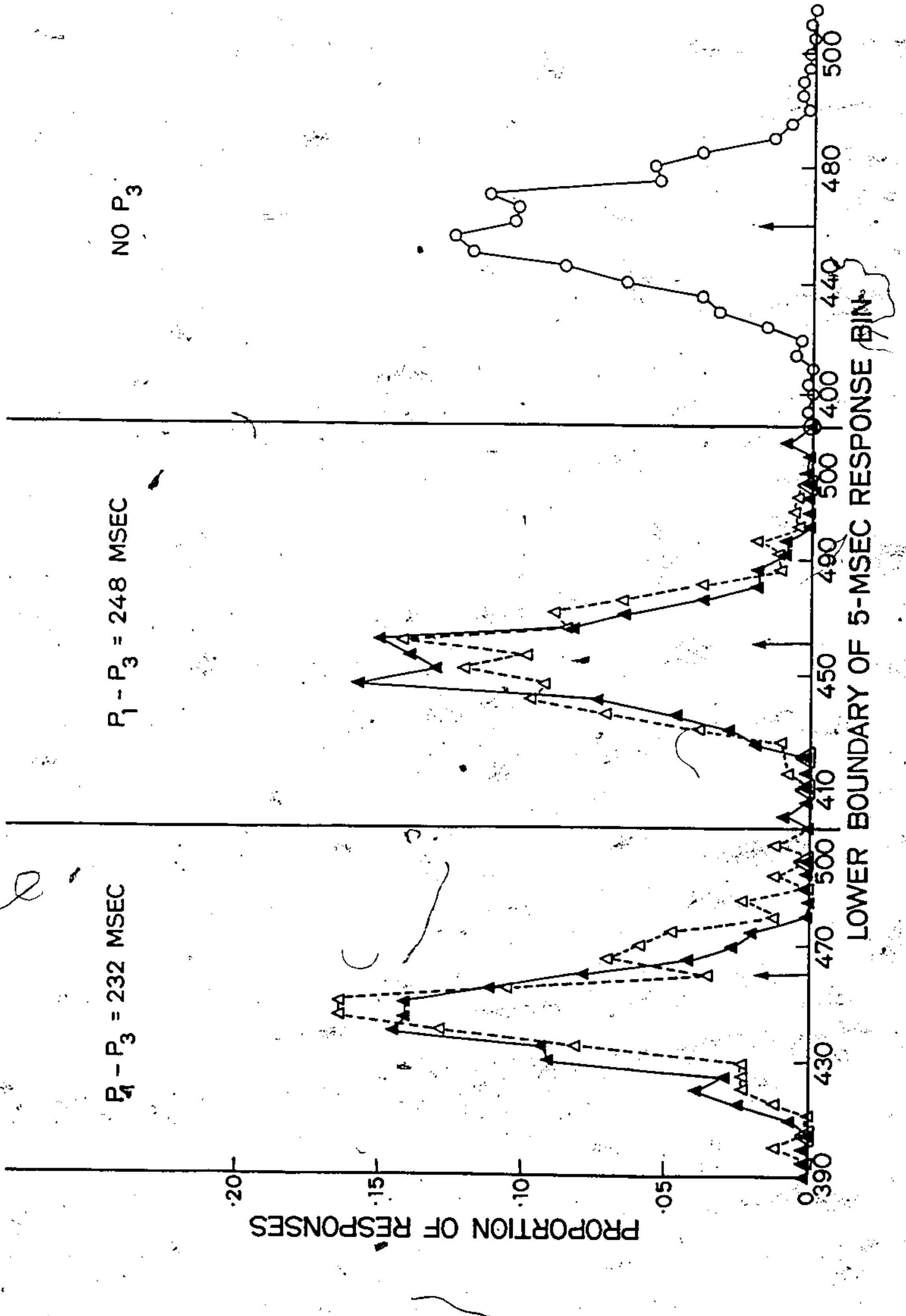
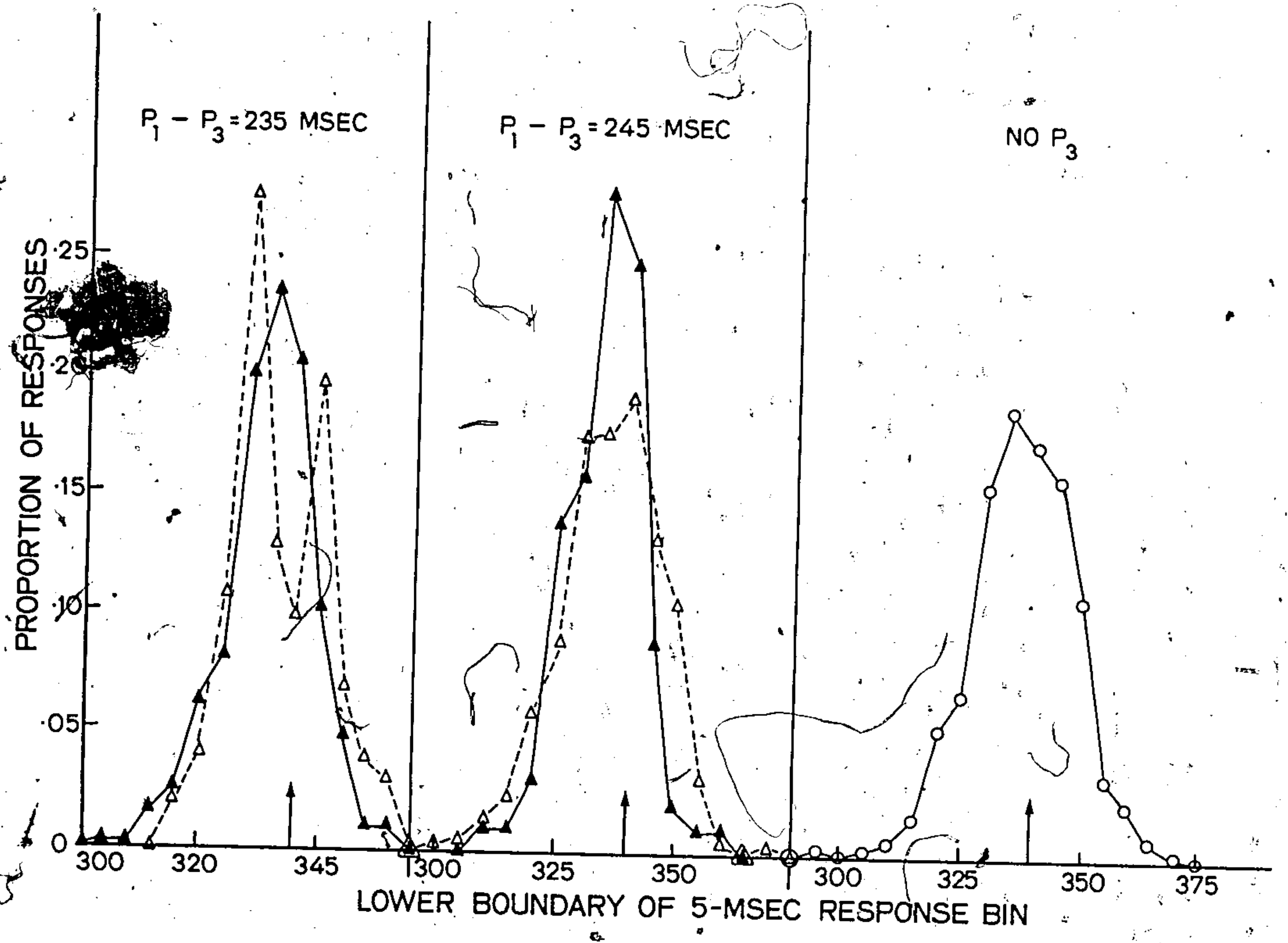

P1 - P3 = 232 MSEC
P1 - P3 = 248 MSEC
NO P3
PROPORTION OF RESPONSES
0
.05
.10
.15
.20
LOWER BOUNDARY OF 5-MSEC RESPONSE BIN
390
430
470
500
410
450
490
500
400
440
480
500

Figure 32. Synchronization response latency distributions, according to duration discrimination response, for the last five sessions for which ΔD = 10 msec. in Experiment 1C. Subject JB. P_1-P_2 = 340 msec. P_1- P_3 = 235 msec.: filled triangles: "short" resp., $\overline{X}$ = 336 msec., S^2 = 87 msec.^{2}, N = 395; open triangles: "long" resp., $\overline{X}$ = 339 msec., S^2 = 110 msec.^{2}, N = 102. P_1- P_3 = 245 msec.: filled triangles: "short" resp., $\overline{X}$ = 337 msec., S^2 = 64 msec.^{2}, N = 101; open triangles: "long" resp., $\overline{X}$ = 338 msec., S^2 = 110 msec.^{2}, N = 403. No P_3: $\overline{X}$ = 340 msec., S^2 = 109 msec.^{2}, N = 496. Overall q estimate = 13.77 msec.


$P_1 - P_3$ = 235 MSEC
$P_1 - P_3$ = 245 MSEC
NO P_3
PROPORTION OF RESPONSES
·25
·20
·15
·10
·05
0
300
320
345
300
325
350
300
325
350
375
LOWER BOUNDARY OF 5-MSEC RESPONSE BIN

msec. for GTH. Here, the variance of synchronization responses is slightly higher for "short" discrimination responses than for "long" discrimination responses. However, this higher variance is mainly due to one or two outlying responses and the synchronization response distribution for "short" discrimination responses is generally narrower than that for "long" responses. According to the Observation Window Model, synchronization responses are longer and more variable when more time has been spent in a state of uncertainty about incoming stimuli, and there are more discontinuities in d. Each break adds a small amount of time to the synchronization response chain. If S were aware of the number of disruptions in d before P_3 is observed, and used this information in deciding whether P_1-P_3 was "short" or "long," the results would look like those in Figures 31 and 32. For a given value of P_1-P_3, when more breaks in d occur before P_3 is observed, S will be more likely to make a "long" duration discrimination response, and synchronization responses will be longer and more variable. It may also be that S is not aware of the number of breaks in d, but that allocation of more resources to the duration discrimination task, which produces more discontinuities in d, is more likely to result in a "long" discrimination response.

For a given value of P_1-P_3, synchronization responses were longer and more variable when the discrimination response was "long" than when it was "short", as has just been described. However, in the data shown in Figures 31 and 32 as well as other sessions, there was no consistent relationship between the synchronization distributions produced on the long stimulus-short response trials and those produced on the short stimulus-long response trials. That is, in terms of the

Observation Window Model, there were not more discontinuities in d when S responded "long" to the short P_1-P_3 interval than there were when S responded "short" to the long P_1-P_3 interval. Thus, the number of discontinuities in d occurring between O_1 and β_{P_3} is probably not the only source of information used to perform the duration discrimination task. In Experiment 1A, duration discrimination performance was severely disrupted when the P_1-P_3 MP was increased. Synchronization performance in that experiment was consistent with a widening of the observation window. This widening would explain the duration discrimination performance if many sessions of practice were necessary to adjust to the perception of a new number of discontinuities. However, in Experiment 1C, and in Experiment 2, the range of possible P_1-P_3 values was changed without detriment to discrimination performance. It is a change in P_1-P_3 MP, rather than a change in the range of possible P_1-P_3 values for a given MP, that disrupts duration discrimination. Therefore, in performing the duration discrimination task, S probably uses a real-time criterion or some other mechanism, independent of the synchronization timer. The present experimental paradigm does not distinguish between different duration discrimination mechanisms, although the results are consistent with the triangular criterion distribution produced by the real-time criterion (Kristofferson, 1977). In addition, the events in the observation window between O_1 and β_{P_3} may contribute to the duration discrimination response, but do not solely determine it.

The predictions of the Observation Window Model should be distinguished from those of the sequential model of the dual task situation, which was illustrated in Figure 4. In the sequential model, a constant synchronization interval, I_2, is timed from the discrimination event, which is an internal criterion or β_{P_3}, whichever occurs first. In the Observation Window Model, the total deterministic time of d, the interval timed to perform the synchronization task, is always the same. Different synchronization response latency distributions result from different numbers of interruptions in d, which in turn result from spending different amounts of time in a state of readiness to process incoming temporal stimuli. In the introduction, the predictions of the sequential model for the dependence of synchronization responses on duration discrimination, were detailed. Both the sequential model and the Observation Window Model predict that synchronization responses will be less variable when the duration discrimination response is "short" than when it is "long" for a given value of P_1-P_3. However, the sequential model predicts that synchronization response latencies will be shorter when the duration discrimination response is "long." The results presented in Figures 32 and 33 do not support the sequential model on this point but they are consistent with the Observation Window Model.

Response-Stimulus Synchronization vs. Duration Discrimination

In response-stimulus synchronization, the synchronization response latency variances are constant when the mean latency is anywhere in the range from 170 to 550 msec. and Ss can change the mean latency of their synchronization responses between sessions with little or no effect on the response variance (Kristofferson, 1976). In duration discrimination, psychometric variance is usually an increasing function of base duration (Abel, 1972a,b; Creelman, 1962; Divenyi &

Danner, 1977; Getty, 1975), and changing the base duration between sessions results in an increase in psychometric variance, which gradually decreases after many sessions of practice (Allan & Kristofferson, 1974b; Kristofferson, 1980). Kristofferson (1977) has suggested that deterministic time intervals may be produced by the initiation of a stable, automatic chain of internal events. In Experiment 1, it was shown that the deterministic synchronization timer is not accessed to perform duration discrimination in the dual task situation. It may be that the critical difference between a temporal interval production task and a duration discrimination task is that in the latter, Ss are required to maintain a state in which incoming stimuli can be temporally processed.

In practised response-stimulus synchronization, S is in control of when the timed interval will end, and it is independent of external stimuli. He can set up a stable chain of internal events that will produce the desired interval. With practice, this chain becomes "automatic". If the required interval is changed between sessions, S need only change the number of links in the chain. The links may be of uniform duration, as would occur if the chain involved something like counting quanta. However, the small adjustments in mean latency that can be made require that at least one link be adjustable in duration, or that the links are very short. In duration discrimination, S is uncertain about when the interval will end; the presented duration is under the control of the experimenter. In this state of uncertainty, the timing that S does is disrupted by the need to keep watch for the stimulus ending the presented interval. This vigilance adds variability to the timing process and the psychometric variance is an increasing function of base duration. After prolonged practice with a particular set of base durations, S may be able to insert a deterministic segment into the duration discrimination timing chain so that the psychometric variance is constant over a range of durations as Kristofferson (1980) has found.

In the dual synchronization-duration discrimination task, if the synchronization chain is "automatic" and independent of the duration discrimination mechanism, why is an observation window inserted into the synchronization chain? Indeed, Ss found it very easy to think about other things while performing the task and the independence of variance of the two components suggests that they do not share a single mechanism. It may be that interruption of the deterministic timer is only necessary when the time of occurrence of a presented stimulus must be noted. That is, attention to stimulus attributes other than timing may not affect temporal interval production. This question could be answered experimentally by interpolating non-temporal tasks within the synchronization interval. For example, would a signal detection task or a lexical decision task within the synchronization interval affect the response latency and variance? If so, it may be that more attentional resources are required to produce a deterministic interval than has previously been thought.

Experiment 3: Separation of the Two Tasks

Several additional experimental manipulations were performed to further examine the relationship between the synchronization and duration discrimination tasks. Although the results of these experiments will sometimes be discussed in terms of the Observation Window Model, they were performed following Experiment 1 and were not specifically designed to test the model.

Experiment 3A: P_2 or P_3

In this experiment, on trials on which P_3 was presented, P_2 was omitted. In the previous experiments, P_1 and P_2 were presented on every trial. When P_3 was presented, the P_3-P_2 interval was usually shorter than the P_1-P_3 interval, especially in Experiment 1. The discussion so far has assumed that duration discrimination responses were based on the duration of the P_1-P_3 interval. However, since the duration discrimination responses were made after the entire P_1-P_3-P_2 stimulus pattern had been presented in the dual task, Ss might have based their duration discrimination responses on the duration of the P_3-P_2 interval, or on some interaction of all three stimuli. By omitting P_2 on trials on which P_3 is presented, Ss will be forced to base their duration discrimination responses on the duration of the P_1-P_3 interval, and comparison of performance in this situation with that obtained in the baseline task will show whether Ss have been using the duration of the P_1-P_3 interval to perform the duration discrimination.

Method

Subjects GTH and CK served in this experiment. For both Ss, P_1-P_2 = 460 msec. and P_1-P_3 MP = 240 msec. The values of ΔD were: GTH - 16 msec.; CK - 10 msec. After 5 sessions of the baseline task, the "P_2 or P_3" condition was imposed. On all trials on which P_3 was presented, P_2 was omitted. On "no P_3" trials, the complete P_1-P_2 interval was presented as usual. Ss were required to synchronize with P_2, or its usual location, on every trial. Delayed feedback on the accuracy of synchronization performance was provided on every trial, as in the baseline condition. When P_3 was presented, S was required to judge whether the P_1-P_3 interval was "short" or "long", following the synchronization response, as usual. Each type of trial, "short" P_1-P_3, "long" P_1-P_3, and "no P_3", occurred on one third of the trials and they were randomly intermixed. During block 1, the only possible P_3 location was the P_1-P_3 MP and only the synchronization response was required, as in the baseline condition. In block 1, P_2 did not occur when P_3 was presented. GTH ran 5 sessions and CK ran 6 sessions in this experiment.

Results and Discussion

Synchronization and duration discrimination performance for this experiment (P_2 or P_3) are presented in the first two lines of Tables 7 and 8 for GTH and CK, respectively. The values presented are the overall data for the last 5 sessions on each condition combined for both Ss. Performance was characterized by an increase of about 40% in synchronization variance and a small decrease in mean synchronization latency, for both Ss. With two exceptions, the means and variances were

Table 7: Synchronization and duration discrimination performance in Experiment 3. Subject GTH. P_1-P_2=460 msec.; P_1-P_3MP=240 msec.; ΔD=16 msec.

EXPERIMENT (listed in order conducted)	SYNCHRONIZATION						DURATION DISCRIMINATION	
	P_1-P_3=232		P_1-P_3=248		no P_3			
	$\overline{X}$	S^2	$\overline{X}$	S2	$\overline{X}$	S^2	q	$\overline{C}$
BASELINE	452.49	235.17	456.85	268.44	458.50	268.02	19.55	238.87
P_2 or P_3	439.61	284.41	445.60	315.90	454.97	431.51	17.30	240.35
BASELINE	460.66	206.13	464.54	213.34	464.04	260.14	17.05	241.43
SYNC. ONLY ALL STIMULI	451.72	295.06	456.53	342.82	452.75	347.86		
SYNC. ONLY P_1-P_2 ONLY					454.45	364.33		
BASELINE	453.56	195.17	459.26	250.83	457.82	216.21	15.52	241.00
DISC. ONLY ALL STIMULI							14.51	240.61
DISC. ONLY P_1-P_3 ONLY							22.49	242.26

Table 8: Synchronization and duration discrimination performance in Experiment 3. Subject CK. P_1-P_2=460 msec.; P_1-P_3MP=240.; ΔD=10 msec.

EXPERIMENT (listed in order conducted)	SYNCHRONIZATION						DURATION DISCRIMINATION	
	P_1-P_3=235		P_1-P_3=245		no P_3			
	$\overline{X}$	S^2	$\overline{X}$	S^2	$\overline{X}$	S^2	q	$\overline{C}$
BASELINE	457.59	106.35	462.49	115.38	458.62	153.96	23.03	239.53
P_2 or P_3	450.94	162.28	454.93	179.30	459.60	170.70	29.64	238.73
BASELINE	460.56	130.51	465.37	117.70	461.03	114.33	20.59	237.94
SYNC. ONLY ALL STIMULI	458.52	91.67	463.56	108.90	460.49	117.31		
SYNC. ONLY P_1-P_2 ONLY					459.20	212.67		
BASELINE	460.64	106.97	466.07	111.93	464.56	141.53	25.27	239.76
DISC. ONLY ALL STIMULI							33.66	239.87
DISC. ONLY P_1-P_3 ONLY							33.98	241.40

ordered as usual: smallest for "short" P_1-P_3 and largest for "no P_3". The changes from baseline performance occurred on all three types of trials. The changes in synchronization performance were probably due to the loss of the immediate feedback provided by the synchrony of P_2 with the response, even though delayed feedback was provided throughout. Hopkins and Kristofferson (1980) found that omitting P_2 in a synchronization task led to a large increase in synchronization variance, even though delayed feedback was retained. In the present experiment, P_2 was presented on one third of the trials (the trials on which no P_3 was presented). However, this was apparently not enough to compensate for the omission of P_2 on the remaining trials.

The "P_2 or P_3" condition did not affect GTH's discrimination performance. It is likely that GTH was basing his duration discrimination responses on the length of the P_1-P_3 interval, although some aspect of his own synchronization response could possibly take the place of the P_2 stimulus. CK's q estimate did increase slightly, although not significantly (Mann-Whitney U=19; $p>.10$), in the "P_2 or P_3" experiment. CK said that he did sometimes use the overall pattern of the three stimuli to make the discrimination decision. However, in the "P_2 or P_3" condition, he was discriminating between P_1-P_3 intervals of 235 and 245 msec. at a level of 65% correct. That is, although CK may sometimes have used the entire P_1-P_3-P_2 pattern to contribute to his duration discrimination decision, it was not his only source of duration information.

Experiment 3B: Synchronization only

After performance is well established in the dual task, what is the effect on synchronization of removal of the duration discrimination task? It has been stressed that synchronization performance in the present dual task is comparable to that found by other researchers studying only response-stimulus synchronization. Having Ss perform the synchronization task alone will provide data from the same Ss against which to compare the dual task performance. Also, if the effect of the interpolation of the duration discrimination task is the insertion of an observation window within the synchronization S-R chain, removal of the duration discrimination task might reduce the synchronization variance.

Method

Subjects GTH and CK served in this experiment. For both Ss, P_1-P_2 = 460 msec. P_1-P_3 MP = 240 msec. and ΔD values were: GTH - 16 msec; CK - 10 msec., when P_3 stimuli were used. Following Experiment 3A, 5 sessions were run in the baseline condition. Then, duration discrimination responses were no longer required. All stimuli, including the different P_1-P_3 values, were presented as usual and Ss synchronized responses with P_2 on every trial. During block 1, the only possible location of P_3 was the P_1-P_3 MP and Ss synchronized responses with P_2 on every trial. After 5 sessions under these conditions, all P_3 stimuli were deleted. In all four blocks of trials, Ss were presented with an empty P_1-P_2 interval and they synchronized responses with P_2 on every trial. Delayed feedback on the accuracy of synchronization performance was provided on every trial throughout, as in the baseline condition. GTH ran 7 sessions and CK ran 5 sessions under these conditions.

Results and Discussion

Synchronization performance for the "synchronization only" experiment is presented in the third, fourth, and fifth lines of Tables 7 and 8 for GTH and CK, respectively. The results are the overall data for the last 5 sessions in each condition combined, for both Ss. GTH showed a decrease in mean synchronization latency in the "synchronization only" condition. When the P_3 stimuli were still being presented, GTH increased his synchronization response variance while CK did not. Although practice was not extended, GTH's overall response variance had decreased to 245.00 msec.^{2}, near his baseline variance, on his last session under the "all stimuli" condition. When the P_3 stimuli were no longer presented, a large increase in the response variance of both Ss was found. This variance showed no sign of decreasing in the number of sessions that was conducted. If the presence of the P_3 stimuli, and the duration discrimination task, were disruptive to synchronization performance, it would be expected that the synchronization response variance would decrease when these were removed. However, an increase in variance was found when the P_3 stimuli were removed. It had been expected that omission of the duration discrimination task, and removal of the observation window from the synchronization chain, would decrease the synchronization response variance. The results that were obtained can still be understood in terms of the Observation Window Model. The observation window, inserted into the synchronization chain when S is expecting discrimination stimuli to be presented, adds variance to the synchronization response. Its range is determined by the possible values of P_1-P_3. When P_3 is omitted, the range of the observation window is no longer clearly defined and it could expand to fill a much larger part of the synchronization interval. Presumably, if practice were extended, Ss would delete the observation window from the synchronization response chain and variances would be reduced to the levels that have been found previously in the response-stimulus synchronization task (Hopkins & Kristofferson, 1980; Kristofferson, 1976). Practice was not extended in the present experiment.

The increase in synchronization variance shown by GTH in the "synchronization only, all stimuli" condition may indicate that the presence of P_3 is insufficient to define the range of the observation window in some cases; a duration discrimination decision may be required. His synchronization response variance did reduce with practice in this condition, however, which suggests that the increase in variance was a temporary disruption due to the change in the overall task. The question of whether a duration discrimination task, or merely the temporal predictability of P_3, is necessary to establish a stable observation window could be answered in a future experiment in which synchronization performance on the dual task is compared with that when the same stimuli are presented but no duration discrimination responses are required. The present experiment does not adequately answer this question because the Ss had had prolonged exposure to the dual task situation and previously established observation windows could be maintained by the presence of the P_3 stimuli. However, when P_3 was first inserted into the P_1-P_2 interval in the training sessions (see

Figures 6, 7, & 8), and in block 1 of most of the experimental sessions where only the synchronization response was required, the pattern of synchronization responses suggested that an observation window had been set up. In both of these cases, P_1-P_3 had only one possible value (the P_1-P_3 MP) so the pattern of stimuli was not the same as in the dual synchronization–duration discrimination task. To see whether a duration discrimination task, or only the temporal predictability of P_3, is necessary to establish an observation window, the "synchronization only, all stimuli" condition should be presented to Ss who have had no experience with the dual task.

Experiment 3C: Discrimination only

This experiment looked at the effect on duration discrimination of the removal of the response-stimulus synchronization portion of the dual task. Although P_2 was omitted on some trials in Experiment 3A, synchronization responses were required on every trial. It has been suggested that the number of interruptions in the synchronization timing occurring in the observation window, inserted in the synchronization interval before ${}^{\beta}P_3$, may make some contribution to the duration discrimination decision. If this is the case, removal of the synchronization task might disrupt duration discrimination performance, because the synchronization interval, with its discontinuities, will no longer be produced.

Method

Subjects GTH and CK served in this experiment. For both Ss, P_1-P_3 MP = 240 msec. ΔD values were: GTH - 16 msec; CK - 10 msec. When P_2

was presented, P_1-P_2 = 460 msec. Following Experiment 3B, 5 sessions were run in the baseline condition. Then, the synchronization response was no longer required. All stimuli were presented as in the baseline condition. Ss made a duration discrimination response, following P_2, on trials when P_3 occurred, and did not respond on trials on which no P_3 was presented. Block 1 was the same as the remaining three blocks. That is, P_1-P_3 had two possible values and only the duration discrimination response was required. GTH ran 5 sessions and CK ran 7 sessions under this condition. In the following sessions, P_2 was omitted. In all four blocks of trials, Ss received only the P_1-P_3 intervals, and made discrimination responses, on every trial. No "no P_3" trials were presented. The two possible values of P_1-P_3 were randomly intermixed. GTH ran 6 sessions and CK ran 5 sessions under this condition.

Results and Discussion

The results of this experiment are presented in the last three lines of Tables 7 and 8 for GTH and CK, respectively. The results are the overall data for the last 5 sessions in each condition, for both Ss. GTH's discrimination performance was unaffected by the removal of the synchronization task, but his q estimate increased when P_2 was no longer presented (Mann-Whitney U=24; p=.02). CK's q estimate increased slightly, but not significantly (Mann-Whitney U=22; p>.05), when the synchronization response was no longer required and was not further affected by the removal of P_2. During the "discrimination only, P_1-P_3 only" condition, GTH's q estimate declined with practice. His q estimate on the last session under this condition was 17.32 msec., near that of the pre-manipulation baseline. CK showed no evidence of improvement in duration discrimination performance with practice throughout the "discrimination only" experiment. Experiment 3A ("P_2 or P_3") showed that GTH was not using P_2 to make duration discrimination judgements. The fact that the removal of P_2 in the present experiment produced only a small and temporary disruption in duration discrimination performance confirms this finding. The results of CK are less clear. Experiment 3A showed that he may have made some use of P_2 for the duration discrimination. However, in the "discrimination only, all stimuli" condition, P_2 was presented on every trial and CK's q estimate was larger than that in Experiment 3A. It has been suggested that, if the Observation Window Model is an accurate description of internal events in the dual task situation, the number of interruptions in the synchronization chain between O_1 and β_{P_3} may make a contribution to the duration discrimination response. When the synchronization response is not required, this source of information is lost. It is also possible that some perceptual aspect of the synchronization response contributes to duration discrimination. The results of the "discrimination only" experiment suggest that CK may have made more use of aspects of the response-stimulus synchronization chain, to perform the duration discrimination, than did GTH.

General Discussion - Synchronization Only and Discrimination Only Experiments

Experiments 3B and 3C, taken together, show that in the dual synchronization-duration discrimination task, the two parts of the task are not entirely independent of one another. When the response requirements of one task, and then the associated stimuli, are removed, the remaining task is disrupted to some extent. The results of these experiments do not contradict the Observation Window Model of the dual task situation. Experiments 1 and 2 showed that, from session to session, the overall synchronization response variance was not related to the psychometric variance in the duration discrimination task. In the formulation of the Observation Window Model, it was assumed that the temporal mechanism used to perform the duration discrimination is independent of the response-stimulus synchronization chain, although some aspect of the synchronization chain may contribute to the duration discrimination decision. Taken together, these findings suggest that when a duration discrimination task is difficult, Ss make use of whatever information is available to them. In addition to a temporal duration discrimination mechanism (possibly a real-time criterion) applied to the P_1-P_3 interval, Ss could use the number of interruptions in synchronization timing occurring between O_1 and P_3 and perhaps some aspect of the overall P_1-P_3-P_2 stimulus pattern.

It has been hypothesized that the critical difference between temporal interval production tasks and duration discrimination tasks is the state of temporal uncertainty and the readiness to temporally process incoming stimuli which Ss must maintain in the latter. In response-stimulus synchronization, S is in control of when his produced interval will end and the interval is the same from trial to trial. This allows S to set up a stable automatic chain of internal events that will produce accurate responding. It has been claimed that consistent mapping of stimuli onto responses is a necessary and sufficient condition for the development of automaticity (Logan, 1979). Although this condition was met in the duration discrimination part of the present dual task, Ss must remain ready to process an incoming stimulus, the time of occurrence of which is uncertain. This characteristic of duration discrimination may require active attention and prevent full automatization of the decision and response mechanisms. Thus, duration discrimination responses may be especially vulnerable to changes in overall experimental context. In the "discrimination only" experiment, the removal of the synchronization task and P_2 may have disrupted the focussing of attention that is necessary to perform the duration discrimination task.

Experiment 3D: Speeded Duration Discrimination

If the duration discrimination criterion formed part of the response-stimulus synchronization chain, as illustrated in the sequential model in Figure 4, Ss might be able to change easily from the present dual task situation to a speeded duration discrimination task like that used by Kristofferson (1977). In this task, Ss respond on only one type of duration discrimination trial ("short" or "long") and they respond as quickly as possible, as soon as they know which stimulus interval has been presented. Thus, the speeded button-press response is the discrimination response. If the sequential model were accurate, Ss would only need to eliminate I_2 from the chain of events. "Short" responses would be initiated by β_{P_3} if it occurred before the criterion, and "long" responses would be initiated by C, unless β_{P_3} occurred first. Thus, instead of initiating I_2 as in the sequential model, the discrimination event would initiate a button-press response.

Method

Subjects GTH and CK served in this experiment. P_1-P_3 MP = 240 msec. for both Ss. ΔD values were: GTH - 16 msec.; CK - 10 msec. On each trial, a P_1-P_3 interval was presented and Ss were instructed to make a button-press response as soon as possible, as soon as they knew which interval had been presented. Ss were instructed to respond on only one type of trial: GTH responded only when P_1-P_3 was "short" (R_S); CK responded only when P_1-P_3 was "long" (R_L). All four blocks of trials in each session were the same. This experiment was conducted immediately following the last session of the "discrimination only" experiment, with no baseline sessions intervening. GTH ran 20 sessions and CK ran 10 sessions in this experiment.

Results and Discussion

The results of this experiment are presented in Table 9. Mean latencies are measured from P_1 onset, as usual. For both Ss, discrimination responses followed the P_1-P_3 MP by more time than had the synchronization responses in the dual task. Responses were extremely variable, with both Ss producing response variances more than 100 times larger than their synchronization response latency variances had been. Practice in this experiment was not extended but both Ss did show a decrease in response latency variance with practice, although final response variances were still more than 10,000 $msec^2$. GTH decreased his mean latency after 20 sessions of practice but after 10 sessions, CK's response latency had actually increased slightly. Kristofferson (1977) found that in speeded duration discrimination, both "short" and "long" responses showed increases in mean and variance as the stimulus marking

TABLE 9: Response latencies and duration discrimination performance in Experiment 3D: speeded duration discrimination. Subjects GTH and CK.

SUBJECT GTH (R_S)

		RESPONSE LATENCIES			DUR. DISC.	
SESSIONS	P_1-P_3	$\overline{X}$	S^2	N	q	$\overline{C}$
1 - 5	232	700.18	30,192	617	22.03	240.79
	248	770.60	44,844	169		
16 - 20	232	563.14	19,878	623	25.03	242.41
	248	560.77	20,292	226		

SUBJECT CK (R_L)

		RESPONSE LATENCIES			DUR. DISC.	
SESSIONS	P_1-P_3	$\overline{X}$	S^2	N	q	$\overline{C}$
1 - 5	235	487.31	42,931	430	51.21	231.10
	245	535.31	45,495	551		
6 - 10	235	570.80	13,465	364	26.71	235.43
	245	576.26	10,058	594		

the end of the stimulus interval moved through the range of the triangular distribution of C, the duration discrimination criterion. That is, the longer was a stimulus interval, relative to the set of stimulus durations, the longer and more variable were the speeded discrimination responses to it, for a given type of response ("short" or "long"). In Kristofferson's study, "short" responses to intervals below the range of C looked like simple RTs to the stimulus ending the interval while "long" responses to intervals above the range of C were initiated by C. In the present experiment, both P_1-P_3 durations were presumably within the range of C. For both the "short" (GTH) and the "long" (CK) responses, responses were generally later and more variable when the longer P_1-P_3 interval was presented, although there are exceptions. The results are generally consistent with the real-time criterion theory of duration discrimination but they are too variable to be used in a specific test of this theory. Practice was not extended sufficiently to reduce the variability of the responses.

The speeded discrimination performance of both Ss was worse than it had been in the last set of baseline sessions and for CK, discrimination performance was inferior to that in the "discrimination only, P_1-P_3 only" experimental condition, where the presented stimuli were exactly the same as those in the present experiment. CK's q estimate decreased after several sessions of speeded discrimination while GTH's discrimination performance did not improve with the amount of practice given here. After practice, CK's discrimination performance was approaching that in his last baseline sessions but GTH's q estimate was still elevated above his baseline.

If the duration discrimination criterion formed part of the synchronization chain in the dual task, as portrayed in the sequential model, Ss should be able to change to the speeded duration discrimination task quite easily. All that would be necessary would be to delete I_2, and to initiate the response from the discrimination event. The difficulty that Ss experienced in performing the speeded duration discrimination task adds to the evidence that the discrimination criterion does not form part of the synchronization chain. In the present experiment, there was no change in the overall stimulus situation from the immediately preceding condition ("discrimination only, P_1-P_3 only"), so such a change cannot account for the disruption in discrimination performance. Some increase in response variance might be expected due to the necessity of withholding responses on some proportion of the trials, in contrast to responding on every trial in the dual task. However, the extremely high variances observed in the present task are unlikely to arise from this source. It is more reasonable to assume that the demands made upon S, and the mechanism by which he accomplishes his task, are different in the speeded discrimination task from those used in the dual synchronization-duration discrimination task. The results of the present experiment support those of Experiments 1 and 2, where it was shown that the psychometric variance is independent of the synchronization variance, in demonstrating that the duration discrimination criterion does not form part of the synchronization response chain in the dual task.

General Discussion

The research presented here has shown clearly that Ss are able to concurrently perform two timing tasks: a temporal interval production task and a duration discrimination task. Ss were required to make a decision about the duration of an interval presented while they were producing another, longer interval. Neither the response-stimulus synchronization nor the duration discrimination were impaired by the presence of the other task. In fact, synchronization variance decreased when the duration discrimination task was first interpolated within the synchronization interval (See Figures 6, 7, & 8). After prolonged experience with the baseline dual task, each task was performed individually by CK and GTH in Experiment 3. Instead of improving, performance on both response-stimulus synchronization and duration discrimination was disrupted when the concurrent task was removed (See Tables 7 & 8). In Experiment 3, practice with the individual tasks was not prolonged so we do not know what level of performance these Ss could have attained in the single-task situations. However, performance in the dual task situation can be compared to that found by other investigators. The response variances in the response-stimulus synchronization component of the dual task were comparable to those found previously in the synchronization task alone, using a similar response apparatus (See Table 1). In addition, the duration discrimination performance in the dual task was at least as good as that reported elsewhere by other investigators for duration discrimination alone, using similar base durations and well-practised subjects (See

Table 2). Thus, not only could the two tasks be performed concurrently, but they were both performed well.

The rationale for the dual task paradigm in the present research was to maximize the chance of finding "virtually perfect" duration discrimination. It was hoped that, by placing the duration discrimination task within the synchronization interval, the deterministic timer used to time the synchronization interval could be accessed to perform extremely accurate duration discrimination. The dual task paradigm did not lead to the use of the deterministic synchronization timer to perform error-free duration discrimination, but we still cannot reject the hypothesis that it might be possible to perform error-free duration discrimination by the production of a deterministic internal criterion. Previous investigators have found that the psychometric variance in duration discrimination is an increasing function of base duration (Abel, 1972 a,b; Creelman, 1962; Divenyi & Danner, 1977; Getty, 1975) and this finding was confirmed, for a very small range of base durations, in the present research. Kristofferson (1980) found that, after prolonged practice, psychometric variance was constant within particular ranges of base durations. However, psychometric variance increased greatly between ranges. Thus, it has not yet been shown that duration discrimination can be performed by the production of an invariant internal criterion, although Kristofferson's (1980) finding that psychometric variance can be constant over a range of base durations suggests that a deterministic timer is involved. Perfect discrimination of the duration of short intervals remains an elusive goal for future investigation.

Not only did the present research show that the deterministic synchronization timer is not used to perform duration discrimination in the dual task situation, but it also seems clear that the timing mechanisms used to perform each task are not the same. The characteristics of both response-stimulus synchronization and duration discrimination that had been previously reported were confirmed in the present research. The distributions of synchronization responses were triangular in shape, and the psychometric variance in the duration discrimination task was well-described by a triangular distribution, as had been previously found (Hopkins & Kristofferson, 1980; Kristofferson, 1976, 1977). However, in the dual task situation, the variance of each of these distributions can be changed without affecting the other. Thus, it must be concluded that the variances do not arise from the same source. The quantal measure "q", which represents half the base of a triangular distribution, only occasionally has the same value for each of the two tasks, even when they are performed concurrently. This does not show that a quantal mechanism does not play a part in the timing of short durations. Indeed, the finding of triangular distributions suggests such a mechanism. However, the functional quantum size depends on the task.

Other previously-observed characteristics of response-stimulus synchronization and duration discrimination were also found in the present research. The variance of synchronization responses did not change with mean latency, as has been found before (Kristofferson, 1976; see also the results of Bartlett & Bartlett, 1959; Naatanen et al., 1974; Saslow, 1974). For the small range of base durations used, psychometric variance in duration discrimination increased with base duration, as discussed above. Although changing the base duration in duration discrimination between sessions was disruptive to performance, discrimination performance improved with practice at the new base duration. These findings are in agreement with previous research on duration discrimination alone (Abel, 1972 a,b; Creelman, 1962; Divenyi & Danner, 1977; Getty, 1975; Kristofferson, 1980). Thus, while being performed concurrently, each task retains its individual characteristics. It must be concluded that response-stimulus synchronization and duration discrimination are not performed by the same mechanism and, indeed, the variability found in each task can be independent of the other, even when they are being performed concurrently. This independence of variance suggests that different timers or "clocks" are used to perform the two tasks but disruption of the duration discrimination task could result from changes in the proportion of trials on which the stimuli are processed, or changes in the response selection mechanism. However, it is not apparent how these aspects of duration discrimination would be dependent on base duration, whereas a timer that accumulates variance with time would produce the characteristic duration discrimination results. Thus, the different characteristics of the two tasks, found in the dual task situation, suggest that different timing mechanisms are used to accomplish the two tasks.

It was mentioned in the introduction that some investigators (Eisler, 1975, 1981 a,b; Getty, 1975, 1976; Triesman, 1963) have studied both temporal interval production and duration discrimination and concluded that a single timing mechanism can account for behaviour in both types of tasks. These studies found that the variances of subject-produced temporal intervals increased with the duration of the interval. Two factors account for the difference between these findings and the present results, as well as those of Kristofferson (1976). The earlier investigators used relatively unpractised Ss who ran only a few sessions each. In addition, most of the intervals used in those experiments were longer than the constant-variance range for response-stimulus synchronization. Kristofferson (1976) showed that, even for well-practised Ss, the variance of synchronization response latencies increases with mean latency when the latency is larger than 550 msec. Thus, the conclusion that the mechanism used to perform response-stimulus synchronization is different from that used to perform duration discrimination must be confined to intervals between 170 msec. and 550 msec. in duration, until further research suggests otherwise.

It has been shown that both response-stimulus synchronization and duration discrimination exhibited their usual individual characteristics in the present dual task, and the variance found in each task was not related to that of the concurrent task. In addition, small changes in the base duration of one task did not affect the performance of the other. This apparent independence is consistent with Saslow's (1974) finding that two different short time intervals can be stored and reproduced without interference, although her Ss were required to produce only one interval on each trial. In contrast, Curtis and Rule (1977) found that when Ss were required to make judgements about the sum of, average of, or difference between two concurrently presented intervals, the two durations interacted in a way that they did not when they were presented sequentially. In the present dual task, Ss were not asked to combine measures of the two intervals; that is, the decisions to be made about each interval were independent of one another. Thus, it has been shown that Ss can, if necessary, deal independently with two simultaneously presented time intervals, at least if they must make different kinds of responses to the two intervals. Independence of performance on two concurrent tasks has been taken as evidence that one of the tasks has become automatized (Logan, 1979). The independence found between the two tasks in the present research is an indication that at least one of the tasks has become automatic. Consistent mapping of stimuli and responses from trial to trial is necessary for the development of automaticity (Logan, 1979; Schneider & Fisk, 1982; Poltrock et al., 1982), and this requirement is fulfilled by both the synchronization and duration discrimination tasks. Thus, a decision about which task becomes automatic cannot be made on this basis. The deterministic nature of the synchronization timing interval implies that a stable process is involved and Kristofferson (1977) has suggested that this timing might be the duration of automatic chains like those proposed by Shiffrin and Schneider (1977).

Although duration discrimination and response-stimulus synchronization performances are largely independent in the present dual task situation, the two tasks are not entirely independent of one another. The presence of the duration discrimination stimuli had systematic effects on synchronization performance. The mean and variance of the synchronization response latency distributions were usually smallest on trials on which the "short" P_1-P_3 interval was presented, next when the "long" P_1-P_3 interval was presented, and largest on trials on which no P_3 was presented. In addition, synchronization response variance was increased when the duration discrimination task was removed. In spite of this relationship, it is clear that the duration discrimination criterion does not form part of the chain of events for the synchronization response. This fact was shown in several ways: (i) the estimated psychometric variance for duration discrimination is independent of synchronization variance; (ii) Ss had difficulty when switched from the dual task to a speeded discrimination task; (iii) the differences between the synchronization distributions that occurred on the three types of stimulus trials were not consistent with the sequential model of the dual task. A qualitative model was proposed which accounts for the observed effects of the interpolation of the duration discrimination task within the synchronization interval. It was assumed that well-practised response-stimulus synchronization is performed by the repetition of a stable, automatic chain of internal events (Kristofferson, 1977). The necessity of making temporal decisions about stimuli presented during the synchronization interval produces interruptions within the synchronization timing chain. Each discontinuity adds a small amount of time to the final response, but does not affect the continuation of the automatic chain, which is immediately resumed. These interruptions occur only during an interval which is called the observation window. The duration and placement of the observation window are determined by experience with the set of possible P_1-P_3 values.

The Observation Window Model not only accounts for the effect of the duration discrimination stimuli within the synchronization interval, but also points out a critical difference between Ss' approach to the two tasks. In duration discrimination, S is uncertain about when the stimulus duration will end and he must maintain a state in which he is ready to process the time of an incoming stimulus, signalling the end of the presented duration. In response-stimulus synchronization, in contrast, S is in control of the time at which the interval will end, and he can set up an automatic chain of events that will produce the desired interval. Uncertainty about the time at which the duration discrimination stimulus will end may prevent the automatization of the discrimination task, even though the requirement of trial-to-trial consistency of stimuli and responses has been met. The necessary conditions for the development of automaticity may not be the same for alphabetic and temporal stimuli. In fact, in studies of automaticity using alphabetic stimuli, the temporal spacing of the sequential stimuli is usually perfectly regular (e.g., Logan, 1979; Poltrock et al., 1982; Schneider & Fisk, 1982; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). As this temporal regularity has not been systematically studied, its role in the development of automaticity is not known. Temporal uncertainty may prevent the development of automatic processing as effectively as does the irregular mapping of responses onto stimuli. Alternatively, temporal uncertainty may only interfere with automatization when a temporal decision must be made about the presented stimulus. The effects of the duration discrimination stimuli on the synchronization task, interpreted as demonstrating the existence of an observation window, may indicate that the two tasks inevitably share some resources and cannot become fully independent. A non-temporal task, such as a letter-search task, could be interpolated within the synchronization interval, with regular or irregular timing of stimuli. If there were no evidence of an observation window, it would show that the observation window indicates the sharing of resources by similar tasks. If all stimulus conditions have systematic effects on synchronization behaviour, it may be that the observation window reflects the presence of any significant events within a produced time interval.

Another view of the relationship between two concurrently produced temporal intervals has recently been presented by Klapp (1979). He had Ss tap rhythms on separate telegraph keys with their left and right hands. The rhythms were specified by tone and/or light stimuli. He found that performance suffered unless the rhythms required of the two hands had the same or harmonically related periods. Jones (1976) has hypothesized that perceptual rhythms become entrained to stimulus rhythms; attentional energy is heightened when it is expected that a stimulus will occur. Such an entrainment could play a role in the development of automaticity in letter-search tasks where the stimuli are regularly spaced, as mentioned above. In addition, Povel (1981) has found that Ss perform best when synchronizing with and imitating temporal patterns made up of inter-stimulus intervals that are even multiples of one another. If regular rhythmic patterns do lead to better temporal performance, it might be that duration discrimination performance in the dual synchronization-duration discrimination task would be optimized if the P_1-P_3 MP were exactly in the middle of the P_1-P_2 interval. Because the experiments reported here had been designed to test whether the deterministic synchronization timer could be used to perform duration discrimination, this possibility was not tested. However, throughout the course of the experiments, the ratio of P_1-P_3 MP to P_1-P_2 took on many different values; at no value of this ratio was discrimination performance strikingly better than at any other. We do know that biological rhythms become entrained to external stimuli (Enright, 1980), and the notion that such a mechanism plays a role in timing task such as response-stimulus synchronization and duration discrimination should be tested by presenting the trials within the context of rhythmically paced temporal patterns.

The experiments reported here showed that duration discrimination and response-stimulus synchronization can be performed concurrently with little or no decrement in the performance of either task. In the dual task situation, the obtained variances on each of the two tasks are mutually independent of one another, indicating that a single timing mechanism does not serve for both tasks. The possibility that there are at least two different mechanisms for the timing of short durations should be taken into account in the formulation of future theories of "time perception." No specific mechanism for duration discrimination is proposed here, although the results are consistent with the real-time criterion theory (Kristofferson, 1977). There is some evidence that the interruptions in timing that occur in the observation window make a contribution to the duration discrimination response in the dual task. When a situation is complex and duration discrimination is difficult, Ss probably make use of any information that is available to perform the discrimination. Kristofferson (1980) has shown that, after prolonged practice in duration discrimination, steps appear in the function relating the standard deviation of the criterion distribution to base duration. The fact that psychometric variance can be constant for a range of base durations indicates that, after prolonged practice, Ss can insert some deterministic timing segments into the interval produced to perform duration discrimination.

However, it has been shown here that, even for base durations within the range for which temporal interval production can be deterministic, a deterministic timing mechanism was not used to perform duration discrimination. Thus, at least two different mechanisms for the timing of short durations are now known to exist and future theories of "time perception" must take this into account.

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APPENDIX A

Tabled values for graphed data

Table 1. Figure 6. Synchronization performance during training sessions, Subject JB.

GROUP OF SESSIONS	NUMBER OF SESSIONS	OVERALL		$P_1-P_3 = 240$		No P_3	
		$\overline{X}$	S^2	$\overline{X}$	S^2	$\overline{X}$	S^2
1	4	459.28	632.02				
2	5	464.47	823.72				
3	5	465.12	1408.61				
4	5	459.43	783.52				
5	5	462.98	507.48				
6	5	460.32	478.55				
7	6	461.18	768.39	455.86	691.59	466.53	836.78
8	5	460.98	593.04	457.76	533.60	464.22	652.35
9	5	458.00	371.36	453.36	337.63	462.69	405.23
10	5	456.60	303.16	452.59	280.85	460.63	325.51
11	5	456.64	303.94	453.13	306.50	460.07	301.39
12	5	458.38	326.50	453.43	298.54	463.27	338.99
13	5	458.38	328.57	372.43	280.67	462.30	340.65
14	5	459.93	479.39	456.44	421.87	463.40	467.96
15	5	459.74	261.19	457.04	231.92	462.39	274.53
16	5	459.15	238.18	456.68	208.43	461.64	251.20
17	5	458.48	235.24	456.10	221.52	460.83	236.14
18	5	457.31	160.97	455.07	148.35	459.52	163.33
19	5	456.39	206.29	453.48	180.41	459.28	213.63
20	5	460.61	175.84	458.51	157.54	462.67	182.85
21	5	461.02	235.43	458.68	218.86	463.34	237.64
22	5	454.66	223.65	452.02	211.71	457.29	218.78
23	5	455.22	173.90	454.08	164.34	456.37	178.30

		MEAN LATENCY			
GROUP OF SESSIONS	NUMBER OF SESSIONS	OVERALL	"short" P_3	"long" P_3	No P_3
24	4	456.46	452.10	456.31	458.62
25	3	453.59	451.78	453.53	454.59
26	2	457.45	452.36	460.39	458.63
27	1	453.70	451.62	453.25	456.21
28	5	458.71	455.62	460.22	460.25
29	5	457.68	455.17	458.62	459.29
30	5	460.40	457.24	464.46	459.54
31	5	462.20	459.44	466.13	460.99
32	5	463.17	460.90	468.22	460.38

TABLE 1 continued

GROUP OF SESSIONS	NUMBER OF SESSIONS	MEAN VARIANCE OVERALL	"short" P_3	"long" P_3	No P_3
24	4	171.71	163.71	195.42	164.52
25	3	164.29	165.53	206.35	143.14
26	2	228.67	158.13	331.24	218.39
27	1	139.19	120.91	160.23	136.62
28	5	167.47	147.29	181.64	173.27
29	5	150.39	148.94	172.68	130.06
30	5	172.47	154.73	204.04	158.79
31	5	154.51	132.99	174.50	155.97
32	5	178.96	134.27	206.35	196.35

Table 2. Figure 7. Synchronization performance during training sessions, Subject GTH.

GROUP OF SESSIONS	NUMBER OF SESSIONS	OVERALL $\overline{X}$	OVERALL S^2	$P_1-P_3 = 240$ $\overline{X}$	$P_1-P_3 = 240$ S^2	No P_3 $\overline{X}$	No P_3 S^2
1	3	470.75	2233.65				
2	5	466.42	1722.61				
3	5	460.91	518.30				
4	5	463.64	625.72				
5	5	459.47	412.71				
6	3	458.12	4186.81	446.57	2584.77	469.39	5367.05
7	5	467.21	1067.23	466.61	1178.93	467.82	938.15
8	5	466.97	476.39	463.42	353.19	470.50	567.62
9	5	461.34	485.95	459.20	415.12	463.44	539.79
10	5	464.37	578.54	464.33	512.41	464.41	639.29
11	5	463.84	410.16	465.25	424.27	462.41	392.96
12	5	458.80	442.48	460.98	445.19	456.62	425.04
13	5	464.79	377.27	466.58	348.37	463.00	397.95
14	5	469.72	426.69	471.05	412.09	468.38	436.27
15	5	465.39	457.59	467.83	499.22	462.93	397.04
16	5	462.28	396.06	464.05	385.43	460.49	397.99
17	5	468.18	481.53	465.18	395.62	471.24	511.99
18	5	458.69	412.98	458.20	357.35	459.15	465.27
19	5	460.67	360.72	461.22	348.37	460.11	369.35
20	5	468.58	436.42	467.79	380.84	469.26	460.43
21	5	455.62	409.69	455.82	375.40	455.42	434.91

MEAN LATENCY

GROUP OF SESSIONS	NUMBER OF SESSIONS	OVERALL	"short" P_3	"long" P_3	No P_3
22	1	469.06	463.27	468.45	475.21
23	5	460.17	452.70	462.41	465.47
24	3	455.44	448.73	457.21	460.45
25	4	455.68	448.52	458.03	460.52

MEAN VARIANCE

22	1	520.52	421.17	376.45	758.41
23	5	351.47	262.11	401.28	391.75
24	3	240.68	202.22	234.35	285.60
25	4	259.91	210.93	272.02	296.54

Table 3. Figure 8. Synchronization performance during training sessions, Subject CK.

GROUP OF SESSIONS	NUMBER OF SESSIONS	OVERALL		$P_1-P_3 = 240$		No P_3	
		$\overline{X}$	S^2	$\overline{X}$	S^2	$\overline{X}$	S^2
1	7	455.61	1652.24				
2	5	460.40	1321.02				
3	5	465.76	461.69				
4	5	461.89	460.72				
5	5	457.96	339.19				
6	5	459.47	373.05				
7	3	462.31	876.57	456.22	862.49	468.13	805.07
8	5	458.19	445.39	455.75	387.35	460.61	487.52
9	5	463.13	350.81	459.97	281.43	466.30	388.80
10	5	459.37	361.83	456.82	340.60	461.89	365.08
11	5	459.64	306.67	456.74	294.74	462.56	290.61
12	5	459.04	399.06	460.95	356.62	457.21	417.03
13	5	457.22	290.64	458.05	260.87	456.40	284.75
14	5	458.97	243.38	458.78	211.76	459.15	268.13
15	5	460.65	169.03	460.73	147.19	460.57	190.44
16	5	462.59	220.65	461.18	167.70	463.97	267.98
17	5	458.19	181.08	457.99	148.25	458.42	205.87

MEAN LATENCY

GROUP OF SESSIONS	NUMBER OF SESSIONS	OVERALL	"short" P_3	"long" P_3	No P_3
18	4	462.86	459.57	465.39	463.69
19	5	459.56	458.35	461.96	458.37
20	5	462.12	459.67	465.85	460.87
21	5	461.21	458.85	464.29	460.54

MEAN VARIANCE

18	4	141.68	125.79	139.20	160.48
19	5	146.25	122.78	137.94	177.21
20	5	158.11	138.55	173.93	162.28
21	5	149.80	136.12	149.51	163.90

Table 4. Figure 9. Synchronization response latency distributions, Subject JB.

LOWER BIN BOUNDARY (MSEC.)	NUMBER OF RESPONSES		
	$P_1-P_3' = 230$	$P_1-P_3 = 250$	No P_3
405	0	0	0
410	0	1	0
415	0	0	1
420	1	1	3
425	2	0	7
430	4	4	7
435	5	4	15
440	33	17	27
445	35	24	51
450	65	25	54
455	75	61	68
460	94	64	73
465	65	68	59
470	56	60	45
475	36	60	50
480	20	44	15
485	7	27	11
490	0	22	6
495	1	7	2
500	0	5	0
505	0	2	0
510	0	1	1
515	0	1	0
520	0	0	0
TOTAL	499	498	495

Table 5. Figure 10. Discrimination performance during baseline task preceding Experiment 1.

SUBJECT	GROUP OF SESSIONS	NUMBER OF SESSIONS	AVERAGE q (MSEC.)	AVERAGE $\overline{C}$ (MSEC.)
JB	1	5	78.59	235.35
	2	5	58.87	238.58
	3	5	49.45	238.43
	4	5	44.75	239.06
	5	5	46.59	238.40
GTH	1	3	21.18	241.93
	2	4	22.17	240.57
CK	1	4	42.48	238.14
	2	5	38.35	236.78
	3	5	21.32	239.19
	4	5	28.29	238.29

Table 6. Synchronization response latency variance and duration discrimination psychometric variance during baseline task preceding Experiment 1.

SUBJECT	GROUP OF SESSIONS	NUMBER OF SESSIONS	SYNCHRONIZATION VARIANCE (MSEC.^{2})		PSYCHOMETRIC VARIANCE (MSEC.^{2})
			OVERALL	NO P_3	
JB	1	5	167.47	173.27	1029.40
	2	5	150.39	130.06	577.61
	3	5	172.47	158.79	407.55
	4	5	154.51	155.97	333.76
	5	5	178.96	196.35	361.77
GTH	1	3	240.68	285.60	74.77
	2	4	259.91	296.54	81.92
CK	1	4	141.68	160.48	300.76
	2	5	146.25	177.21	245.12
	3	5	158.11	162.28	75.76
	4	5	149.80	163.90	133.39

Table 7. Figure 12. Estimates of q and $\overline{C}$ for consecutive sessions in Experiment 1A. Subject CK.

SESSION	P_1-P_3 MP	q (MSEC.)	$\overline{C}$ (MSEC.)
1	240	35.21	237.94
2	240	31.53	238.82
3	240	23.43	238.55
4	240	22.80	236.55
5	240	28.50	239.65
6	245	20.70	244.15
7	250	26.37	247.72
8	255	24.30	254.07
9	260	19.63	260.13
10	265	31.92	264.14
11	270	33.58	268.02
12	275	33.16	270.52
13	280	29.93	275.91
14	285	59.02	279.41
15	285	71.31	285.74
16	285	29.15	283.69
17	285		
18	285		
19	285	37.34	280.00
20	285	46.25	281.14
21	285	59.95	271.18
22	285	42.01	277.84
23	285	27.39	282.36
24	285	52.35	283.88
25	285	32.56	284.93
26	285	31.72	281.27
27	285	27.61	283.42
28	285	24.71	281.76
29	285	41.40	281.89
30	285	25.77	284.62
31	285	41.99	283.78
32	285	33.57	279.67
33	285	31.72	275.57
34	280	32.78	275.17
35	275	24.15	274.33
36	270	35.69	265.18
37	265	16.28	265.00
38	260	25.88	256.96
39	255	35.22	253.96
40	250	31.53	248.82
41	245	34.43	243.25
42	240	18.46	239.00
43	240	19.02	239.36
44	240	20.75	238.47
45	240	18.70	238.12
46	240	26.63	239.67
47	240	35.16	243.19

Table 8. Figure 13. Synchronization performance in Experiment 1A. Subject CK.

			MEAN LATENCY (MSEC.)		
SESSION	P_1-P_3 MP	OVERALL	"short" P_3	"long" P_3	No P_3
1	240	460.66	456.48	465.17	460.40
2	240	463.10	461.94	468.15	459.31
3	240	459.95	483.43	462.59	458.86
4	240	461.38	457.50	463.22	463.37
5	240	460.97	459.88	462.30	460.75
6	245	465.04	460.45	468.87	465.74
7	250	459.02	458.56	462.22	456.17
8	255	459.10	457.83	460.31	459.15
9	260	460.39	453.81	457.32	470.05
10	265	459.61	456.23	461.87	460.95
11	270	462.15	457.90	461.68	467.02
12	275	453.14	448.76	449.34	461.35
13	280	463.86	458.96	463.04	469.61
14	285	460.89	454.73	461.72	466.25
15	285	461.52	456.76	459.41	468.18
16	285	249.56	454.24	457.11	467.16
17	285	462.03	459.31	458.56	468.08
18	285	458.94	456.03	458.36	462.68
19	285	461.68	458.26	457.92	468.74
20	285	464.56	462.13	463.16	468.62
21	285	462.18	459.80	461.72	465.00
22	285	460.76	456.39	459.84	466.07
23	285	460.74	457.70	460.13	464.59
24	285	453.19	451.28	451.29	456.92
25	285	456.06	453.37	454.51	460.33
26	285	464.49	461.32	464.50	467.81
27	285	459.49	456.84	457.63	463.84
28	285	461.17	456.70	460.94	465.96
29	285	461.23	459.19	462.28	462.20
30	285	459.54	459.60	458.44	460.54
31	285	460.86	459.02	459.26	464.37
32	285	457.35	456.88	456.57	458.57
33	285	460.67	459.26	459.13	463.58
34	280	455.68	452.12	453.56	461.17
35	275	459.35	455.82	457.84	464.33
36	270	461.93	460.03	463.89	461.93
37	265	459.73	457.05	463.25	458.93
38	260	457.69	455.90	459.21	457.85
39	255	463.36	458.68	464.79	466.53
40	250	463.58	462.72	465.54	462.50
41	245	461.81	458.68	464.59	462.19
42	240	461.41	458.79	464.06	461.41
43	240	458.47	455.64	461.33	458.50
44	240	463.14	461.97	465.61	461.89
45	240	460.48	458.25	464.25	458.94
46	240	457.64	455.96	460.12	456.81
47	240	458.00	456.02	461.15	456.91

TABLE 8 continued

LATENCY VARIANCE (MSEC.^{2})

SESSION	P_1-P_3 MP	OVERALL	"short" P_3	"long" P_3	No P_3
1	240	190.56	154.31	207.30	210.42
2	240	148.99	146.80	152.25	147.97
3	240	161.44	144.12	155.78	183.96
4	240	113.53	122.45	88.88	129.75
5	240	134.46	112.90	143.35	147.42
6	245	158.14	121.20	143.99	207.31
7	250	150.97	136.31	154.27	161.94
8	255	125.32	137.39	109.93	128.61
9	260	208.31	146.92	184.66	293.34
10	265	148.85	117.42	172.84	158.37
11	270	149.43	151.87	115.81	182.64
12	275	203.89	193.83	148.24	271.08
13	280	217.28	204.77	184.56	262.30
14	285	212.59	126.38	256.14	255.25
15	285	235.04	209.64	175.79	316.19
16	285	171.01	135.12	117.66	259.18
17	285	252.35	264.44	201.61	290.34
18	285	167.20	147.69	164.78	190.68
19	285	128.67	124.53	113.85	147.10
20	285	182.72	195.22	153.59	199.65
21	285	140.10	101.60	136.75	181.69
22	285	137.45	118.83	152.48	141.52
23	285	136.74	111.10	113.83	187.40
24	285	126.31	124.91	138.94	115.16
25	285	150.81	130.27	143.54	178.83
26	285	133.23	86.96	136.65	178.50
27	285	168.92	139.96	174.34	191.47
28	285	139.09	98.47	122.32	197.30
29	285	185.49	174.93	172.84	208.45
30	285	175.04	170.77	163.19	190.75
31	285	164.20	153.88	193.47	144.44
32	285	298.49	243.26	303.86	349.20
33	285	162.54	137.79	159.24	190.30
34	280	138.47	141.57	147.02	126.92
35	275	121.29	87.99	140.11	136.52
36	270	101.14	65.91	114.55	124.05
37	265	127.71	101.72	109.71	171.05
38	260	118.23	93.89	126.00	133.56
39	255	125.71	101.31	125.09	150.23
40	250	124.46	105.34	109.61	157.75
41	245	94.81	62.44	79.06	141.84
42	240	109.00	94.24	99.32	135.42
43	240	106.28	97.75	68.88	152.87
44	240	152.70	111.40	164.16	182.76
45	240	116.41	103.42	75.42	149.00
46	240	127.40	107.91	139.28	134.33
47	240	110.69	81.96	106.09	131.17

Table 9. Figure 14. Estimates of q and $\overline{C}$ as a function of P_1-P_2 interval in Experiment 1B. Subject GTH.

	DECREASING P_1-P_2			INCREASING P_1-P_2		
P_1-P_2	NUMBER OF SESSIONS	q (msec.)	$\overline{C}$ (msec.)	NUMBER OF SESSIONS	q (msec.)	$\overline{C}$ (msec.)
460	1	23.46	239.90	1	17.35	241.95
455	2	21.16	240.60	1	20.34	244.76
450	1	16.27	240.60	1	16.04	241.37
445	1	17.82	241.09	1	18.12	243.44
440	1	16.08	241.29	1	17.74	240.45
435	1	17.69	238.34	1	20.42	242.94
430	1	17.21	240.30	1	14.55	244.47
425	1	16.59	238.87	1	17.76	241.06
420	1	16.54	241.82	1	14.85	242.15
415	1	17.95	240.93	1	14.60	242.49
410	1	19.13	239.09	1	14.02	242.62
405	1	23.05	241.74	1	16.79	240.19
400	1	22.44	239.90	2	20.26	242.83
395	1	19.34	238.14	1	17.31	242.87
390	1	18.69	240.27	2	18.43	243.60
385	1	23.89	241.56	0		
380	1	30.10	241.93	1	20.83	239.01
375	1	27.13	242.90	0		
370	1	33.73	240.49	2	28.36	239.11
365	2	24.39	238.30	0		
360	1	57.74	240.43			

Table 10. Figure 15. Estimates of q and $\overline{C}$ as a function of P_1-P_2 interval in Experiment 1B. Subject JB.

	DECREASING P_1-P_2			INCREASING P_1-P_2		
P_1-P_2	NUMBER OF SESSIONS	q (msec.)	$\overline{C}$ (msec.)	NUMBER OF SESSIONS	q (msec.)	$\overline{C}$ (msec.)
460	1	55.03	240.78			
455	1	44.79	242.33			
450	1	51.00	238.12			
445	2	80.49	237.58			
440	2	40.46	240.48			
435	1	88.73	244.82			
430	1	57.72	241.06			
425	1	31.95	241.84			
420	1	38.63	241.60			
415	1	34.67	241.27			
410	1	24.39	241.42			
405	1	35.32	242.32			
400	1	26.32	241.05			
395	1	25.79	242.08			
390	1	20.85	243.59			
385	1	21.75	239.07			
380	1	23.91	242.19			
375	1	28.26	244.94			
370	1	42.92	238.06			
365	1	36.82	244.01			
360	1	25.04	238.67			
355	1	37.89	242.06			
350	1	21.79	241.06			
345	1	21.77	240.67			
340	1	32.66	237.24			
335	1	46.93	235.39	2	23.85	240.66
330	1	44.34	233.70	1	19.95	239.83
325	1	46.[illegible]9	236.83	0		
320	1	43.78	240.52	1	34.65	241.15
315	1	41.41	240.83	0		
310	1	50.26	247.98	1	50.59	244.99
305	1	43.68	239.08	0		
300	1	47.58	243.77	1	66.54	238.07
295	1	64.74	243.02	0		
290	1	63.53	239.89			

Table 11. Figure 16. Synchronization performance as a function of P_1-P_2 in Experiment 1B. Subject GTH.

		SYNCHRONIZATION LATENCY VARIANCE			
		DECREASING P_1-P_2			
P_1-P_2	NUMBER OF SESSIONS	OVERALL	P_1-P_3 = 232	P_1-P_3 = 248	No P_3
460	1	308.77	273.15	332.16	320.51
455	2	419.45	440.80	356.70	457.41
450	1	261.70	212.84	253.25	317.46
445	1	235.52	186.97	245.13	274.45
440	1	253.43	172.42	242.12	349.43
435	1	278.56	228.36	267.60	344.05
430	1	264.77	190.54	282.14	320.12
425	1	326.88	311.06	294.24	377.00
420	1	316.53	228.12	329.21	389.60
415	1	258.42	342.84	191.83	236.47
410	1	345.70	270.92	319.59	444.35
405	1	264.28	229.15	248.09	313.89
400	1	326.28	321.19	316.49	340.91
395	1	326.69	294.48	290.74	399.10
390	1	330.50	279.60	377.35	338.11
385	1	366.30	356.93	396.21	346.06
380	1	291.68	245.62	333.89	295.96
375	1	314.08	279.72	349.92	312.96
370	1	419.49	364.20	457.28	438.50
365	2	304.17	304.86	272.36	335.83
360	1	421.60	437.98	274.79	469.23
		INCREASING P_1-P_2			
370	2	340.17	284.03	352.77	383.76
380	1	390.27	357.16	467.47	347.31
390	2	318.95	297.24	283.44	374.70
395	1	277.05	331.71	274.93	423.92
400	2	296.44	254.12	338.77	295.16
405	1	279.58	192.92	318.76	327.43
410	1	256.76	251.05	288.42	229.52
415	1	195.21	162.92	219.51	204.09
420	1	258.71	197.15	309.44	269.73
425	1	334.32	345.54	392.92	268.79
430	1	320.13	220.49	308.37	431.89
435	1	343.19	270.34	294.73	466.47
440	1	307.74	296.84	302.38	324.10
445	1	212.61	160.56	190.16	291.54
450	1	183.53	129.94	175.58	244.80
455	1	350.42	335.44	353.29	362.89
460	1	180.88	145.21	197.11	200.49

Table 12. Figure 17. Synchronization performance as a function of P_1-P_2 in Experiment 1B. Subject JB.

SYNCHRONIZATION LATENCY VARIANCE

DECREASING P_1-P_2

P_1-P_2	NUMBER OF SESSIONS	OVERALL	P_1-P_3 = 230	P_1-P_3 = 250	No P_3
460	1	182.15	147.56	225.47	172.55
455	1	125.60	109.26	126.69	140.41
450	1	167.53	134.07	196.47	171.18
445	2	229.53	179.57	319.83	190.42
440	2	281.93	283.59	337.28	223.57
435	1	228.65	175.00	334.99	176.98
430	1	207.33	160.91	280.28	183.67
425	1	253.69	214.56	319.45	226.25
420	1	239.74	224.21	251.96	242.91
415	1	159.41	162.57	195.71	119.10
410	1	145.60	145.94	151.80	139.11
405	1	207.06	182.57	207.72	230.43
400	1	187.03	179.61	201.74	179.53
395	1	185.16	202.31	127.27	225.10
390	1	191.89	188.09	190.21	197.27
385	1	337.13	315.66	322.05	373.38
380	1	334.67	313.33	245.32	441.43
375	1	293.70	240.71	359.84	281.63
370	1	301.44	248.41	309.11	345.56
365	1	212.35	203.40	194.62	238.23
360	1	216.82	198.73	228.48	223.96
355	1	177.04	156.07	177.71	197.76
350	1	131.17	124.12	113.59	155.20
345	1	191.23	158.21	191.04	223.78
340	1	238.55	223.64	291.21	201.38
335	1	259.62	240.67	227.60	311.78
330	1	192.60	195.41	182.34	200.15
325	1	198.02	228.94	196.91	167.28
320	1	375.10	288.36	390.57	445.41
315	1	258.22	252.05	264.95	257.64
310	1	287.26	291.10	258.91	310.23
305	1	176.67	151.38	208.86	170.85
300	1	192.81	203.55	168.14	206.08
295	1	250.64	278.76	293.12	180.05
290	1	296.22	294.24	328.77	265.68

INCREASING P_1-P_2

P_1-P_2	NUMBER OF SESSIONS	OVERALL	P_1-P_3 = 230	P_1-P_3 = 250	No P_3
300	1	209.99	218.52	206.49	204.79
310	1	199.55	207.53	220.19	169.75
320	1	191.56	209.57	202.27	161.54
330	1	181.76	161.27	214.69	169.26
335	2	162.13	153.53	166.89	165.84

Table 13. Figure 18. Estimated q as a function of ΔD in Experiment 1C. Subject JB. Data are from last five sessions when more than five sessions were run.

ΔD	NUMBER OF SESSIONS	q (MSEC.)	$\overline{C}$ (MSEC.)
2	5	13.92	240.53
4	5	15.09	239.94
6	7	15.07	240.05
8	6	12.10	239.76
10	8	13.82	239.96
12	5	14.10	239.58
14	9	15.66	239.65
16	5	16.26	239.85
18	7	16.49	239.37
20	5	16.32	239.64
22	3	16.25	239.38
24	3	16.94	238.45
26	5	19.30	239.43
28	3	18.70	240.14
30	3	19.54	240.02
32	4	20.64	238.62
34	5	20.55	239.66
36	3	21.48	239.58
38	7	24.48	239.91

Table 14. Figure 19. Synchronization performance as a function of ΔD in Experiment 1C. Subject JB. Data are from last five sessions when more than five sessions were run.

		MEAN SYNCHRONIZATION LATENCY (MSEC.)			
ΔD	NUMBER OF SESSIONS	OVERALL	"short" P_3	"long" P_3	No P_3
2	5	338.80	338.07	338.28	340.04
4	5	339.47	338.55	339.22	340.64
6	7	338.41	337.25	338.69	339.32
8	6	339.81	339.43	340.07	339.94
10	8	338.17	336.85	337.90	339.77
12	5	339.58	338.28	339.42	341.03
14	9	338.37	336.85	337.29	341.00
16	5	338.97	336.89	338.93	341.09
18	7	339.97	338.19	339.65	342.11
20	5	340.07	338.76	339.64	341.80
22	3	339.55	337.91	339.78	341.02
24	3	335.27	333.44	335.03	337.34
26	5	339.04	336.82	339.32	341.03
28	3	339.33	336.62	339.91	341.51
30	3	336.66	335.12	335.85	338.95
32	4	339.14	336.16	340.56	340.71
34	5	337.57	335.91	337.90	338.89
36	3	339.68	336.36	341.10	341.62
38	7	338.53	336.42	338.84	340.35
40	3	334.55	331.55	335.38	336.71
		SYNCHRONIZATION VARIANCE (MSEC.^{2})			
2	5	94.57	90.86	95.30	94.88
4	5	101.04	93.31	97.14	110.08
6	7	118.18	118.70	118.16	114.91
8	6	98.93	78.17	109.28	109.41
10	8	102.10	92.13	100.50	108.95
12	5	92.33	88.31	85.68	98.84
14	9	114.30	115.09	103.97	113.05
16	5	112.25	102.38	116.09	109.19
18	7	127.10	106.96	126.44	139.94
20	5	104.90	99.39	102.77	107.34
22	3	113.82	111.90	105.49	118.56
24	3	135.95	114.93	128.78	155.77
26	5	125.35	95.68	133.52	137.93
28	3	118.92	90.97	140.64	112.35
30	3	145.71	111.87	149.20	166.89
32	4	128.32	108.02	122.63	140.73
34	5	166.85	149.74	166.37	179.39
36	3	146.17	110.09	165.59	145.79
38	7	154.50	140.89	157.74	156.67
40	3	203.70	167.46	217.23	211.17

Table 15. Figure 20. Synchronization response latency distributions for ΔD = 32 msec. in Experiment 1C. Subject JB.

LOWER BIN BOUNDARY (MSEC.)	NUMBER OF RESPONSES		
	P_1-P_3 = 224	P_1-P_3 = 256	No P_3
295	0	0	0
300	1	1	0
305	1	1	2
310	9	3	6
315	12	7	7
320	23	22	21
325	54	17	33
330	66	69	50
335	96	63	56
340	63	72	64
345	36	69	64
350	20	38	53
355	13	22	22
360	3	12	12
365	1	3	5
370	0	2	1
375	1	1	0
380	0	0	0
385	0	0	1
390	0	0	0
TOTAL	399	402	397

Table 16. Figure 21. Synchronization response latency distributions for ΔD = 4 msec. in Experiment 1C. Subject JB.

LOWER BIN BOUNDARY (MSEC.)	NUMBER OF RESPONSES		
	P_1-P_3 = 238	P_1-P_3 = 242	No P_3
295	0	0	0
300	1	0	0
305	1	2	0
310	4	3	3
315	9	7	8
320	23	24	23
325	40	45	41
330	78	72	62
335	123	97	81
340	89	97	89
345	67	76	95
350	47	48	54
355	14	21	27
360	6	7	8
365	0	0	5
370	1	0	0
375	0	0	1
380	0	0	0
TOTAL	503	499	497

Table 17. Figure 22: Probability of a "long" duration discrimination response as a function of P_1-P_3 interval in Experiment 2. Subject JB.

THESE DATA ARE PRESENTED IN APPENDIX B.

Table 18. Figure 23. Number of "long" duration discrimination responses as a function of P_1-P_3 interval in Experiment 2. Subject GTH.

P_1-P_2 INTERVAL	TOTAL DISCRIMINATION RESPONSES	NUMBER OF "LONG" RESPONSES
219	211	2
220	225	4
221	215	3
222	218	5
223	220	4
224	225	4
225	219	4
226	214	15
227	214	14
228	220	9
229	217	21
230	208	17
231	205	22
232	210	38
233	206	42
234	206	44
235	197	47
236	211	63
237	201	78
238	199	83
239	194	67
241	216	121
242	213	153
243	210	142
244	214	167
245	206	147
246	220	181
247	209	174
248	211	189
249	206	187
250	208	185
251	202	189
252	200	190
253	197	190
254	207	200
255	226	218
256	224	221
257	224	219
258	230	228
259	219	215
260	229	229
261	219	216

Table 19. Figure 24. Estimated q as a function of ΔD in Experiment 2. Subject JB.

ΔD	q (MSEC.)	$\overline{C}$ (MSEC.)
2	20.69	239.42
4	16.86	238.87
6	20.27	238.87
8	12.86	240.21
10	14.84	239.97
12	13.60	239.60
14	15.50	239.38
16	16.05	239.84
18	15.07	239.15
20	15.92	238.82
22	17.37	240.29
24	16.13	240.34
26	15.84	238.73
28	17.38	239.61
30	19.17	239.90
32	18.47	240.00
34	20.51	240.75
36	20.78	240.00
38		
40		
42	23.15	240.00

Table 20. Figure 25. Estimated q as a function of ΔD in Experiment 2. Subject GTH.

ΔD	q (MSEC.)	$\overline{C}$ (MSEC.)
2	8.66	240.46
4	11.90	239.03
6	19.09	239.27
8	14.17	239.22
10	18.10	240.60
12	15.98	239.54
14	17.89	239.46
16	16.99	238.77
18	16.26	239.73
20	17.77	240.59
22	18.31	239.26
24	17.17	240.26
26	18.95	239.10
28	20.50	238.83
30	19.45	240.73
32	19.42	239.76
34	21.28	240.22
36	21.77	239.10
38	23.15	240.28
40		
42	24.75	240.34

Table 21. Figure 26. Synchronization performance as a function of P_1-P_3 interval in Experiment 2. Subject JB.

P_1-P_3	NUMBER OF RESPONSES	LATENCY (MSEC.)	VARIANCE (MSEC.^{2})
219	229	335.91	110.25
220	218	334.32	107.56
221	216	335.76	98.11
222	223	336.34	94.94
223	221	333.81	102.26
224	223	334.71	76.84
225	202	335.82	93.17
226	212	336.22	119.25
227	208	335.66	94.75
228	218	334.91	100.46
229	212	336.34	97.49
230	220	336.42	113.15
231	209	336.04	103.41
232	214	337.03	102.32
233	202	336.47	105.56
234	208	335.91	82.58
235	208	336.25	90.40
236	199	337.33	103.06
237	199	336.73	87.86
238	198	337.58	80.77
239	198	339.17	102.53
241	225	337.58	108.48
242	223	337.70	104.79
243	224	337.19	109.79
244	220	338.08	107.45
245	215	338.87	89.17
246	213	336.91	113.63
247	209	337.96	113.44
248	207	338.59	103.59
249	200	336.05	127.57
250	203	339.20	145.91
251	203	337.96	90.33
252	207	337.91	105.61
253	204	338.47	117.66
254	201	338.48	150.15
255	222	341.01	122.47
256	224	337.06	107.80
257	232	338.00	107.48
258	224	339.23	134.16
259	232	339.77	117.46
260	227	337.11	123.99
261	231	340.32	102.18
No P_3	1488	339.60	129.10

Table 22. Figure 27. Synchronization performance as a function of P_1-P_3 interval in Experiment 2. Subject GTH.

P_1-P_3	NUMBER OF RESPONSES	LATENCY (MSEC.)	VARIANCE (MSEC.^{2})
219	210	444.88	253.22
220	227	446.40	225.90
221	215	445.04	184.56
222	218	445.39	198.61
223	220	447.86	198.44
224	224	446.76	155.00
225	219	448.52	198.32
226	214	446.14	295.63
227	213	447.99	214.05
228	220	448.14	234.76
229	217	451.28	235.58
230	212	451.35	241.21
231	208	450.51	278.19
232	210	448.26	241.79
233	206	450.76	290.49
234	207	449.54	229.18
235	200	451.47	208.24
236	211	449.39	272.11
237	201	451.48	215.36
238	199	453.08	287.92
239	194	449.78	207.79
241	215	449.11	234.64
242	217	452.07	260.72
243	211	451.82	257.44
244	214	451.58	207.89
245	208	454.56	287.77
246	221	451.36	254.19
247	209	454.09	313.61
248	213	452.03	294.84
249	206	455.63	270.29
250	208	456.79	219.19
251	201	456.47	230.09
252	201	457.15	280.32
253	199	453.21	253.39
254	207	453.77	330.20
255	225	458.75	275.24
256	223	455.91	216.11
257	228	454.66	309.97
258	228	455.31	287.02
259	220	454.58	222.84
260	230	456.79	316.45
261	220	456.04	258.54
No P_3	1496	456.25	277.73

Table 23. Figure 28. Synchronization performance as a function of ΔD in Experiment 2. Subject JB. Values for "short" and "long" values of P_1-P_3 are given in Table 21. Values for "no P_3" trials are given below as a function of the largest value of ΔD.

ΔD	NUMBER OF RESPONSES	LATENCY (MSEC.)	VARIANCE ($MSEC.^2$)
30	214	339.69	102.67
32	209	337.50	104.83
34	214	339.20	129.46
36	217	342.05	120.19
38	214	340.84	147.45
40	207	337.84	129.09
42	213	340.13	125.54

Table 24. Figure 29. Synchronization performance as a function of ΔD in Experiment 2. Subject GTH. Values for "short" and "long" values of P_1-P_3 are given in Table 22. Values for "no P_3" trials are given below as a function of the largest value of ΔD.

ΔD	NUMBER OF RESPONSES	LATENCY (MSEC.)	VARIANCE (MSEC.^{2})
30	210	458.30	209.78
32	218	457.27	214.42
34	208	455.24	255.59
36	213	455.43	230.94
38	215	454.99	203.89
40	213	457.37	257.29
42	219	454.95	368.47

Table 25. Figure 31. Synchronization response latency distributions, according to duration discrimination response, for five sessions preceding Experiment 1. Subject GTH.

LOWER BIN BOUNDARY (MSEC.)	NUMBER OF RESPONSES $P_1-P_3 = 232$ "short"	 "long"	 $P_1-P_3 = 248$ "short"	 "long"	 No P_3
390	0	0	0	0	0
395	1	0	0	0	1
400	1	1	1	0	0
405	0	0	0	0	1
410	3	0	0	0	0
415	10	1	0	3	3
420	16	2	0	0	2
425	12	2	2	4	8
430	37	2	3	15	16
435	38	7	5	27	19
440	59	11	8	37	32
445	57	14	17	35	42
450	57	14	14	46	58
455	45	9	15	38	61
460	32	3	16	54	51
465	17	6	9	32	50
470	11	5	7	34	55
475	8	4	4	25	26
480	1	1	2	14	27
485	0	2	2	4	19
490	1	0	1	4	7
495	1	1	1	7	4
500	0	0	0	1	1
505	0	1	0	2	2
510	0	0	0	1	2
515	0	0	0	0	1
520	0	0	0	0	1
525	0	0	0	0	0
530	0	0	1	0	1
535	0	0	0	0	0
TOTAL	407	86	108	383	490

Table 26. Figure 32. Synchronization response latency distributions for the last five sessions for which $\Delta D = 10$ msec. in Experiment 1C. Subject JB.

LOWER BIN BOUNDARY (MSEC.)	NUMBER OF RESPONSES $P_1-P_3 = 235$ "short"	 $P_1-P_3 = 235$ "long"	 $P_1-P_3 = 245$ "short"	 $P_1-P_3 = 245$ "long"	 No P_3
290	0	0	0	0	0
295	0	0	0	0	1
300	1	0	0	1	0
305	1	0	0	2	1
310	6	0	1	5	3
315	10	2	1	9	8
320	25	4	3	23	27
325	32	11	14	35	34
330	79	28	16	70	77
335	93	13	28	71	93
340	81	10	25	77	86
345	40	20	9	53	79
350	19	7	2	42	54
355	4	4	1	12	17
360	4	3	1	2	11
365	0	0	0	0	4
370	0	0	0	1	1
375	0	0	0	0	0
TOTAL	395	102	101	403	496

Appendix B

Comparison of triangular and normal distribution fits for duration discrimination data of Experiment 2. Subject JB.

Triangular distribution function:

$$P(\text{"long"}) = \begin{cases} 0.0093 & P_1 - P_3 < 223.86 \\ \dfrac{0.985(P_1-P_3)^2 - 441.00(P_1-P_3)}{480.5} + 102.74 & 223.86 < P_1 - P_3 < 239.36 \\ \dfrac{502.07(P_1-P_3) - 0.985(P_1-P_3)^2}{480.5} - 132.18 & 239.36 < P_1 - P_3 < 254.86 \\ 0.9943 & P_1 - P_3 > 254.86 \end{cases}$$

Normal distribution: mean = 239.56
standard deviation = 7.25

P_1-P_3	TOTAL NUMBER OF RESPONSES	P("long")	TRIANGULAR PREDICTION	NORMAL PREDICTION
219	229	0.0044	0.0093	0.0023
220	218	0.0	0.0093	0.0035
221	216	0.0139	0.0093	0.0052
222	223	0.0090	0.0093	0.0077
223	221	0.0090	0.0093	0.0112
224	223	0.0090	0.0093	0.0159
225	202	0.0248	0.0117	0.0223
226	212	0.0236	0.0181	0.0307
227	208	0.0337	0.0286	0.0416
228	218	0.0275	0.0432	0.0554
229	212	0.0613	0.0618	0.0726
230	221	0.0995	0.0846	0.0936
231	209	0.1053	0.1114	0.1188
232	214	0.1308	0.1423	0.1485
233	202	0.1733	0.1773	0.1828
234	208	0.1731	0.2163	0.2216
235	208	0.2212	0.2595	0.2647
236	199	0.2216	0.3067	0.3118
237	199	0.4121	0.3580	0.3621
238	198	0.4495	0.4134	0.4149
239	198	0.4798	0.4729	0.4693
241	225	0.5733	0.5944	0.5789
242	223	0.6682	0.6495	0.6319
243	224	0.6830	0.7005	0.6826
244	221	0.7511	0.7475	0.7301
245	215	0.7814	0.7903	0.7737
246	214	0.8598	0.8291	0.8130
247	209	0.8702	0.8637	0.8478
248	207	0.8792	0.8943	0.8780
249	200	0.9400	0.9209	0.9037
250	203	0.9557	0.9433	0.9252
251	204	0.9265	0.9617	0.9428
252	208	0.9615	0.9759	0.9570
253	205	0.9951	0.9861	0.9682
254	203	0.9852	0.9923	0.9769
255	222	0.9775	0.9943	0.9834
256	224	0.9911	0.9943	0.9884
257	232	0.9784	0.9943	0.9920
258	224	0.9911	0.9943	0.9945
259	232	1.0	0.9943	0.9963
260	227	0.9956	0.9943	0.9976
261	231	0.9957	0.9943	0.9985

Triangular model: $\chi^2_{37} = 19.47$

Normal model: $\chi^2_{39} = 22.73$

Appendix C

Calculation of triangular parameters from duration discrimination performance.

$$q = \frac{\Delta D}{2-\sqrt{2P(R_L|S_S)} - \sqrt{2P(R_S|S_L)}}$$

$$\bar{C} = q\left(1- \sqrt{2P(R_L|S_S)}\right) + (P_1 - P_3)\ \text{short}$$

$P(R_L|S_S)$ = Proportion of "long" discrimination responses, given "short" P_1-P_3.

$P(R_S|S_L)$ = Proportion of "short" discrimination responses, given "long" P_1-P_3.