PULSE TRAIN DURATION DISCRIMINATION AND THE TIMING OF SYNCHRONIZATION AND CONTINUATION PHASE INTERRESPONSE INTERVALS

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ABSTRACT

The purpose of the present investigation was to examine the nature of the timing mechanisms used by humans in two very distinct tasks and to determine whether there was any evidence to suggest that there was a common timekeeper. The duration discrimination experiment involved the presentation of a train of isochronously spaced auditory pulses with the interval between the last two pulses either slightly longer or shorter than the interval between any other two immediately successive pulses. The subject was instructed to make a judgment as to whether the final interval was long or short relative to the preceding intervals. This task was patterned after Kristofferson's (1980) many-to-few duration discrimination task which did not incorporate an explicit pulse train preceding the test stimulus. The second task, which was modelled after Wing (1973), involved two phases of repetitive finger tapping. In the first phase, a train of auditory pulses was presented to the subject and the subject was instructed to tap a Morse telegraph key in synchrony with the pulses. The second phase was a continuation of the first in the absence of any pulses. Subjects were instructed to continue tapping at the rate defined by the exogenous pulses in the synchronization phase.

The main reason for using the pulse train duration discrimination method was to evaluate the role of using an explicit standard in the context of duration discrimination. Using Kristofferson's (1976) Real Time Criterion Model to obtain variance estimates of the internal timekeeper, it was possible to determine how those estimates changed with changes in the base duration. The function relating variance to base duration is flat over short base durations and rises in accord with Weber's law over longer base duration. This is in contrast to earlier findings with the same subject and similar amounts of practice in which the implicit standard many-to-few method of duration discrimination

was used. In that experiment a quantal step function emerged (Kristofferson, 1980). This difference implies that the nature of the stimulus plays an important role in the functioning of the internal timekeeper. More specifically, it appears that implicit standards elicit a quantal timekeeping mechanism whereas explicit standards elicit a non-quantal timekeeping mechanism. Explicit standards appear to elicit timekeeping mechanisms that obey Weber's law.

Weber's law also characterizes the relationship between the variance and mean of the internal timekeeper in the continuation phase of the finger tapping experiment. After extensive and concentrated practice, it was shown that the above relationship is better described as being linear in timekeeper standard deviation than in timekeeper variance. Since no stepwise increments occurred in these functions, it seems unlikely that a quantal timekeeper is involved in the timing of interresponse intervals. Thus, the statistical principle of timing appears to apply to both explicit standard duration discrimination and the timing of repetitive finger taps in the form of a proportional standard deviation model.

Although Weber's law better characterizes the tapping functions in general, one subject's bias corrected timekeeper variance versus mean function is very similar to his step function obtained in a many-to-few duration discrimination task. This similarity suggests that the motor timekeeper may have quantal characteristics under some circumstances and that the perceptual timekeeper may be related to the timekeeper involved in motor movement.

A second reason for using the tapping paradigm was to evaluate Wing's (1973) Two Process Model over a wider range of base temporal intervals. In this regard all of the predictions of the Two Process Model were upheld when it was applied to the short

base temporal intervals (T less than or equal to 466 msec) but a major prediction of the model often was not borne out when the model was applied to longer base intervals (greater than or equal to 734 msec). It was concluded that it is appropriate to apply the model to evaluate tapping performance using base intervals in this shorter range, but that its application to base intervals in the upper range is probably inappropriate.

Although the synchronization phase of the tapping paradigm has been used in the past primarily to start and set the motor timekeeper for controling continuation phase tapping, it was here evaluated with the use of the Stimulus as Clock Model. This new model, which has its roots in the Two Process Model, evaluates synchronous interresponse interval tapping performance. The model accurately predicts one major characteristic of the timing of synchronization phase timing of interresponse intervals. However, its utility in terms of helping one understand the nature of the internal timekeeping process is limited.

The role of concentrated practice was examined in the context of both experimental paradigms. In both, practice steadily and significantly reduced variability in performance. Such a reduction played a major role in the shape and location of the variance functions and thus in estimates of various parameters.

Results of the two experiments are discussed with reference to previous investigations of response-stimulus synchronization with an attempt to integrate the vastly different results on a theoretical level. This discussion led to a new method by which to generate various parameters of the internal timekeeping mechanism.

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LIST OF ABBREVIATIONS

ABBREVIATION	EXPANSION
AR(1)	First Order Autoregressive Process
BD	Base Duration
BTT	Behavioural Timing Theory
CE	Constant Error
CNS	Central Nervous System
CP	Continuation Phase
CPG	Central Pattern Generator
DD	Duration Discrimination
DS	Duration Scaling
FEE	Fundamental Error Equation
IPP	Information Processing Paradigm
IRI	Interresponse Interval
ISI	Interstimulus Interval
JND	Just Noticeable Difference
MA(1)	First Order Moving Average Process
MF	Many-to-Few
MFDD	Many-to-Few Duration Discrimination
ms.	milliseconds
OTM	Optimal Timing Model
PMH	Perceptual Moment Hypothesis
PCM	Poisson Counter Model

LIST OF ABBREVIATIONS

ABBREVIATION	EXPANSION
PTDD	Pulse Train Duration Discrimination
R-SS	Response-Stimulus Synchronization
RT	Reaction Time
RTCT	Real Time Criterion Theory
S	Subject
SCM	Stimulus as Clock Model
SD	Standard Deviation
SP	Synchronization Phase
SRT	Simple Reaction Time
SS	Single Stimulus
SSE	Sum of Squared Errors
STT	Scalar Timing Theory
T	Duration of stimulus in milliseconds
TPM	Two Process Model
VAR	Variance
2AFC	Two Alternative Forced Choice

GENERAL INTRODUCTION

Human beings live in a complex, dynamic, and demanding environment. To adequately cope with the many demands facing them they must accurately perceive events taking place around them and behave appropriately with respect to those events. It is generally accepted that such behaviour is the result of processing at three structurally and functionally distinct stages in the nervous system. The afferent system processes the external stimuli via a sensory organ (transduction) and then transmits the result along afferent pathways to the next stage, the central processor. The central stage is commonly referred to as the decision process as it is there where judgments are made and all higher level information processing takes place. Once a decision to act has been made, a signal is sent from the central processor to the efferent system. This last stage transmits the information it receives to the skeleto-muscular system which is mobilized to generate the response. All three stages have space, energy, and time requirements and constraints, so an analysis of behaviour would require specifying the parameters of all those requirements, and their interrelationships, at all stages of processing. A limited approach might be to specify the characteristics of only one. This limited approach is adopted in this thesis with the temporal characteristics of behaviour being the focus of investigation.

For centuries, answers to questions concerning the temporal characteristics of behaviour have been sought. In a comprehensive review of early thought on timing Nichols (1891) reviewed timing hypotheses which date back to Aristotle. Philosophical explanations of psychological time gave way to experimental investigations during the second half of the 19th century. At that time philosophical hypotheses were replaced by organically based ones. They, in turn, were being investigated by empirical observation and the scientific method. The transition to the scientific investigation of psychological phenomena was, in great part, due to G. Fechner, the founder of psychophysics. Fechner's (1860) important insights led to the indirect measurement of psychological phenomena and they opened the way for future scientific investigations of human behaviour.

Shortly after the inception of the scientific inquiry of psychological phenomena, a wave of investigations began which spawned many new experimental methodologies. Allan (1979) reviewed some of those that are used in the study of time perception and identified two major categories; duration scaling (DS) and duration discrimination (DD). In the method of DS, a subject (S) is queried about the duration of several clearly distinct stimuli usually in an attempt to measure the magnitude of the subjective duration. Examples of methodologies belonging to this category are magnitude estimation, category rating, ratio-setting, and synchronization (Allan, 1979). In many but not all methods subsumed under the heading of DS, the timing of a motor response is an integral part of the task. For present purposes they will be called "motor timing" tasks.

DD differs from DS in that S must discriminate among indistinct or ambiguous stimuli. Examples of methodologies under the DD heading are the method of comparison, the method of single stimulus, identification, and the many-to-few method (Allan, 1979). With rare exceptions, the timing of a response is not a critical component of DD tasks; a judgment is made and sometime later, the length of time is unimportant, a response is made. These tasks will be referred to as "perception" tasks.

Using these new experimental methods researchers conducted many studies to determine, for example, the method, the stimulus modality, the stimulus intensity, or the stimulus duration, that produces the best (most accurate and most precise) results (see Allan, 1979 for an excellent review of this research). But investigations using motor timing and perception tasks were generally conducted separately, presumably because it was assumed that different and unrelated processes mediate performance in each. Undoubtedly a lack of theorizing contributed to the absence of attempts to relate performance between them. However, several lines of evidence suggest that the underlying processes may be related. Lashley (1951), for example, observed persons listening to a musical rhythm and noticed that they tended to start walking, talking, and even breathing in time with it. Such an interaction between perceptual and motoric phenomena strongly suggests the non-independence of the underlying temporal processors. Based on this and other examples of rhythmic actions (e.g., in music, speech, and typing) and of spatial orientation, Lashley (1951) concluded "...that there exist in the nervous organization, elaborate systems of interrelated neurons capable of imposing certain types of integration upon a large number of widely spaced effector elements; in the one case transmitting temporally spaced waves of facilitative excitation to all effector elements; in the other imparting a directional polarization to both receptor and effector elements. These systems...contribute to every perception and to every integrated movement" (p. 127-128). He further summarized his thoughts by stating that "every bit of evidence available indicated a dynamic, constantly active system, or, rather, a composite of many interacting systems" (p. 135). Lashley (1951) emphasizes two important points. The first point is that both perceptual and motoric behaviours are mediated by central mechanisms and the second is that these mechanisms are interrelated.

More recent experimental evidence addressing the question of the relatedness of the underlying processes mediating the perceptual judgment of duration and the timing of responses in motor production tasks has been carried out by several investigators (e.g., Keele & Ivry, 1987; Keele, Pokorny, Corcos, & Ivry, 1985; Pokorny, 1985; Wing, 1980). Wing (1980) and Pokorny (1985) show that a brief auditory stimulus can interfere with the timing of an ongoing motor task. This observation suggests that the timing systems underlying duration perception and the timing of motor movements might be related. Of course it is possible that the same system mediates timing in both duration perception and motor movements. This latter, stronger position, is the one adopted by Fetterman and Killeen (1990) in their evaluation of Killeen and Weiss's (1987) Optimal Timing Model (OTM).

There is, however, another, more compelling line of evidence that leads to the same conclusion. It is the measurement of performance using several DD and DS methods to identify general principles of timing. Evidence emerging from this approach indicates that some timing principles are common to both perception and motor production tasks.

A comprehensive understanding of human timing abilities will require much more than specifying whether or not the underlying processes are related or whether the same principles are operative in different tasks. It will require the specification of all structural and functional characteristics of the system and how they are affected by internal and external conditions. In this context many organic and psychological mechanisms have been proposed as being temporal mediators of behaviour (e.g., Michon, 1967; Kristan, 1980). But since unequivocal links between those mechanisms and human temporal abilities have not been made, the emphasis in research has shifted to the investigation of the properties of hypothetical processes.

Many theories of psychological time are based upon the idea that psychological time is a function of an internally generated, clock-like, periodic time base originating from within the central nervous system (CNS). The better theories give rise to specific quantitative models of behaviour which make testable predictions about performance. Most of those predictions specify the characteristics of the distribution of psychological duration over a range of stimulus values. In addition, they may outline how various parameters of these distributions are related to one another or how they are affected when experimental conditions vary.

By comparing statistics obtained from perceptual and production tasks to each other and to theoretical predictions, more can be learned about the underlying timing principles which govern them. As a result we can further our understanding of the processes involved.

There are limitations to this comparative approach. Different experimental paradigms have different sources of variance associated with them. They may, for example, involve different stages of processing that contribute to variability in performance. All of these sources of variance must be accounted for, and estimates of variability made if we are to move toward an understanding of the component processes involved. Comparing estimates of variability among different methods is of questionable utility if they contain multiple sources of variability.

In light of the preceding discussion, the approach taken in the present investigation is to compare performance from two experimental paradigms; a perception experiment (using a specific DD paradigm) and a motor timing experiment (using a repetitive finger tapping DS paradigm). The theoretical bases upon which the variability in performance from both paradigms may be decomposed into all their component parts already exist. Thus, it should be relatively straight forward to compare parameter estimates between them to bring evidence to bear on the temporal nature of the underlying processes involved.

In the next section, a selection of theories of human DD and several important issues that those theories address will be reviewed. A similar review of theories and issues of motor timing follows. In the last section, an outline of the rationale and specific goals of the present investigation will be provided.

INTRODUCTION TO DURATION DISCRIMINATION

In recent history many major trends in experimental psychology have been heavily influenced by the Information Processing Paradigm (IPP; Michon, 1985). In general, a model based on the IPP consists of a series of components through which information passes and is processed. At a fundamental level these components are 1) sensory stores, 2) short-term memory, 3) long-term memory, and 4) a decision/response production centre (e.g., Gleitman 1981; Spear, Penrod, & Baker, 1988; Church & Broadbent, 1990).

The application of the IPP to time perception has been extremely fruitful as it has generated many new models (e.g., Creelman, 1962; Treisman, 1963; Kristofferson, 1977; Treisman, Faulkner, Naish, & Brogan, 1990; Gibbon, Church, & Meck, 1984; Church & Broadbent, 1990) to name just a few. Most of these models are similar in that they consist of the basic components of the IPP mentioned above. At the core of these models is the time base, which is generally thought to be a flow of successive signals that are generated by an internal "clock" or pacemaker. These signals are sent to a counter (or accumulator) which is provided with a switch to gate the flow of information entering into it. Following the counter, information is transferred to a memory store and then on to the comparator.

Models that are based on the IPP for timing differ in where they place variability in the system in order to account for variability observed in behaviour. In some models there is only one clock with its time base being either constant (e.g., Stroud, 1955; Kristofferson, 1967) or variable (e.g., Treisman, 1963). In other models there are multiple clocks each having a different period (e.g., Church & Broadbent, 1990) or multiple pulse sources that fire at random and independently of one another (e.g., Creelman, 1962). Some models also place variability in the counter (e.g., Kristofferson, 1980; Killeen & Weiss, 1987) while others place it in higher processes such as memory or attention (e.g., Allan & Gibbon, 1984; Ornstein, 1969). In general, models based on the IPP for timing have provided excellent quantitative descriptions of time perception data. Because of this success in accurately representing time perception data the IPP has been widely accepted and has become the standard approach used by investigators in the field (Church & Broadbent, 1990). The following review will be limited to models based on the IPP.

INTERNAL CLOCK MODELS

STROUD'S PERCEPTUAL MOMENT HYPOTHESIS (PMH)

One of the first hypothetical process models to attempt to account for temporal information processing is Stroud's (1955) Perceptual Moment Hypothesis (PMH). According to the PMH, physical time is continuous in nature whereas psychological time is discrete. A physical stimulus of duration T is processed and transformed into a sequence of identical units of psychological time "moments". Stroud (1955) described a moment as "the least possible timewise element of experience" (p. 180) and stated that each successive pair of moments is delimited by a point in time called a "date", (Stroud, 1955).

Stroud (1955) never discussed the PMH in the context of DD but a simple model of it could be developed. S should be able to judge whether a test stimulus is longer or shorter than a standard by comparing the number (n) of "dates" spanned by the test stimulus to a criterion number, n_c, that corresponds to the number spanned by the standard. In order to do that it must be assumed that S can accurately count the number of dates that occur during the test stimulus and base the judgment on a comparison between it and n_c. Of course, it follows that if n is greater than or equal to n_c then the stimulus will be judged as being longer than the criterion.

From such a simple model it follows that the psychometric function should be linear in shape. The psychometric function describes the relationship between the probability of judging the test stimulus as long (P(L)) relative to the standard, as a function of the difference in duration between them (δT). But because psychometric functions in DD typically are sigmoidal in shape, and not linear as predicted by the model based on the PMH presented above, that model and the theory that gives rise to it must be rejected. A valid theory of DD must lead to the prediction that variability in judgments of duration will result in a sigmoidal psychometric function.

Creelman (1962) developed a model that predicts a sigmoidal psychometric function. Both Creelman's model and Stroud's PMH assume a perfect internal pulse counter but Creelman's (1962) Poisson Counter Model (PCM) is based on the idea that the durations between internal pulses (events which are similar to Stroud's dates) randomly vary. This internal variability results in a change in the characteristics of the distribution of the number of pulses counted during the presentation of a test stimulus.

CREELMAN'S POISSON COUNTER MODEL

Creelman's (1962) model assumes that there exists a large number of independent pulse sources, or elements, and that each has a fixed probability of "firing" per unit time. Second, it assumes that there is a counter mechanism that precisely counts the number of firings that occur in the source between the onset and the offset of a stimulus. As with most internal clock models, the PCM assumes that the perceived duration of a stimulus depends directly on that count; the higher the count the longer the apparent duration of the stimulus.

According to the PCM, variability in subjective duration results from the random firing of elements. The PCM makes the assumption that the intervals between successive firings are exponentially distributed. Given that these intervals are exponentially distributed, statistical theory requires that the number of elements firing during a given interval of time (T), and therefore the count registered in the counter, should be Poisson distributed with mean and variance equal to λT, where λ is the average rate of element firings (Creelman, 1962). If the only source of variance is in the element firing mechanism, a major prediction of the PCM is that the variance of the number of counts over a given interval (and therefore the variances of the temporal estimates) should increase in proportion to T. Furthermore, since the Poisson distribution rapidly approaches the Normal distribution as λT increases, a second prediction of the PCM is that psychological duration should be approximately normally distributed. This prediction specifies that the psychometric function should be sigmoidal in shape because the cumulative form of the normal distribution is a sigmoidal function.

Creelman (1962) tested his model against auditory DD data and reported good agreement between theory and data. His experiments were concerned with the ability of human subjects to discriminate two successive auditory stimuli that differed slightly in duration. The shorter stimulus was T msec in duration and the longer stimulus was T + δT msec, where δT is a small fraction of T. On each trial stimuli were presented randomly with respect to order with each being approximately equally likely to be the first presented. Throughout all experiments there was an inter-stimulus-interval (ISI) of 800 msec, with ISI being defined as the duration of the interval between the offset of the first stimulus and the onset of the second. This is known as the two-alternative forced-choice (2AFC) procedure.

In the 2AFC procedure S is required to identify which of the two successively presented stimuli is longer or shorter. That decision depends on a comparison of the number of counts accumulated over the duration of each stimulus. Creelman (1962) models the decision making process on the constructs of Signal Detection Theory (Green & Swets, 1966). Each stimulus has associated with it a distribution of counts, which as stated earlier, is approximately normally distributed. Since δT is very small relative to T, the distributions of counts will overlap to some degree. Under conditions of ambiguity such as these, S makes a judgment based on a comparison of the counts registered during each stimulus. If the count (c_1) corresponding to the stimulus of duration T is less than the count (c_2) corresponding to the longer stimulus then the longer stimulus will be correctly identified as the longer of the two. Likewise, if c_1 is greater than c_2 then the shorter stimulus will be erroneously identified as the longer of the two. In the rare event in which c_1 equals c_2, presumably S guesses which one of the two stimuli is longer.

Applying his model to an auditory DD task Creelman (1962) reports good agreement between theory and data when δT was greater than 5 msec. However, below that level the model failed to accurately predict behaviour; discriminability deteriorated more rapidly than predicted.

Following Creelman's (1962) lead, several quantitative models were developed in an attempt to account for performance in various temporal paradigms. The development of those new models was made possible by the emergence of alternative theories about the nature of psychological time.

TREISMAN'S MODELS

In common with Creelman's PCM, Treisman's (1963) internal clock model assumes that subjective time depends upon the accumulation of internal pulses generated by an internal clock. However, Treisman's model differs from Creelman's in an important way. According to Treisman's model there is only one pacemaker, or pulse generator, and that a specific arousal center can influence it by modifying the rate at which pulses are produced. Of course Treisman's model maintains all the other major components of a clock-counter model (i.e., short term memory, counter, comparator, etc.).

Treisman (1963) evaluated his model and showed that it accounted well for two empirically based psychophysical phenomena. First, with some additional assumptions his model accurately predicts the linear generalization of Weber's law and provides meaningful interpretations of the constants of that model. Second, Treisman (1963) shows how his model accounts for the overestimation of short intervals and underestimation of long intervals, a phenomenon known as constant error.

Recently Treisman et al. (1990) presented a revised internal clock model that includes a modified temporal pacemaker. The new temporal pacemaker consists of a temporal oscillator that emits pulses at a regular frequency and a calibration unit that receives the output from the oscillator. The calibration unit transforms the signal it receives into an output that is fed into the other components of the internal clock. The temporal oscillator provides a stable reference frequency that serves as a clock to all sensory and motor systems. The reference frequency is, for the most part, fixed, but the temporal oscillator is subject to specific arousal from strong sensory input. Such arousal would result in perturbation of the functioning of the oscillator. However, in general, modification of the pacemaker output comes about by mechanisms acting on the calibration unit. This "calibration factor" may be set by central sources or by sensory input.

Using a computer simulation technique, Treisman et al. (1990) derived several predictions from their model and, then, from a set of time estimation experiments using human subjects, tested those predictions. Their experimental results support the model and estimates of the frequency of the oscillator were on the order of 24.75, 37.3, and 49.5 Hz. These frequencies translate into clock periods that are approximately equal to 40, 27, and 20 ms. respectively.

Treisman's et al. (1990) model is important because it provides some support for the existence of an internal temporal oscillator and hence the internal clock hypothesis. All of the models discussed this far (e.g., Stroud, Creelman, and Treisman's) are internal clock models with each being based on the proposition of a dedicated internal clock, or structure, whose function is reserved entirely for temporal information processing. Other internal clock models rest on entirely different assumptions and propositions, some of descriptions of empirical data and sometimes provide similar estimates of the parameters of the internal clock. One non-dedicated internal clock model was originally developed by Kristofferson (1967).

KRISTOFFERSON'S QUANTAL THEORY OF INTERNAL TIME

Kristofferson's (1967) quantal theory of internal time states that the "...temporal integration of the data processing activities of the human central nervous system is achieved through the control of a 'clock' which generates a succession of equally spaced points in time", (p. 93). Each time point is thought to be separated from the next by an interval of about 50 msec, a duration which was defined as the time quantum, q. Because the time points are the product of an internal process they are assumed to be temporally unrelated to external stimulation. These are the main components of Kristofferson's quantal theory of time.

Kristofferson (1967) suggested that the time points serve two main functions. First, they define a limitation of one's ability to switch attention from one "input channel" to another, where an input channel is described as "a set of all possible messages which can be admitted simultaneously into the central processor", (p. 94). Only one channel can be attended to at any given moment and attention can switch to another channel at the time point instants, but never between them. In connection with this function it is assumed that an unattended channel can cause the attention mechanism to switch to it thereby admitting the message it contains into the central processor. However, when a switch does occur there will be a delay associated with the transfer of information into the central processor. Second, the time points control the flow of information between stages within the central processor. Specifically, they determine when information can be transmitted from one stage to the next. Internal time then, is thought of as a continuous variable but variability in it is caused by a quantal process.

Kristofferson (1967) conducted two experimental investigations to evaluate his quantal theory of time. In the successiveness discrimination study Ss were presented with two pairs of stimuli on each trial. The synchronous pair consisted of a light-sound combination in which their onsets and offsets occurred simultaneously. The asynchronous pair was different in that the offset of the light occurred t msec before the offset of the sound. The two pairs of stimuli were presented in random order and the S was instructed to identify which pair had asynchronous offsets.

Kristofferson (1967) defined the function relating the probability of correctly identifying the asynchronous pair vs. t as the successiveness discrimination function. According to Kristofferson's (1967) theory of internal time, the successiveness discrimination function is predicted to be linear in shape. Furthermore, assuming that afferent latencies are equal for auditory and visual stimuli, the function should rise from t=0, when the probability of making a correct identification equals 0.5, to t=M, when that probability equals 1.0. The measure M should provide an estimate of the duration of q.

Kristofferson (1967) found that the successiveness discrimination function was linear in shape but that it was shifted about 10 msec to the right. That shift was interpreted as the difference in auditory and visual afferent latencies - in this particular case indicating that auditory afferent latencies were, on average, 10 msec faster than their visual counterparts. More important however is the magnitude of the estimate of q. Kristofferson (1967) reports that, on average, M was equal to 54 msec.

The second study reported by Kristofferson (1967) used a reaction time (RT) paradigm. The same auditory and visual stimuli that were used in the successiveness discrimination experiment were used in the RT experiment but only one was presented on each trial. Two conditions were defined: In the certain condition Ss knew which stimulus modality was about to be presented so they could attend to the appropriate channel. In the uncertain condition Ss knew that the reaction stimulus could be either visual or auditory but did not know which. Ss were instructed to respond as quickly as possible to the stimulus on each trial.

Using the RT method Kristofferson was able to measure an effect of channel uncertainty on response times. That measure, which was symbolized by K, can be interpreted as being equal to the increment in time that is added to the process as a result of uncertainty. According to the theory, that increment should be the same regardless of stimulus modality since the time required to switch attention from one channel to another is under the control of the internal periodic process. Kristofferson (1967) showed that K was the same for both modalities and that it was equal to approximately 53 msec on average, in excellent agreement with his successiveness discrimination results.

One more measure obtained from Kristofferson's (1967) RT study is pertinent to the present discussion. By modelling the distribution of response times obtained under the condition of certainty, Kristofferson estimated the duration of the quantum. That estimate was called Q and it equalled 53 msec. Thus, from three different behavioural measures and from two different experimental tasks Kristofferson (1967) provides evidence supporting 1) his quantal theory of internal time and 2) his ideas about how attention switching is related to the period of the internal clock.

Kristofferson's (1967) quantal theory of internal time lent itself to the development of quantitative models of successiveness discrimination and reaction time. The general nature of the theory should permit it to give rise to the development of quantitative models to account for performance in other experimental paradigms such as duration discrimination. A model based on Kristofferson's theory should, at the very least, reflect the quantal nature of psychological duration. Kristofferson (1977) developed such a model which accounts well for duration discrimination data. However, prior to presenting Kristofferson's model, a precursor, the onset-offset model, which was developed by Allan, Kristofferson, and Wiens (1971) will first be presented.

The Onset-Offset Model

The onset-offset model (Allan et al., 1971) specifies that psychological duration is a continuous rather than a discrete variable and that variability in psychological duration is produced by a quantal process. The model states that variability in DD judgments is caused by the transfer of information into the central temporal processor and that the central process itself adds no variability to those judgments. According to the model there are two sources of variability that contribute to performance variability. The first source is the psychological onset time, which refers to the variable interval between stimulus onset and that point in time when the internal temporal process begins timing. The psychological offset time, which is defined as the variable interval between the offset of the stimulus and that point in time when the internal timing process stops timing, is the second source of variability.

If entry into the central processor is gated according to Kristofferson's (1967) theory then both onset and offset times will be uniformly distributed over an interval of q msec. If it is assumed that these two random variables are mutually independent, then Allan et al. (1971) show that the distribution of internal durations is a convolution of these two identical uniform distributions. That convolution is an isosceles triangle distribution with base equal to 2q msec and variance equal to $q^2/6$ $msec^2$. Since the cumulative form of the triangle distribution is sigmoidal in shape, the predicted form of the psychometric function according to the onset-offset model is also sigmoidal and, while different from the normal ogive, is difficult to distinguish from it.

Allan et al. (1971) evaluated the onset-offset and Creelman's PCM in the context of single stimulus (SS) DD. In SS DD only one of the two possible stimuli is presented on each trial and S must judge which stimulus is presented. The decision process according to the two models is similar but differing predictions should provide a basis upon which to decide between them. The decision process according to the PCM, as presented above, must be modified for the SS DD situation. Because only one stimulus is presented on each trial, it must be assumed that S compares the count generated by that stimulus to an internal criterion. If the count is greater than the criterion, that stimulus is called long, otherwise it is called short. The distributions of counts associated with the stimuli are the same as presented in the 2AFC case; they are Poisson distributed with the distribution associated with the longer stimulus having a greater variance. The decision process according to the onset-offset model is similar. However, it is assumed that the two distributions, which represent psychological durations rather pulse counts, have equal variances and are triangular in shape. They have equal variances because, in the onset-offset model the variance of the triangle distribution is not affected by δT. If the psychological duration of the stimulus exceeds an internal criterion then the stimulus is called long.

Discriminability may be measured according to both models for SS DD data and Allan et al. (1971) outline the procedure to do that. For the PCM it is measured as the difference between the means of the counting distributions in standard deviation units of the distribution generated by the shorter stimulus. Allan et al. (1971) called this measure d'. For the onset-offset model discriminability is measured as the difference in the means of the two distributions of internal duration in terms of units of q msec. This quantity they label d_q. They go on to specify how d' and d_q are predicted to be related to T and δT according to both models. According to the PCM d' is expected to increase in proportion to δT for a given value of T. Also, if δT is held constant, d' should be inversely proportional to the square root of T. The onset-offset model, in contrast, predicts that d_q is not related to T but that it is proportionally related to δT (Allan et al., 1971).

Allan et al. (1971) tested these predictions and found evidence that was contrary to Creelman's PCM but that supported the onset-offset model. An analysis of operating characteristic curves showed that best fitting data generated by the PCM deviated more from the observed points than those data generated by the onset-offset model. Based on those results Allan et al. (1971) concluded that the underlying distributions have equal variances, not unequal variances as predicted by the PCM. However, their analysis supports the idea that the distributions were well described as being normal. But, they also found that the isosceles triangle distribution describes them equally well. Therefore both models predict the shape of the psychophysical function equally well but the onset-offset model better predicts the variances of the underlying distributions. On the basis of these results and on the finding that when the variance does increase with T it does not do so in strict proportion to T, as required by the PCM (see Allan & Kristofferson, 1974 for a review of these findings), the PCM was rejected.

The onset-offset model, however, was not without problems of its own. The main problem with it is that it incorrectly predicts that variability in DD judgments will be independent of T. Because the variability in DD judgments generally is not independent of base duration, the onset-offset model was abandoned. The rejection of this model led Kristofferson (1977) to develop the Real Time Criterion Theory (RTCT) of DD and a model based on it.

KRISTOFFERSON'S REAL TIME CRITERION THEORY

The models of Stroud (1955), Creelman (1962), Treisman (1963), and Allan et al. (1971) all assume that S estimates the duration of a stimulus and compares that estimate to an internal criterion to judge whether the stimulus is longer or shorter than the standard. They hypothesize that errors in judgments are made as a result of variabilty in the estimate of the stimulus duration; the criterion is assumed to be fixed, or invariant. Kristofferson (1977) provides an alternative theoretical perspective in his RTCT.

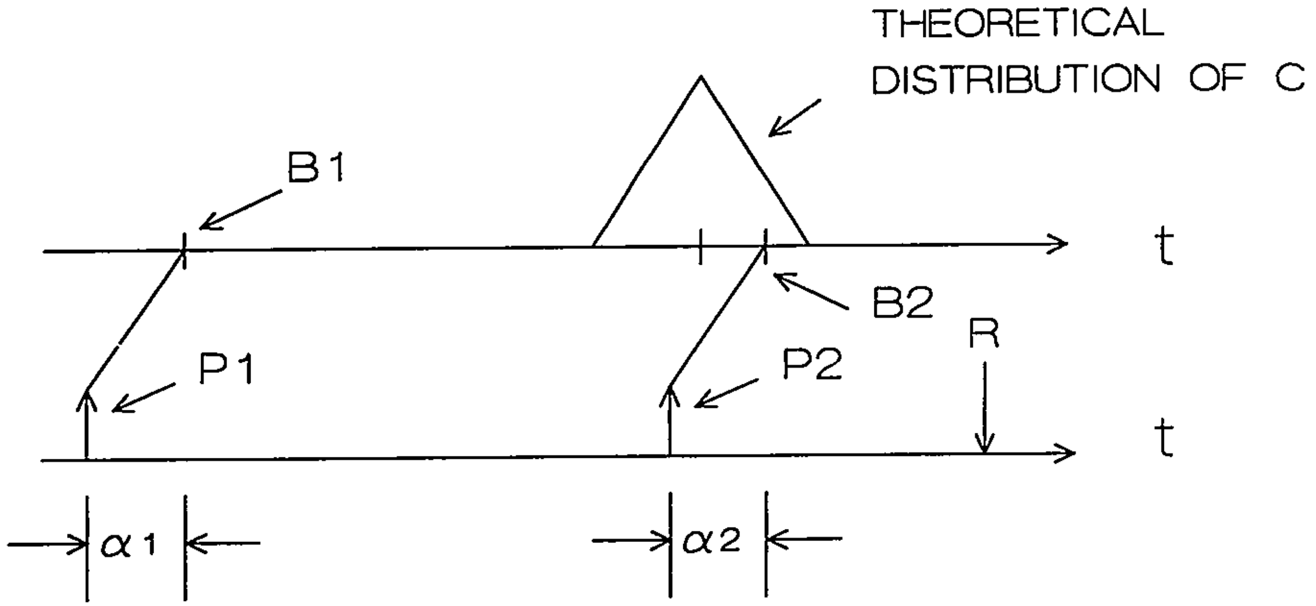
There are two major differences between Kristofferson's RTCT and the other theories discussed above. The first is that, rather than basing a judgment on a measure of the duration of an external stimulus over its entirety, S generates an internal interval and bases his decision upon which ends first. The second is concerned with the source of variability in DD judgments. According to the RTCT that variability is a direct result of variability in the terminus of the internally generated interval, not in a measure of the temporal information of the stimulus.

Kristofferson's (1977) RTCT of DD is pictured in Fig. 1.1. P_1 and P_2 are 10 msec auditory markers whose onsets correspond to the beginning and end of the test stimulus respectively. The difference between P_1 and P_2 equals T, the test stimulus duration. The RTCT states that P_1 and P_2 precipitate two corresponding internal events, B_1 and B_2 respectively. The interval between P_1 and B_1 or between P_2 and B_2 represents afferent latency which is symbolized by A_j ($j= 1,2$). B_1 initiates the generation of an internally timed standard interval, I, the end of which defines a point, C, the criterion. Because it is assumed that I is variable in time, the time at which C occurs relative to P_1 must also be variable in time. To decide whether the test stimulus is long or short S must decide whether C or B_2 occurs first. If in his judgment C occurs prior to B_2 then the stimulus is called long. If these two events are perceived to occur in the reverse order then the test stimulus is called short. Thus, the decision is based on a race between C and B_2.

The RTCT provided the theoretical context to evaluate DD results using the many-to-few (MF) single stimulus (SS) method (Kristofferson, 1977). The SS method involves presenting one stimulus on each trial and the subject is to judge whether it is longer or shorter than an internally generated standard. For each trial, in the MF case, the duration of the test stimulus is chosen from a set of several possible values. For all of Kristofferson's (1977; 1980; 1983; 1984) experiments that set consisted of four values; two longer and two shorter than the standard, or base duration (BD). They were arranged such that the midpoint of the shortest and longest stimuli, and the

FIGURE 1.1

A pictogram of Kristofferson's (1977) Real Time Criterion Theory of Duration Discrimination. P1 and P2 are auditory markers whose onsets correspond to the beginning and end of the test stimulus respectively. P1 and P2 precipitate two corresponding internal events, B1 and B2 respectively. a1 and a2 are afferent latencies, R marks the time of the response and C the criterion. The triangle represents the theoretical distribution of C.


THEORETICAL
DISTRIBUTION OF C
B1
B2
t
R
P1
P2
t
$\alpha 1$
$\alpha 2$

midpoint of the two intermediate stimuli, equalled the BD. Since a stimulus equal to the BD is never presented, subjects are forced to infer its duration from the set of test stimuli. Based on that inference Ss must learn to generate the internal interval I.

In Kristofferson's (1977) experiments Ss responded according to the "go-no go" response procedure in which a button is pressed to indicate one condition and not pressed to indicate the other condition. On some trials the subject was required to press the button if he judged the test stimulus to be longer than the standard, and to withhold from pressing the button otherwise. On other trials pressing the button signaled a short response. Subjects were instructed to respond as quickly as possible on all trials, and they always received rapid feedback regarding the correctness of their responses.

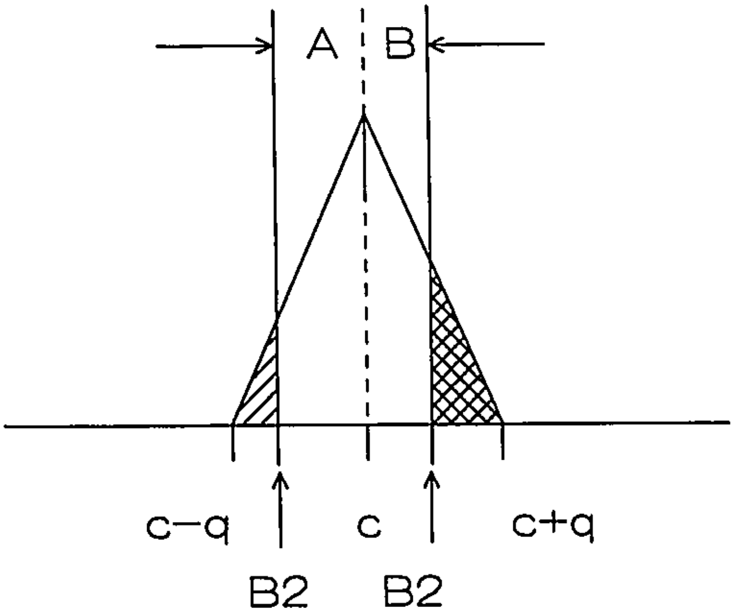
Kristofferson (1977) presented a specific model based on the RTCT and provided strong support for it using the DD paradigm and the MF method. The RTCT model specifies that all temporal variability in the discrimination process arises from variability in the time at which C occurs. Suppose that Kristofferson's (1967) quantal theory of central intermittency is adopted and there are two independent, central stages of processing. If we assume that the time for information to enter and/or exit each stage is uniformly distributed and that it must pass through both before a decision is made, then the resulting distribution of C would be a convolution of the two identical uniform distributions. That would give rise to an isosceles triangle distribution with a base equal to 2q, twice that of each of the contributing distributions, and a variance equal to $q^2/6$. Because afferent variability is negligibly small the psychometric function, which is defined as the function relating the proportion of long responses to each member of the set of test stimuli for a particular BD, must represent the cumulative form of the distribution of C. Kristofferson and his colleagues (Allan et al. 1971) have shown that the cumulative form of an isosceles triangle distribution fits the obtained DD psychometric function extremely well.

Additional evidence in support of the RTCT model comes from testing specific predictions arising from the model (Kristofferson, 1977). Consider the causal factors giving rise to an R_l. According to the RTCT , the chain of events culminating in R_l is P_1-B_1-C-R_l. The variance of the R_l latencies is equal to the sum of the variance of all the contributing components of which there are three; afferent, central, and efferent latencies. An R_s on the other hand is triggered by B_2. The chain of events preceding it is P_2-B_2-R_s. Since it involves afferent and efferent latency components only, the variance of R_s latencies will be a sum of the variance associated with each component. The difference between the variances of the R_l and R_s latencies should provide one estimate of the variance of the central component if no other sources of variance enter into the response latency times. In order to avoid such unwanted extraneous sources of variance from entering into these estimates, a procedural modification was adopted - Ss were required to respond as fast as possible.

An independent estimate of the variance of C can be obtained from the distribution of response probabilities. Because we know the characteristics of the triangular distribution, an estimate of q may be calculated once we know the empirical proportions of each stimulus being called "long". Let us assume that the criterion C has the triangular distribution illustrated in Figure 1.2. The distribution ranges from c-q to c+q and it has a mean equal to c. Since comparison stimuli will be chosen to produce imperfect discrimination they should be represented within this range. The representation of stimulus T-δt should be located to the left of c by a proportion, A, of q. Likewise that of T+δt should be located above c by a proportion, B, of q. The areas under the distribution to the left of the marker corresponding to a stimulus equals the probability that that stimulus will be called "long". If $P(R_L \mid S1)$ and $P(R_L \mid S2)$ equal the probabilities of S1 and S2 being called

FIGURE 1.2

The isosceles triangle distribution of the internal criterion, C, according to the model based on the RTCT. Symbols are explained on page 18 in the text.


A
B
c−q
c
c+q
B2
B2

long, where S1 represents a stimulus of duration T-δT msec and S2 a stimulus of duration T+δT msec, then we may estimate q as follows:

$$q = (S2 - S1) / (A + B) \tag{1.1}$$

$$\text{with } A = 1 - (2P(R_L \mid S1))^{1/2} \tag{1.2}$$

$$\text{and } B = 1 - (2(1-P(R_L \mid S2)))^{1/2} \tag{1.3}$$

Central variability, σ_c^2, may be estimated from the estimate of q;

$$\sigma_c^2 = q^2/6. \tag{1.4}$$

The estimate, M, of the mean of the internal duration distribution, μ, is equal to (T-δt) + (Aq) msec.

If the RTCT is to maintain its integrity these two estimates must be approximately the same: Kristofferson (1977) found that they were almost identical. For T equal to 1150 msec the estimate of σ_C^2 from latency distributions was 1520 msec^2 and from response probabilities it was 1512 msec^2.

According to the RTCT model presented above, long responses are the result of an internally generated estimate of a temporal interval. The distribution of long response latencies, then, should be symmetrical which is typical of time estimation latency distributions (Kristofferson, 1976). Short responses, however, are simple reactions to B_2. Latencies from them, therefore, should be distributed as simple reaction time latencies which have been described as being positively skewed, asymmetrical, with sharply peaked modes (Snodgrass, Luce, and Galanter, 1967). Because both R_l and R_s latency distributions conform to these predicted shapes (Kristofferson, 1977), the theory and model gain even more support.

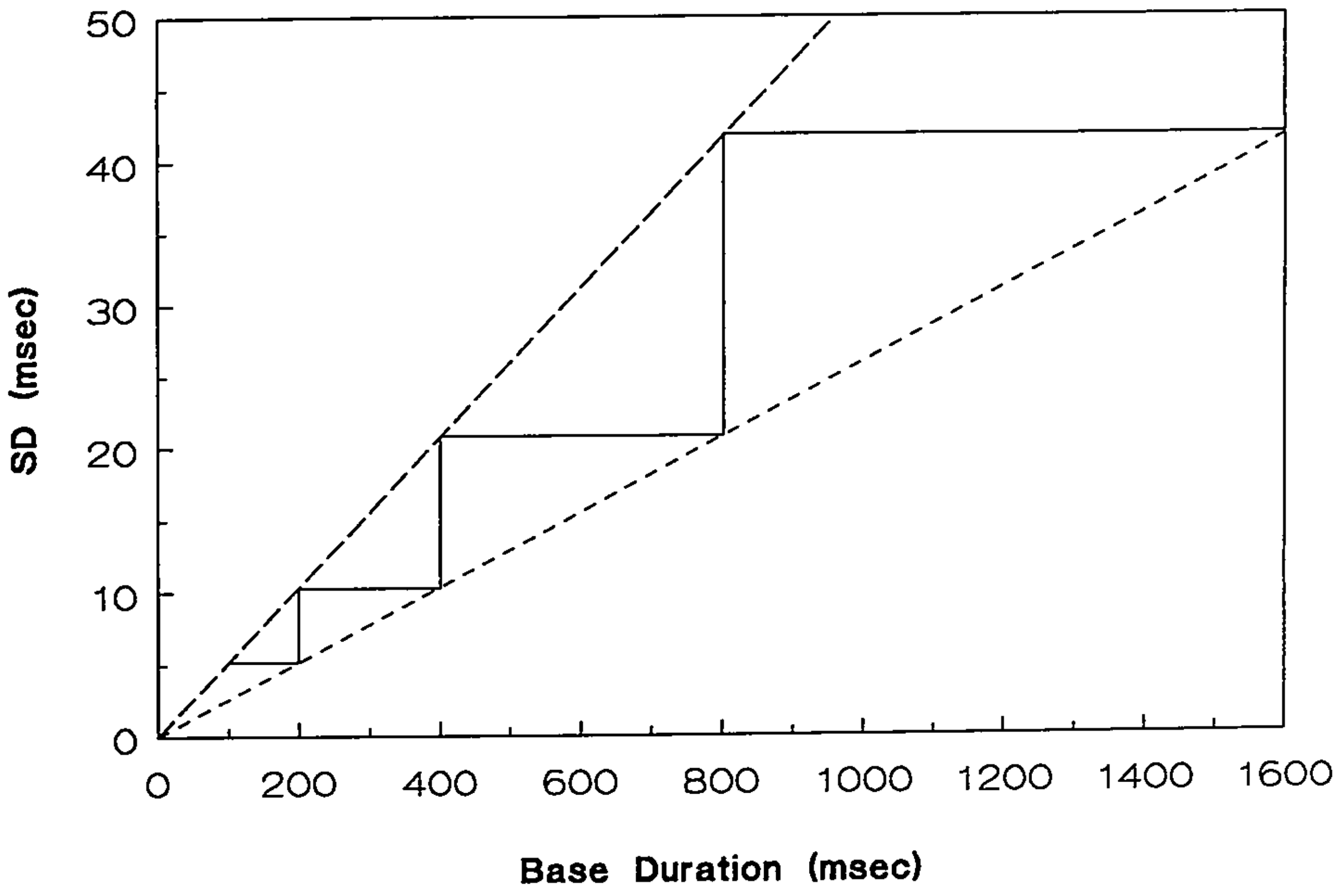
The RTCT model provides a good account of the MFDD results for the two Ts, 1150 msec (experiment 1) and 850 msec (experiment 2), studied by Kristofferson (1977). The next step was to find if the model could be generalized to other Ts. To do that Kristofferson (1980) reanalyzed some previously obtained DD results. Although the MF method was used in the collection of those data, several other procedural differences existed. In Kristofferson's (1980) experiment subjects were tested at many Ts (13 of them ranging between 100 and 1480 msec), responding was not speeded (the technology had not been developed, Kristofferson, 1980), response latencies were not measured, the subject pressed one button for a "long" response and another button for a "short" response, and a considerable amount of practice was given at each T before changing to a new one.

One of the primary manipulations of Kristofferson's (1980) experiment was the level and kind of practice given. Ss were required to complete 20 sessions on consecutive days at each T before changing to a new T. Each session consisted of 300 trials, for a total of 6000 trials at each T. This is an enormous amount of practice at one T. Such a high degree of practice was given because it was apparent (see Fig. 4, Kristofferson, 1980) that an asymptotic level of performance had not been attained.

The effect of practice on DD performance is dramatic. When the function relating T and q for the first 5 sessions is compared to that for the last 3 sessions a clear difference emerges. The function for the first 5 sessions, which is illustrated by the dotted line in Fig 1.3, shows that there was a proportional relationship between q and BD with the best fitting straight line going through the origin. The slope of the line equals 0.131. This translates into a slope of 0.053 for the same function when q is transformed into the SD of the psychometric function. Extensive and specific practice reveals an orderly departure from this line. A rising step function emerges with the slopes of the treads being nearly equal and slightly greater than zero. The magnitudes of the slopes appear to be approaching zero, and with even more practice Kristofferson (1984) shows that they probably would have. The value on the ordinate corresponding to each tread is twice that of the next lower tread (or half that of the next higher tread). Similarly, each tread spans twice the range of

FIGURE 1.3

Kristofferson's (1980) quantal step function shown as the standard deviation of an isosceles triangle vs base duration. The upper dashed line represents a zero intercept Weber function with slope equal to 0.051 and the lower dashed line a similar function with slope equal to 0.026.


SD (msec)
0
10
20
30
40
50
0
200
400
600
800
1000
1200
1400
1600
Base Duration (msec)

values of BDs as it's lower neighbour. Kristofferson (1980) describes this relationship as obeying a "doubling" rule; doubling T doubles its corresponding estimate of q. Kristofferson's (1980) quantal step function, as it might appear after more practice at each T, is shown with its flat steps by the solid line in Fig. 1.3.

The emergence of the step function means that practice did not have the same effect at each T. There was almost no reduction in the duration threshold for Ts at the low end of each tread. Conversely, the most dramatic reduction occurred at the high end of each tread. Because both the variance of the internally timed intervals and the range of durations that each q encompasses depends on the size of q, Kristofferson (1980) assumed that the timing of the internal interval, I, must also depend on q.

No existing quantal counting model could readily account for the obtained step function. The idea that the counting mechanism may not be free of error and that there may be a limit to the number of quanta counted, provided Kristofferson (1980) with the necessary ideas to describe this special function from within his theoretical perspective. Kristofferson (1980) suggested that internal timing is carried out by counting quantal units and that there was a maximum number of them that could be counted without introducing error in the counter. For his data that number was 16. How then can an interval that is greater than 16q msec be timed? Kristofferson (1980) suggests that that can be accomplished by doubling q which would then double the maximum timeable interval as it would halve the number of quanta needed to be counted for any given interval duration.

A S can, perhaps, count more than 16 quanta, but if counting accuracy rapidly declines as the count increases beyond that limit, it would be to the Ss advantage to keep the number (N) small. But reducing N necessarily increases the size of the quantum for a given T. If central variability also increases with the duration of the quantum, then minimizing the duration of the quantum would be a good strategy for S to adopt if he is motivated to be as accurate as possible. Thus, there are two competing processes; the first is to keep the duration of q to a minimum, and the second is to keep N to a minimum. A "compromise" between these two processes must be reached to achieve minimum timing variance.

Taken together these two hypothetical processes can explain why the steps of the function are located where they are, why the values on the flat sections of the steps are what they are, and why the treads may have a small positive slope. In addition, the decreasing slope (Kristofferson, 1984) of the treads with practice can be explained as a slow reduction in the variability of the counting process for a specific quantum value. The fact that the treads are linear suggests that variability in counting increases linearly with N for N between 8 and 16.

For a given interval there appears to be a minimum value that q can assume. Stepping down to the next lower quantum value, after counting error has been reduced nearly to zero, will reduce error due to the timing process. But overall variability will be less only if such a change increases counting error by an amount that is more than compensated for by the reduction in timing error. An interval that requires counting fewer than 8 quanta will be timed more accurately by reducing the duration of the quantum, thereby increasing the number of them to be counted. Likewise, an interval requiring more than 16 quanta will be timed more accurately if q is doubled so that there is a corresponding halving in the number to be counted. Optimal timing occurs for a given q when the interval to be timed lies between 8 and 16 q msec.

As mentioned above, practice significantly reduced estimates of s_C^2 for certain base durations. Kristofferson (1980) attributed that change to a reduction in quantal counting error but other considerations may have been key factors. The method by which the criterion is established may play a major role in determining its variability. In MF DD the criterion is established implicitly, the subject never experiences the standard stimulus directly. Perhaps if it were established by a more direct method even better performance would result. The pulse train duration discrimination (PTDD) method served to provide such a method.

PTDD involves the presentation of n auditory pulses that define n-1 temporal intervals between the onsets of each adjacent pair of pulses. The onset asynchronies between the first n-1 pulses are identical and they define T, the standard interval. The interval between the onsets of the last two pulses defines the duration of the test stimulus which equals $T \pm \delta T$ msec. The subject must judge whether it is longer or shorter than the standard. This method is identical to the MF method except that one or more standard intervals of duration T are presented immediately prior to the test stimulus when n is greater than two. When n equals 2 the conditions are identical to the SS MF method of DD in that no standard stimulus is presented prior to the test stimulus on a trial.

A major difference between PTDD and MFDD is that the standard interval is implicit in the latter method and explicit in the former. In MFDD the internally timed interval I is derived from experience with a set of test stimuli symmetrically arranged around the standard, T. Because the subject never experiences an overt stimulus equal to T, I must be determined indirectly and it must be memory controlled. In PTDD the standard is overtly presented on each trial immediately prior to each test stimulus. I therefore, is probably determined directly from presentations of the standard. Kristofferson proposed that this methodological difference might lead to a memory-driven internal criterion for MFDD and a stimulus-driven criterion for PTDD.

Jezdic (1986) tested Kristofferson's idea by varying the number of pulses in the pulse train, from a minimum of two (i.e., MFDD) to a maximum of nine but he kept the number of pulses in a trial constant throughout a session. T was either 233 or 367 msec and δT was ±8 msec. Jezdic's major finding was that discriminability was the same at each T regardless of the length of the pulse train. Particularly noteworthy is the case when the number of pulses in the train was two. In that case, no standard preceded the test stimulus - a condition identical to MFDD, yet discriminability remained at the same high level. In conclusion, Jezdic (1986) stated that the internal standard, against which the test stimulus is compared, is retrieved from a memory store in both MFDD and PTDD.

It is interesting to note that Jezdic (1986) reports better discriminability for the n=2 condition in his experiment than Kristofferson (1980) reports in his MF DD experiment. This is true even though Kristofferson's (1980) subject received more practice at the n=2 condition at each base duration than Jezdic's (1986) subjects. The across subject mean estimates of the clock standard deviation were 5.7 and 6.7 msec for base durations of 233 and 367 msec respectively. By comparison, the lowest previous estimates obtained from MFDD (Kristofferson, 1980) were approximately 10 msec for each of the above values of T, and that was after 20 sessions of practice. Jezdic's (1986) subjects required only a moderate amount of practice (about 5 sessions) to attain these low estimates.

Although Jezdic's (1986) conclusion is justified, his results do not bear on the importance of how MFDD discrimination performance may be affected by previous experience with PTDD, and vice versa. Jezdic's (1986) subjects experienced many sessions with n>2 prior to shifting to the n=2 condition. Perhaps this experience led to lower discrimination thresholds as a result of having established an internal standard during PTDD which was then transferred to the n=2 condition. The criterion in both cases is memory controlled, but if it is established via experience with an overt standard it is less variable.

Halpern and Darwin (1982) also used the PTDD method to determine if Weber's law characterizes the relationship between the SD of the psychometric function and T. An estimate of the SD was obtained, assuming that the function took the form of a cumulative normal probability density function. That estimate will be symbolized by s_n. For each T there were 11 possible values of δT, five greater than zero, five less than zero, and one equal to zero. Subjects had to discriminate each test stimulus 17 times for a total of 187 discriminations at each T. This is a very small amount of practice when compared to Kristofferson's (1980) 6000 trials at each T. Fortuitously, they used 8 values of T (ranging from 400 to 1450 msec in 150 msec steps) that fall within the range used by both Getty (1975) and Kristofferson (1980).

Halpern and Darwin (1982) found that s_n increased with T in a fashion that was well described as being linear. For whatever reason, each parameter of their equation was too high by a factor of exactly 8, the number of base durations studied. The correct equation, based on a regression of the data they present in their paper is $s_n = 0.049\ T + 3.54$. The Weber fraction of 0.049 is nearly identical to Kristofferson's (1980) estimate from data of unpracticed Ss, and close to Getty's (1975) estimate 0.055.

Finally, Schulze (1989) used the PTDD method to determine whether Ss could detect irregularity in the pulse train as opposed to discriminate between two stimuli on the basis of their temporal characteristics. His method differed slightly from those cited above in that the test interval was either equal to or greater than T. The test stimulus was never shorter in duration than the standard. The pulse trains Schulze (1989) used varied in length from 4 to 7 pulses and T was either 50, 100, 200, or 400 msec.

Schulze (1989) reports results that confirm Jezdic's (1986) findings on a number of counts. He found that the number of pulses in a train is unrelated to the detection of irregularity in the 200 to 400 msec range, although detection of irregularity seemed to decrease with the number of intervals below that. Furthermore, Schulze (1989) found that the difference limen did not change significantly over the 200 to 400 msec range (when averaged across Ss and trials of 3,4,and 5 intervals in length the mean was 9.3) and that it was higher for the two lower values of T (the mean was 12.25). This finding is consistent with the results of Jezdic (1986), Kristofferson (1980), and Kristofferson (1984) in that discriminability changes little between interval durations of 233 and 367 msec. In addition, when the difference limen is converted to SD units (multiplied by a factor of 0.68) then an average of Jezdic's (1986) and Schulze's (1989) estimates are virtually identical. They are 6.2 and 6.3 msec respectively.

Several temporal psychophysics investigations have shown that estimates of variability are independent of T over one or more ranges of durations. Kristofferson (1976) first identified such a range in the context of response-stimulus synchronization (R-SS). He interpreted that independence as evidence that a non-variable time delay could be inserted into the internal sequence of events. The duration of such a delay could be set to any value between zero and 400 msec.

A similar deterministic delay appears to be involved in PTDD but while the range of its operation seems to have an upper limit of 400 msec, the lower limit is unconfirmed because stimuli below 200 msec were not used in those experiments.

All of the IPP internal clock models presented above have some elements in common and others that make each model unique. Many of the models place variability in the pacemaker mechanism and none in the counter/accumulator although one notable exception was mentioned (Kristofferson, 1980) in which variability in the counter was entertained as a possibility. Recently Killeen and Weiss (1987) proposed a generalized clock-counter model which formally introduced variability in the counter.

KILLEEN AND WEISS' OPTIMAL TIMING MODEL (OTM)

In the Optimal Timing Model (OTM), Killeen and Weiss (1987) formally introduce counting variability, in addition to timing variability, into modeling of temporal processes. Killeen and Weiss's (1987) generalized clock-counter model is really a metamodel because it subsumes many specific models. It is discussed here because it provides an alternative conceptual framework that integrates many of the models presented earlier in this chapter.

Suppose D_j are independent random variables representing the durations of the subintervals with mean, d, and variance, σ_D^2. Suppose further that N is a random variable representing the count of the subintervals which is independent of D_js and is a positive integer with mean, n, and variance, s_N^2. If the total interval which is timed is defined as random variable T, with mean equal to t, and it is simply N subintervals of duration D_j, then the following equalities must hold;

$$t = n \cdot d, \qquad 1.5$$

$$\sigma_T^2 = n \cdot \sigma_D^2 + d^2 \cdot \sigma_N^2 \qquad 1.6$$

These are Killeen and Weiss's (1987) equations 2 and 3 respectively.]

The OTM allows for many forms of error in both timing and counting processes and can theoretically accommodate any subinterval duration of mean d, where $0 \leq d \leq T$, and any number of mean n of them, where $0 \leq n < \infty$. The OTM, like Kristofferson's (1980) revised model of DD, assumes that counting error increases with the number of counts and that timing error increases with the duration of the subinterval timed. "Optimal timing" is achieved by adopting a specific combination of the number and duration of subintervals.

How the values of n and d are chosen to produce optimal timing depends on how the variance in timing a subinterval (σ_D^2) is related to d, and on how the variance in counting the number of subintervals (σ_N^2) is related to n. Killeen and Weiss (1987) propose that these relationships are governed by processes described by their "fundamental error equations" (FEEs). Killeen and Weiss (1987) suggest that the variance of each variable is a quadratic function of the variable with all coefficients being non-negative. Thus,

$$\sigma_D^2 = \alpha_2 d_2 + \alpha_1 d + \alpha_o \qquad (1.7)$$

and

$$\sigma_{N2} = \beta_2 n_2 + \beta_1 n + \beta_o. \qquad (1.8)$$

(These are Killeen and Weiss's (1987) equations 4 and 5 respectively.) They are quick to point out that the theory does not require quadratic FEEs; any of the coefficients may be equal to zero depending on the model one is constructing.

According to the OTM, an S who is motivated to reduce timing error will settle on values of n and d that minimize σ_T^2 in Eq. 1.6 and at the same time satisfy the relationship expressed in Eq. 1.5. The theoretical optimal value of d can be obtained if Eq. 1.6 is re-written in terms of d, differentiated with respect to d, set to zero, and solved for d. The optimal value of d can be determined for all values of the parameters in the FEEs but the general solution is vastly simplified if α_o and α_2 are constrained to positive values. If these conditions prevail then Killeen and Weiss (Killeen & Weiss, 1987; Eq. 8) show that the following relationship holds

$$d = (\alpha_o/(\alpha_2+\beta_2))^{1/2}. \qquad (1.9)$$

Using this result in combination with Eq. 1.6 it is now possible to predict the form of the central variability vs. T function. That relationship, expressed by Eqs. 9-12 in Killeen & Weiss (1987), is

$$\sigma_T^2 = At^2 + Bt + C \qquad (1.10)$$

where $A = \beta_2, \qquad (1.11)$

$$B = \alpha_1 + 2(\alpha_o(\alpha_2+\beta_1))^{1/2}, \qquad (1.12)$$

and $C = \alpha_o\beta_o/(\alpha_2+\beta_1). \qquad (1.13)$

A quick glance at Eq. 1.10 suggests that the relationship between σ_T^2 and t depends on the values of the parameters of the FEEs. It was stated earlier that the original version of Creelman's (1962) PCM predicts that σ_T^2 should be proportional to t. Killeen and Weiss (1987) show that Creelman's model can be represented in OTM terms by Eq. 1.10 with A = C = 0, and B > 0. This makes sense because all β_j (j=0,1,2) should be equal to zero for an error free counter, as assumed by Creelman's model. Thus, it is a relatively simple matter to state Creelman's PCM in terms of Killeen and Weiss's OTM. Similarly they go on to show that Getty's (1975) generalization of Creelman's model and Getty's (1975) generalizaton of Weber's law can be stated in OTM terms. Other models can also be accommodated by the OTM but it is difficult to specify Kristofferson's (1980) step function generalization in terms of the OTM because of the discontinuous nature of that function.

Although their OTM is extremely flexible in that it subsumes many existing and potential models, Killeen and Weiss (1987) point out that a major shortcoming of it is that it does not permit discrimination among the models on the basis of the data. Because of this serious limitation the OTM cannot be used as an evaluative tool and will not be applied to the present data sets.

All of the theoretical developments discussed thus far have emerged from direct experimentation using human subjects. Recently several important theoretical advances have emerged from the animal timing literature (e.g., Gibbon, 1977; Gibbon, Church, & Meck, 1984; Killeen & Fetterman, 1988; Church & Broadbent, 1990), some of which are relevant to human timing.

GIBBON'S SCALAR TIMING THEORY (STT)

Gibbon's (1977) internal clock, Scalar Timing Theory (STT) is the major timing model currently available in the animal timing literature. Recently STT has been revised and refined (e.g., Gibbon, Church, & Meck, 1984; Zeiler, Scott, & Hoyert, 1987; Wearden & McShane, 1988; Wearden, 1991; Allan & Gibbon, 1991) to the extent that several investigators have borrowed methods that have been developed to study animal timing and applied them to study human timing.

The STT acknowledges that subjective time varies but predicts that mean subjective time should equal real time. The scalar property of timing refers to the variance of subjective time. It states that the standard deviation of temporal estimates should be a fixed proportion of the mean subjective time. This second property ensures that a direct manifestation of the scalar timing property will result in behaviours that are consistent with Weber's law.

Zeiler, Scott, and Hoyert (1987) used a human analog of the temporal differentiation procedure to evaluate the STT in humans and report that their data were not consistent with the STT. However, the bulk of investigations report results that are consistent with STT. Wearden and McShane (1988), for example, used an analog of the peak procedure (interval production) and report results consistent with STT in both of its main predictions. Their results show that mean production time is almost perfectly related to target time and that the standard deviation of production times is well described by a linear function of mean production times.

Wearden and McShane (1988) then collapsed their data into relative frequency polygons in order to analyze it according to the way peak procedure data is traditionally analyzed. Gaussian curves were fitted to the relative frequency polygons and the best fitting cases were described in terms of the peak location and the ratio of the standard deviation of the curve to its mean, the coefficient of variation. Again, these results conformed to STT but one observation deserves further comment. When subject' data were collapsed within each target time category, the peak of best fitted Gaussian curves always underestimated the real peak of the distribution. This pattern emerged in 19 of 20 of the individual distributions as well. These results suggest that the Gaussian distribution might not be the best distribution to describe the results and that a more leptokurtic distribution (e.g., a triangle) might be better.

To further strengthen the triangular distribution idea is the observation that the sides of the distributions shown in Wearden and McShane (1988; Fig. 2) appear to be relatively straight and the distributions are fully bounded. It should also be kept in mind that these distributions are a combination of the variances of the internal clock and the efferent system since the motor end of the two responses that define each interval produced has variance associated with it.

More recently Wearden (1991a) reviewed evidence from many human temporal tasks (i.e., interval production, analogs of temporal bisection and temporal generalization tasks, and chronometric counting) and shows how most of it is consistent with STT. Wearden (1991a) states that the findings suggest that while scalar timing operates in humans, the decision process in humans differs from the decision process in animals. Finally, from all the evidence reviewed, Wearden (1991a) suggests that a coefficient of variation in the 0.10 to 0.16 range is a possible defining characteristic of scalar timing in humans.

Coefficients of variation in human experimentation pre-dating STT are rarely in the STT range and usually they are in the 0.015 to 0.05 range for healthy human subjects (e.g., Getty, 1975; Wing & Kristofferson, 1973). For this reason it is probably not valid to apply STT to traditional timing procedures involving human subjects unless significant modifications of it are first developed.

Having said that it must be noted that both Wearden (1991b) and Allan and Gibbon (1991) have found evidence that STT is consistent with human performance. In both of these investigations human subjects were used in an analog of an interval bisection task (note; interval bisection has been used in animal timing studies by Church & Deluty (1977), Meck (1983), Maricq, Roberts, & Church (1981) and others). In a typical trial of a bisection discrimination experiment, subjects are presented with one of a set of probe stimuli which they must categorize as being more similar to an established short or long reference stimulus. The data generate psychometric functions for each standard duration interval which is defined as the arithmetic mean of the two reference points. This is the procedure taken by Allan & Gibbon (1991) and for which they report results consonant with STT. Interestingly, their results are the first STT analyzed data to produce Weber ratios that are very similar to those typically reported in the human timing literature for stimuli in the same temporal range. For this reason it would be interesting to apply the STT to PTDD and tapping but these procedures do not lend themselves to analysis by STT. Consequently, although STT is a major advancement and primary alternative to the other theories cited above, it will not be applied to the results of the current investigation.

CHURCH AND BROADBENTS CONNECTIONIST VERSION OF STT

A more recent advancement in timing theory (Church & Broadbent, 1990) does not use the generally accepted information processing model but rather builds upon the parallel distributed processing paradigm (Rumelhart, Hinton, & McClelland, 1986). Church and Broadbent's (1990) new connectionist model of STT is similar to the IPP models in that all of the major components of the internal clock (i.e., pacemaker, memory, and decision process) are maintained but their model makes fundamentally different assumptions about the properties of these components. First, the pacemaker is conceived to be a set of oscillators each with its own period. This modification is thought to be more plausible from a biological point of view. Second, each oscillator has its own status indicator that records information about the phase of the oscillator, rather than the number of cycles it has gone through, as is typically the case for an IPP accumulator. These are the two main connectionist modifications of the pacemaker/accumulator system.

Under the connectionist model, working and reference memory are replaced by matrices of connection strengths or weights. Among the advantages of storing a time within a matrix as opposed to a one-dimentional number, Church and Broadbent (1990) cite that a fixed size matrix can hold information about a large number of stimulus samples, and that a single matrix can store many values. Another major modification concerns the decision process. Decisions under the connectionist approach are made on the basis of a comparison between the input vector with the output vector from the memory matrix.

Church and Broadbent (1990) ran some simulation tests and found that their model reproduced three empirical facts about time perception in rats using the peak procedure. To date the model has not been applied to time perception experiments using human subjects and it remains to be seen how such an application would be carried out. Until Church and Broadbent's (1990) connectionist model is refined and its application to such experimental paradigms as duration discrimination in humans is made possible, there seems little value in trying to discuss the results of the present investigation in terms of their model. Their connectionist model is an exciting contribution to the timing literature, with immediate relevance to animal timing, but it cannot yet be evaluated in the present context.

KILLEEN AND FETTERMAN'S BEHAVIOURAL THEORY OF TIMING

Kileen & Fetterman's (1988) Behavioural Theory of Timing (BTT) is based on the principle of reinforcement. They propose that reinforcing stimuli elicit adjunctive behaviours that serve as the basis for conditional discriminations of the passing of time. However, because their theory depends heavily upon the rate of reinforcement and that reinforcement as such is not involved in either PTDD or tapping, their BTT will not be evaluated in the present program.

In the preceding pages a number of unresolved and interrelated issues in DD were identified. They are 1) the form of the psychometric function, 2) the relationship between the variability of the psychometric function and T (i.e., does it conform to a stochastic principle such as Weber's law, a quantal principle such as outlined by Kristofferson, 1980, and/or a deterministic principle), and 3) the role practice plays in in the changing nature of the first two issues.

THE FORM OF THE PSYCHOMETRIC FUNCTION

In order to estimate the mean and variance of the psychometric function one must first specify its shape. The cumulative normal distribution or close approximations to it have been suggested as the correct shape by some (e.g., the Phi-Gamma hypothesis; Creelman, 1962; Getty, 1975; Halpern & Darwin, 1982), while the isosceles triangle distribution has been used for that purpose by others (e.g., Kristofferson, 1977; Allan et al., 1971).

The cumulative form of several distributions (e.g., the normal, the isosceles triangle, and the logistic) represent the psychometric function very well because they are all sigmoidal in shape. Because of the excellent correspondence between these functions and the obtained psychometric functions it is very difficult if not impossible to determine which one fits the best.

Unfortunately, specifying the functional form of the relationship between the variability and the mean of the psychometric function will not necessarily provide detailed information about the underlying timing mechanism. Getty (1975) presents two very different cases, both of which specify that SD should obey Weber's law, but only one of which specifies that Weber's law also applies to the hypothetical distribution of psychological duration. Thus, specifying the correct form of the above relationship will provide the necessary information to decide among classes of models that are consistent with one form or another. The Weber's law class predicts that SD should be proportional to M and the proportional variance class of models predicts that the variance (VAR) should be proportional to M. If we can show that the functional form of the relationship between variability and M follows the prediction of one of these classes, and not the other, then a model based on the latter must be rejected.

PROPORTIONAL STANDARD DEVIATION MODELS - WEBER'S LAW

Originally Weber's law (Fechner, 1860) described the relationship between the just noticeable difference (JND) between two duration stimuli in DD, and the duration of the shorter stimulus of the pair (Allan, 1979). This form of Weber's law states that the ratio (JND/T), which is known as the Weber fraction, should be a constant for all T. However, the contemporary version of Weber's law is often stated in terms of the SD and M of the psychometric function. In these terms SD should be a constant proportion of M. More formally

$$SD = kM. \tag{1.14}$$

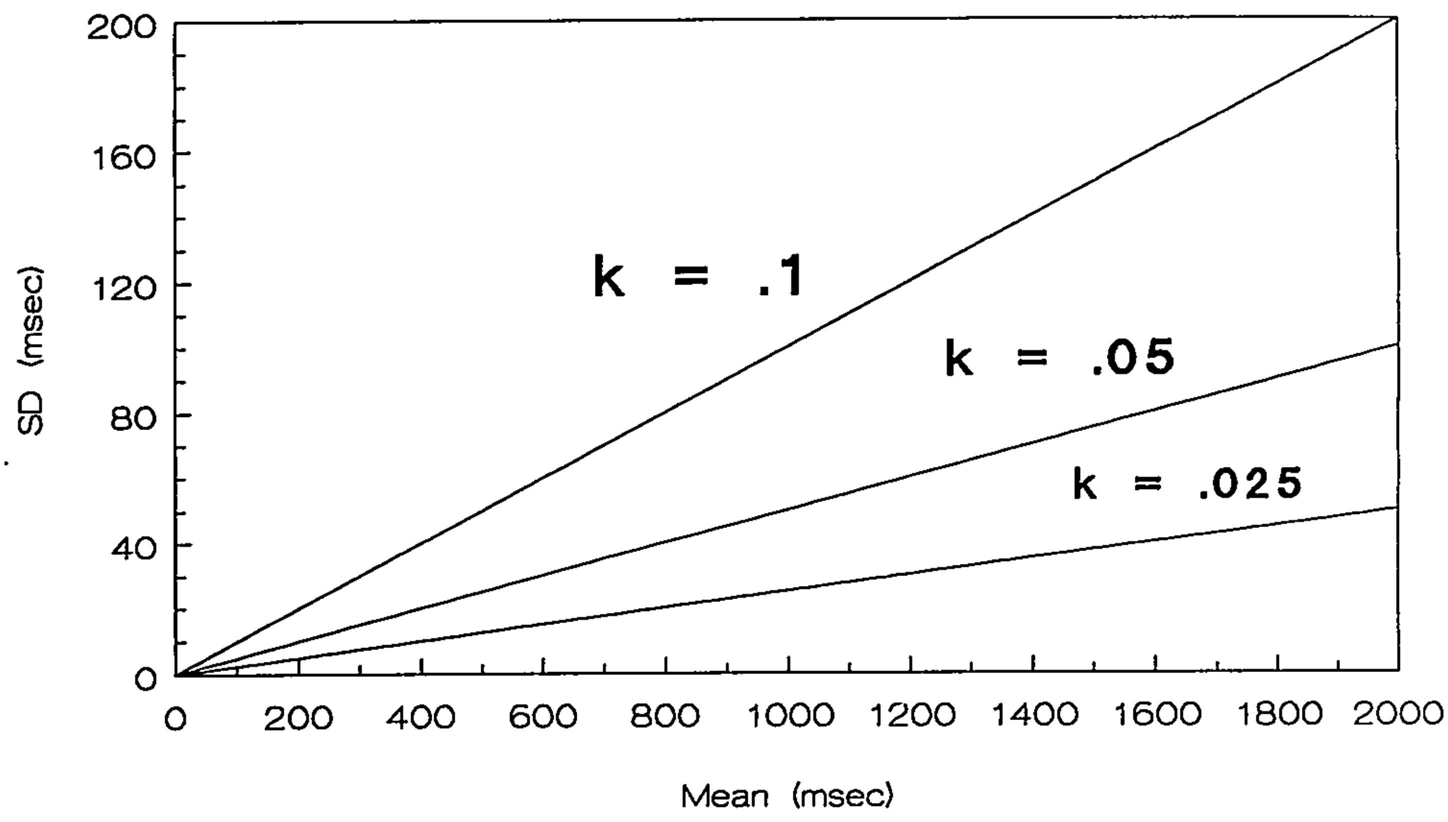
From Eq. 1.14 one can see that the function relating SD to M, over a range of values of T, should be a zero intercept straight line with slope k. A few theoretical examples of this functional form are shown in Fig 1.4.

Throughout the history of psychological research several generalizations of Weber's law have emerged because it was clear that the original version did not describe DD results over a wide range of durations (e.g., Allan & Kristofferson, 1974). Instead the original version appears to be valid only over a restricted range of intermediate stimulus durations. Fraisse (1963), Creelman (1962), and Allan et al. (1971), for example, found that the original form of Weber's law did not describe results for durations below approximately 200 msec. Getty (1975) and Fraisse (1963) found that the function for durations greater than 2000 msec was non-linear, a result also incompatible with Weber's law.

Fechner (1860) first proposed that the decrease in discriminability observed for very short stimuli is due to a constant minimum amount of variability inherent in the

FIGURE 1.4

Three examples of the contemporary interpretation of the original version of Weber's law illustrating the relationship shown in equation 1.14.


SD (msec)
200
160
120
80
40
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Mean (msec)
k = .1
k = .05
k = .025

sensory system. Incorporating this component into the Weber's law equation forces the function to be linear in SD rather than being strictly proportional. Thus, the mathematical statement of Fechner's generalization is;

$$SD = kM + c \tag{1.15}$$

where c represents the minimum sensory noise component. This form of Weber's law is illustrated in Fig. 1.5. But Getty (1975) points out that if the sensory noise component is independent of the stimulus component then a convolution of their distributions should result in an addition of their variances, not in an addition of their standard deviations. With this idea in mind Getty (1975) formulated a different generalized version of Weber's law that takes the following form;

$$SD = (k^2T^2 + V_r)^{.5}, \tag{1.16}$$

where V_r symbolizes the variability arising from all sources that are independent of T (note: he did not specify the source(s) of V_r and he used T in place of M). Two examples of this form of Weber's law are illustrated in Fig 1.6. The non-linear function has an intercept equal to $V_r{}^{.5}$ and it increases with T, approaching a zero intercept straight line as the V_r/k^2T^2 ratio approaches zero. Notice that when V_r equals zero, this generalization reduces to the original form of Weber's law.

Kristofferson (1976) offered yet another generalization of Weber's law. The main difference between Kristofferson's and Getty's generalizations is that under Getty's model SD is a function of stimulus magnitude for all values of the stimulus, whereas under Kristofferson's generalization it is proportional to stimulus magnitude only for increments in magnitude greater than L msec. For stimuli less than L msec in duration, variability is a constant, V_o, where V_o reflects a residual amount of variability in the system. Kristofferson's generalization is;

$$SD = (V_o + k^2(M-L)^2)^{.5} \tag{1.17}$$

and two examples of it are shown in Fig. 1.7.

FIGURE 1.5

Two examples of Fechner's generalization of Weber's law illustrating the relationship shown in equation 1.15.

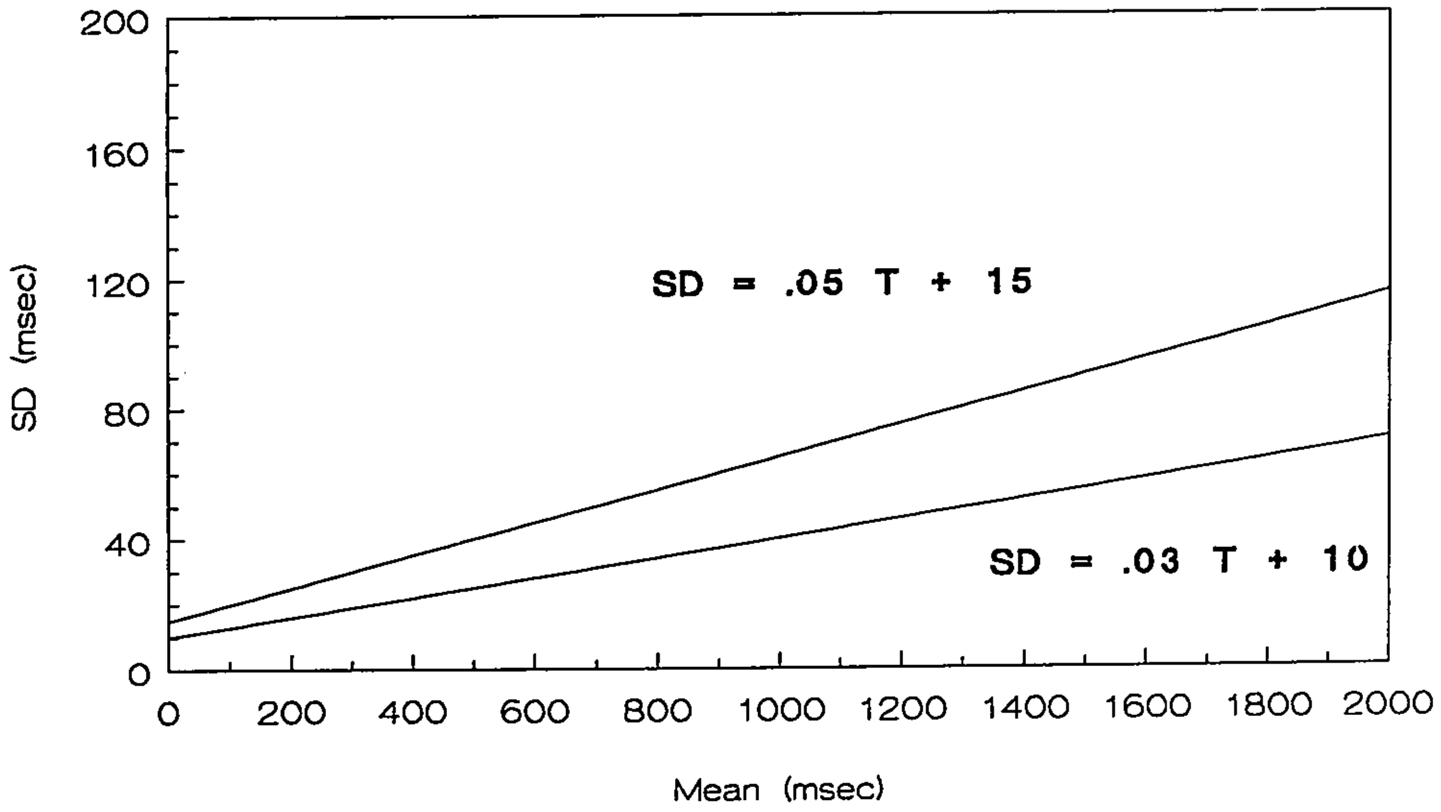

SD = .05 T + 15
SD = .03 T + 10
SD (msec)
200
160
120
80
40
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Mean (msec)

FIGURE 1.6

Two examples of Getty's generalization of Weber's law illustrating the relationship shown in equation 1.16.

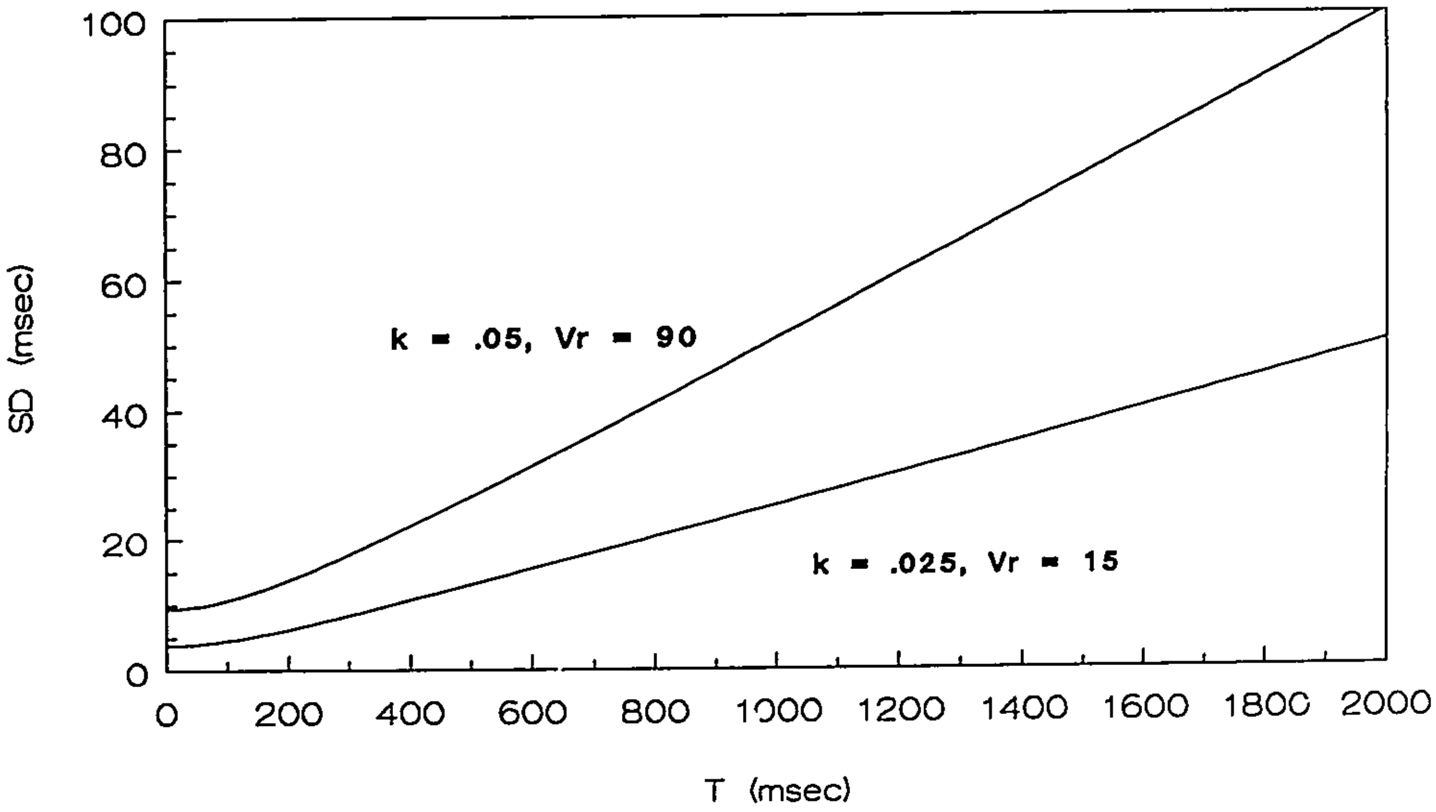
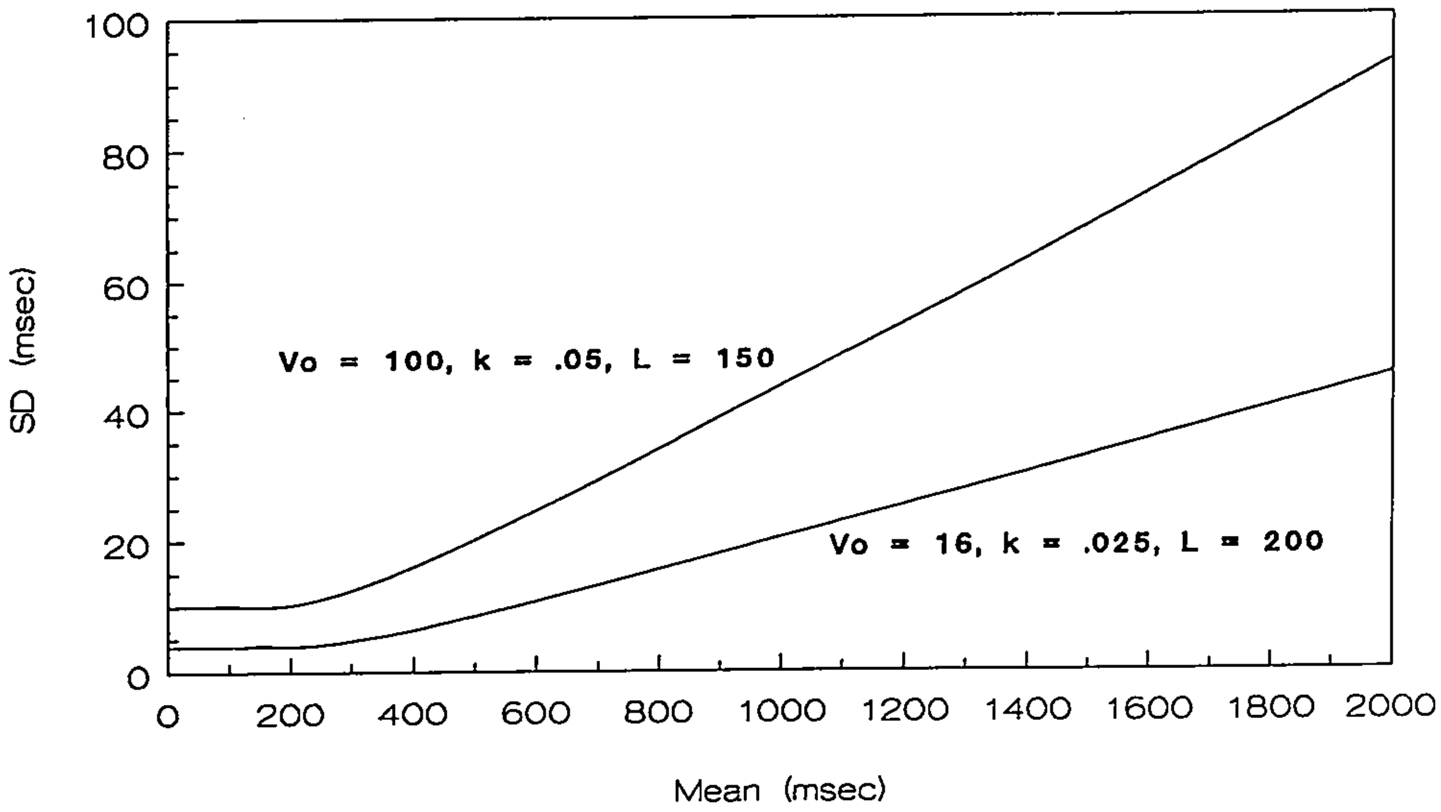

SD (msec)
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
T (msec)
k = .05, Vr = 90
k = .025, Vr = 15

FIGURE 1.7

Two examples of Kristofferson's generalization of Weber's law illustrating the relationship shown in equation 1.17.



100
80
60
40
20
0
SD (msec)
Vo = 100, k = .05, L = 150
Vo = 16, k = .025, L = 200
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Mean (msec)

The last generalization that will be considered in this subsection is Kristofferson's (1980) quantal step function. It is considered to be a generalization because when the upper or lower ends of the risers are connected the two resulting functions are straight lines that intersect the origin (i.e., they are consistent with the original form of Weber's law). It differs, obviously, because the treads connecting these two functions are flat. The step function is illustrated in Fig. 1.3 from which it can be seen that doubling M results in doubling the corresponding values of SD. The dotted lines represent the two Weber law functions mentioned above.

Although the strict form of Weber's law cannot account for much existing DD data, the emergence of the several generalizations mentioned above suggests its utility in describing the relationship between variability and stimulus magnitude. However, one major alternative has been given serious consideration in the literature. That alternative constitutes the proportional variance class of models.

PROPORTIONAL VARIANCE MODELS

Proportional variance models, as the name suggests, state that it is VAR, rather than SD that is proportional to M. In its most basic form, the mathematical statement of this model is;

$$\mathrm{VAR} = cM \qquad (1.18)$$

where c is the constant of proportionality. Rewritten in SD terms this model becomes;

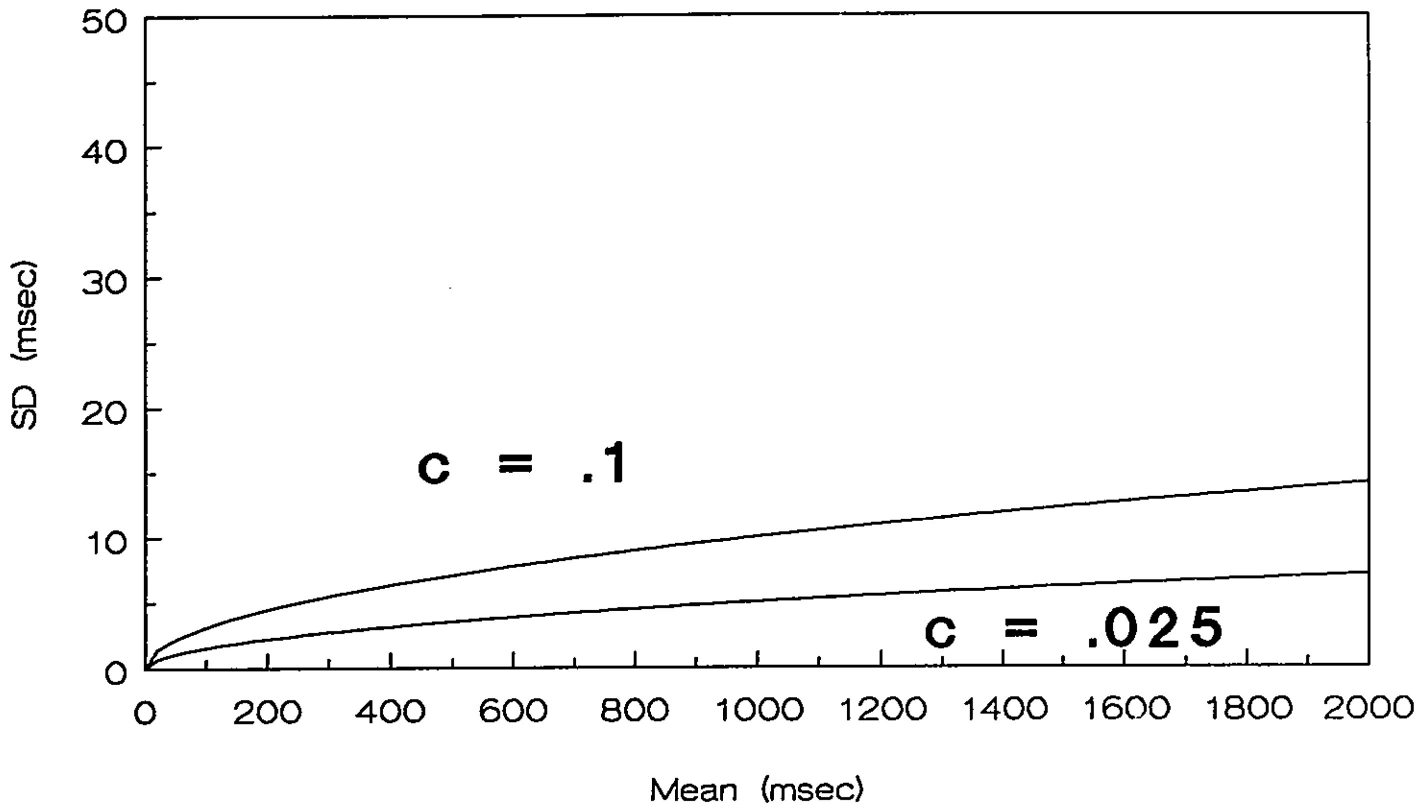
$$\mathrm{SD} = (cM)^{.5} \qquad (1.19)$$

in which it can be seen that SD is proportional to the square root of M. Examples of this function are shown in Fig. 1.8.

Creelman's (1962) PCM is perhaps the best known psychological model of DD that is a member of the proportional variance class of models. Although Creelman introduced several modifications to his original model, the basic form of the relationship between variability and M derived from his model is expressed in Eq. 1.18.

FIGURE 1.8

Two examples of the original version of the proportional variance law illustrating the relationship shown in equation 1.18.


50
40
30
20
10
0
SD (msec)
c = .1
c = .025
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Mean (msec)

Getty (1975) developed a generalized version of Creelman's (1962) model in which he assumed that some portion of the observed variance arises from sources that are related to T (note: Getty used T rather than M), a component he called V(T). The remainder of the variance was generated from sources unrelated to T, sources he classified as residual variance, Vr. Assuming independence among all sources within and between both variance components, as he did for his generalized Weber's law model, total variance, VAR, will equal the sum of the variances generated by all sources.

$$VAR = V(T) + V_r. \qquad (1.20)$$

If V(T) is proportionally related to T, as predicted by the PCM, then Getty's generalization of the PCM becomes;

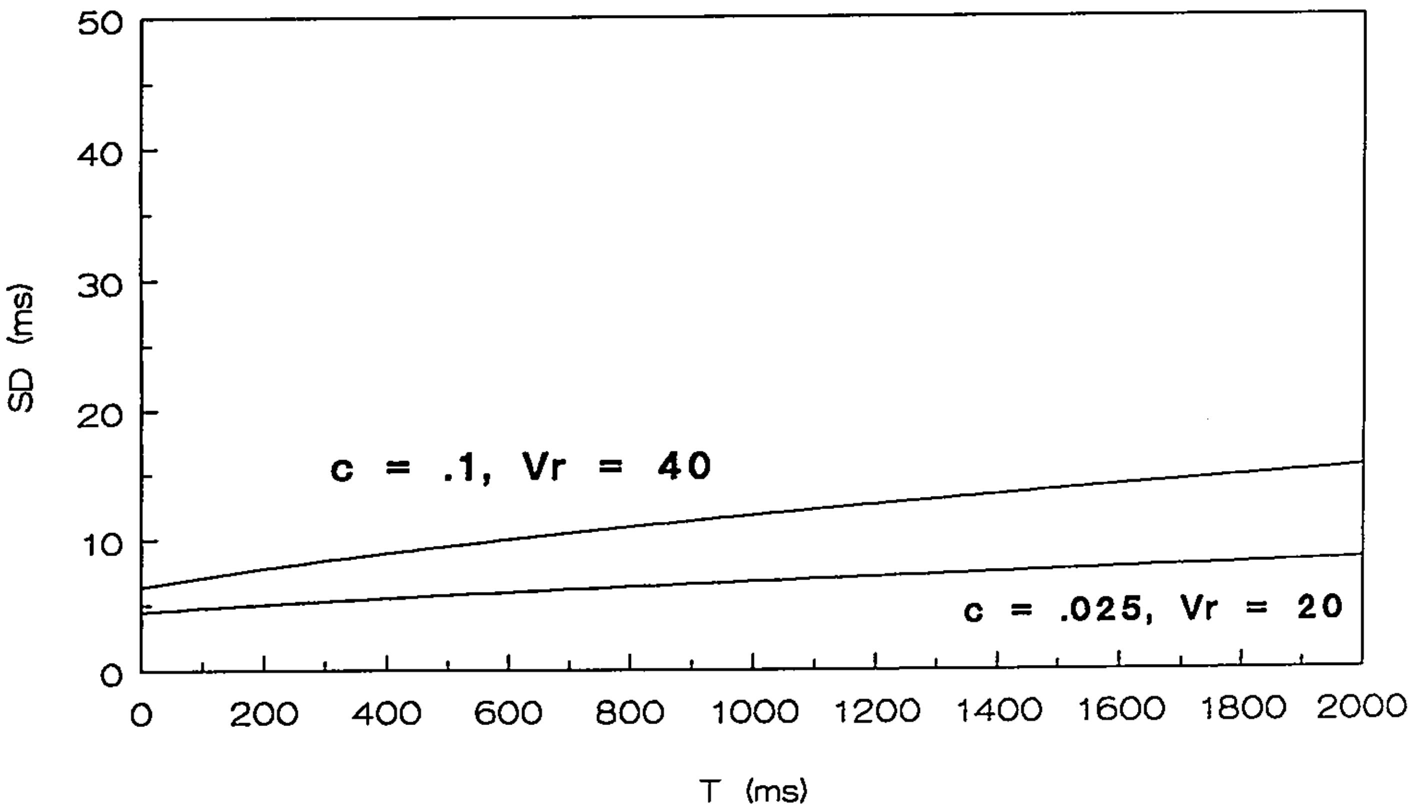
$$VAR = cT + V_r, \qquad (1.21)$$

where c is the slope constant and V_r is the intercept. This function is non-linear when stated in terms of SD. Example SD vs T functions, which are shown in Fig. 1.9, are well described as being monotonically increasing, negatively accelerating functions of T.

In order to evaluate which of his two generalized models more adequately describes the DD function, Getty (1975) measured auditory duration thresholds using the 2AFC method for 15 stimulus durations ranging between 50 and 3200 msec inclusive. Getty (1975) measured the threshold as the SD of the psychometric function, assuming that that function was the cumulative form of a normal density function. He concluded that the SD vs T functions increased continuously and monotonically. They did not, however, conform to the original form of Weber's law. The obtained functions were better described as monotonically increasing from a residual limit at T = 0 msec, and quickly approaching linearity and maintaining near linearity to an upper limit of T = 2000 msec. Beyond that upper limit the slope of the function continuously and rapidly increased. When Getty's generalized Weber's law model was fitted to the data within these two limits, he reports that k, the Weber constant, was about .055.

FIGURE 1.9

Two examples of Getty's generalization of the proportional variance law illustrating the relationship shown in equation 1.21.


SD (ms)
50
40
30
20
10
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
T (ms)
c = .1, Vr = 40
c = .025, Vr = 20

Getty (1975) reports that his generalized Weber's law model accounts for about 93% (an average between the 2 Ss) of the variance in the data as compared to only about 81% for the generalized PCM. Thus, within a limited, but wide (50-2000 msec) range of base durations, Getty's (1975) results provide support for Weber's law.

THE ROLE OF PRACTICE

Kristofferson (1980) demonstrated that practice affects the estimated level of variance in DD. Practice was shown to lower the SD vs M function and fundamentally alter its shape from a straight line to the doubling step function. The type and level of practice were most likely major contributors to this transition. Very long term experience with each T was provided to S prior to changing to a different T. This type of practice will be referred to as concentrated practice. Getty (1975) also provided quite extensive practice at each T (although substantially less than Kristofferson's Ss received) but the practice they received was not concentrated at each T but rather was diffused across many T. His Ss ran many sessions at each T but they were not run in a block. Significantly Getty's (1975) SD vs T functions did not transform into step functions and it is impossible to compare pre- to post-practice functions because Getty (1975) does not provide data collected on the earliest sessions at each T.

GOALS OF THE PTDD EXPERIMENT

The main goal of the duration discrimination experiment in the present research program is to reveal the nature of the PTDD function following concentrated (extensive and specific) practice at each T. From a broader perspective, the results of the PTDD experiment will be compared to those obtained from a tapping experiment in order to draw comparisons between perceptual and motor timing.

INTRODUCTION TO MOTOR TIMING

The control of motor movement is a complex and multi-faceted process. It involves parameters of space, energy, and time because it requires 1) the selection of an appropriate muscle or group of muscles, 2) the control over the range and force of the movement, and 3) the control over its timing. The processes underlying the temporal control of skilled responses made by human subjects is the focus of the second experiment described in this thesis.

Many actions consist of the generation of a repetitive sequence of movements. Walking, breathing, speaking, writing, chewing, scratching, playing a drum, and tapping a finger or foot are some examples of simple actions all of which are commonly displayed in the repertoire of human behaviour. Investigators concerned with the temporal control of repetitive motor acts often debate whether the mediating processes are located in the central or peripheral nervous system (e.g., Delcomyn, 1980).

The central control hypothesis maintains that a central timekeeper controls the timing of muscle activation independent of sensory feedback. It is widely believed that such control is mediated by a "pacemaker" neuron or group of neurons often referred to as a "central pattern generator" (CPG, Delcomyn, 1980). Juxtaposed to this view is the peripheral control hypothesis. It is based on the idea that movement timing critically depends upon sensory feedback signals from the effectors in motion.

Pearson (1976), Delcomyn (1980), and Grillner (1985) reviewed the literature addressing the central/peripheral issue for motor control as it pertains to repetitive movements in non-human subjects. Their coverage includes a diverse range of animal species spanning several classes and phyla. The articles they reviewed used many procedures (e.g., deafferentation, isolation, and paralysis) and studied more than a dozen behaviours (e.g., walking, swimming, and flying). There is a consensus among the reviewers that it is incorrect to think that all timing is achieved through either a central or a peripheral timing mechanism. Both mechanisms exist and it is the nature of the task that determines which is used and if both are used, how the two systems interact.

Researchers investigating motor timing abilities of repetitive acts in humans have also reported evidence supporting each hypothesis (e.g., Adams & Creamer, 1962; Glencross, 1975; Jones, 1972; Pardew, 1976; Turzuolo & Viviani, 1980; Tyldesley & Whiting, 1975; Wing, 1973; Wing & Kristofferson, 1973). In the following sections several studies and models that address motor timing issues will be reviewed. The review will focus on procedures using simple keypress responses made by healthy human Ss.

WOODROW'S REPRODUCTION STUDIES

Woodrow (1930, 1933) conducted two extensive experiments designed to determine the relationship between interval duration T and the accuracy of repeated attempts to reproduce T. The duration of the interval to be reproduced was defined by two brief auditory clicks (S1 and S2), with T being equal to the difference between their onsets. Thirteen values of T ranging from 200 msec to 30 sec were studied. T remained constant for all fifty trials in each session. Ss were instructed to attempt to reproduce T by pressing a response key twice following the terminating click of the stimulus. The interval separated by their responses was taken as a measure of their ability to reproduce T. Ss were explicitly instructed not to count or rhythmically move any body parts to improve estimates, and no experimenter-supplied feedback was provided.

Woodrow (1930) reports that the mean among subjects standard deviations of the reproductions (s_r) were about 9% of the mean reproduction interval (m_r) over the range of 200 to 2000 msec. Between 4 and 30 sec s_r nearly doubled, relative to m_r, to about 17%. In a follow-up study Woodrow (1933) further investigated the ability of Ss to reproduce time intervals over the 400 to 6000 msec range and arrived at the same conclusion. From these studies it appears that s_r is a constant proportion of m_r for intervals up to about 2000 msec.

RESPONSE-STIMULUS SYNCHRONIZATION (R-SS)

The method of R-SS has frequently been used to study the ability of human Ss to synchronize a response to an external stimulus (e.g., Näätänen et al., 1974; Kristofferson, 1976; Hopkins & Kristofferson, 1980; and Hopkins, 1984). The stimulus presentation in this paradigm is very similar to that used in Woodrow's reproduction studies in that the interval separating the onsets of two stimuli (S1 and S2) defines a temporal interval T. Unlike the reproduction task, in R-SS S is required to synchronize his overt response to the onset of S2. In order to achieve true synchronization the response must be initiated and carried out to completion at the onset of S2. As T increases, S is required to modify his response latency accordingly. Strictly speaking this procedure involves both perceptual and motor aspects and therefore should really be considered as a mixed case of perceptual and motor timing.

Using the R-SS procedure to shift response latencies along the temporal axis, Kristofferson (1976) found that latency variance estimates reached unprecedented low levels. Surprisingly, those levels were even lower than the lowest levels achieved using the simple response time (SRT) paradigm (e.g., Saslow, 1974; Snodgrass et al., 1967; Ollman & Billington, 1972). The response latency variance estimates for T between 165 and 550 msec were all between 100 and 125 msec^2. Kristofferson (1976) suggested that R-SS variance estimates may be lower than SRT variance estimates because the reaction stimulus in SRT may interfere with the response mechanism. If that is the case then one would expect that the variance of time estimation response distributions should be lower than SRT latency distributions. Such a prediction goes contrary to previous assumptions about the relationship between SRT and time estimates (e.g., Snodgrass et al., 1967;

Ollman and Billington, 1972) and it casts doubt on the notion that SRT variance estimates should provide the lowest possible levels of response variability.

Estimates of R-SS latency variance (Kristofferson, 1976) in this low range were all nearly the same. However, the latency variance of distributions for S1-S2 intervals greater than 550 msec increased above that constant low level. They increased "in the way that would be expected if SD/M were constant for the delay in excess of 550", (Kristofferson, 1976; p.89). Kristofferson (1976) described the R-SS latency variance (V_{RS}) versus mean latency (M_{RS}) function of his ascending series by a model that can be partitioned into two additive variance components. That model is presented in Eq. 1.22.

$$V_{RS} = V_O + K^2(M_{RS} - L)^2 \qquad (1.22)$$

It states that there is a residual amount of variance (V_O) that is constant for M_{RS} below a certain level, L. For his data V_O equals 142 msec^2 and L equals 550 msec. For M_{RS} greater than L, an amount of variance equal to $K^2(M_{RS}-L)^2$ is added to V_O to generate the predicted level of V_{RS}. Kristofferson (1976) reports that for his data K = 0.034. Thus it appears that for R-SS, timing of the increment in synchronization intervals in excess of 550 msec conforms to Weber's law.

Kristofferson (1976) offered several accounts of how V_{RS} could be independent of M_{RS} for temporal intervals between the reaction time limit and L. The first specifies that an adjustible, non-variable time delay of between 0 and 400 msec can be inserted into the temporal chain of events. Kristofferson (1976) suggested that delays of that kind would probably be located in the afferent end of the system because there is evidence that afferent latencies are almost variance free. Efferent delays, on the other hand, are not variance free, so deterministic delays are not likely to be located in that end of the system. Further indirect evidence suggesting that the deterministic delays are located in the afferent end of the system comes from tapping experiments. Wing and Kristofferson (1973) found that central variance estimates increased monotonically with the base tapping interval, suggesting that deterministic timekeeping was not operating at the central level. However, it is conceivable that deterministic timing operates at the level of the central timekeeper. Kristofferson (1976), for example, suggests that if the central mechanism is a quantal counter then deterministic delays may be the result of the deterministic nature of the fixed quantum. A deterministic interval would emerge for a given quantal unit if no errors in counting were made.

The second account of deterministic timing (Kristofferson, 1976) involves the balance between at least two factors. At least one factor serves to increase variability as ISI increases and at least one other serves to decrease variability simultaneously. The combined effects would cancel each other out leaving what appears to be deterministic timing. I know of no empirical evidence to support this hypothesis.

Although Kristofferson's (1976) Ss achieved amazing results, even lower values of V_{RS} were obtained by Hopkins and Kristofferson (1980) after several procedural modifications were incorporated into the R-SS paradigm. First, the key press response was replaced by a finger withdrawal response. This modification eliminates all mechanical movement on the part of the response apparatus and thus all variability associated with that movement. Second, all trials were subject- rather than experimenter-paced in order to eliminate the problem of momentary lapses of attention. When S initiates the trial it is more likely that he is attentive to the task at hand than if the trial is initiated by the experimenter. Finally, more extensive feedback in terms of a delayed stimulus signal was inserted into the stimulus chain of events following S2.

Hopkins and Kristofferson (1980) were able to reduce V_{RS} to less than 50 $msec^2$ for S1-S2 intervals between 310 and 550 msec. Hopkins (1980) later extended the lower bound of that range to the simple reaction time limit (approximately 170 msec). This reduction in variance further reduces the amount of variability that can be attributable to the central stage once an estimate of motor variance is removed. These low variance estimates led Hopkins and Kristofferson (1980) to question whether the central stage of timing might be non-variable. Could it be the case that timing at both afferent and central stages are deterministic under optimal conditions? Intuitively that seems highly unlikely, but with the levels of performance seen in Hopkins and Kristofferson's (1980) Ss it is a possibility worth considering. If that were the case then the 50 msec^2 variance estimate should be an estimate of efferent variance.

Hopkins (1980, 1984) developed a model of R-SS similar to that of Kristofferson's (1977) RTCT model, but with several key modifications. According to Hopkins' (1980, 1984) model, it is assumed that the variance due to timing the central interval arises from two independent sources. When sensory stimulation is transferred from the sensory organ to the central processor Hopkins (1984) hypothesizes that it must wait in a buffer for W1 msec before it can enter the central processor. W1 is variable because the model states that the buffer is "read" continually, once every n msec. It is assumed that the periodic process controlling when this buffer can be accessed is independent of the external stimulus. Thus, W1 is uniformly distributed over w1 msec.

Once the central timekeeping mechanism receives stimulus information, it times out a non-variable delay, the duration of which depends on T. Following this delay a signal is sent from the central processor to the response processor. For this signal to gain access to the response processor it must wait for another variable period of time, W2, in an output or response buffer. Hopkins (1984) assumes that W2 is uniformly distributed over a very slightly different period (w2) than that of W1. This assumption is necessary to maintain independence between waiting times in the two buffers. After the response processor is triggered, the response mechanism is set in motion and, following a variable efferent delay, the overt response is made.

Response latency variance, according to Hopkins' (1980) model, should equal the sum of central variability arising from the waiting times in the two buffers plus efferent delay variability. Based on the evidence presented earlier, Hopkins (1980) assumes that the afferent delay is variance free. Errors contributed by the central source should be almost triangularly distributed (the convolution of two similar uniform distributions) with a base equal to w1 plus w2. For the sake of computational ease Hopkins (1980) assumed that efferent delays were logistically distributed.

Hopkins (1984) showed that his model provided an excellent description of the data of a highly practiced S for an S1-S2 interval equal to 460 msec. Estimates of central and delay variance were 21.7 and 13.0 msec^2 respectively. Unfortunately Hopkins' model has not been assessed over a range of T so it is not known how estimates of central and delay variance change as a function of the mean.

In addition to the simple R-SS method outlined above, several other synchronization methods have been used to study human timing abilities. One of those requires S to synchronize responses to each of a series of isochronously spaced stimuli. I will refer to this method as multiple response sensorimotor synchronization.

MULTIPLE RESPONSE SENSORIMOTOR SYNCHRONIZATION

In Woodrow's (1932) synchronization experiment S was instructed to synchronize a response to each pulse in a train of isochronously spaced pulses with onsets separated by T msec. Woodrow (1932) studied 8 Ts equal to 250, 400, 571.4, 666.7, 800, 1000, 2000, and 4000 msec. According to his data, which are reproduced in part in Table and shown graphically in Fig. 1.10, the SD of the distribution of reproductions changed only slightly as a function of T (the slope = 0.012) for values of T ranging between 400 and 800 msec. The average SD in that range was 24.9 msec.

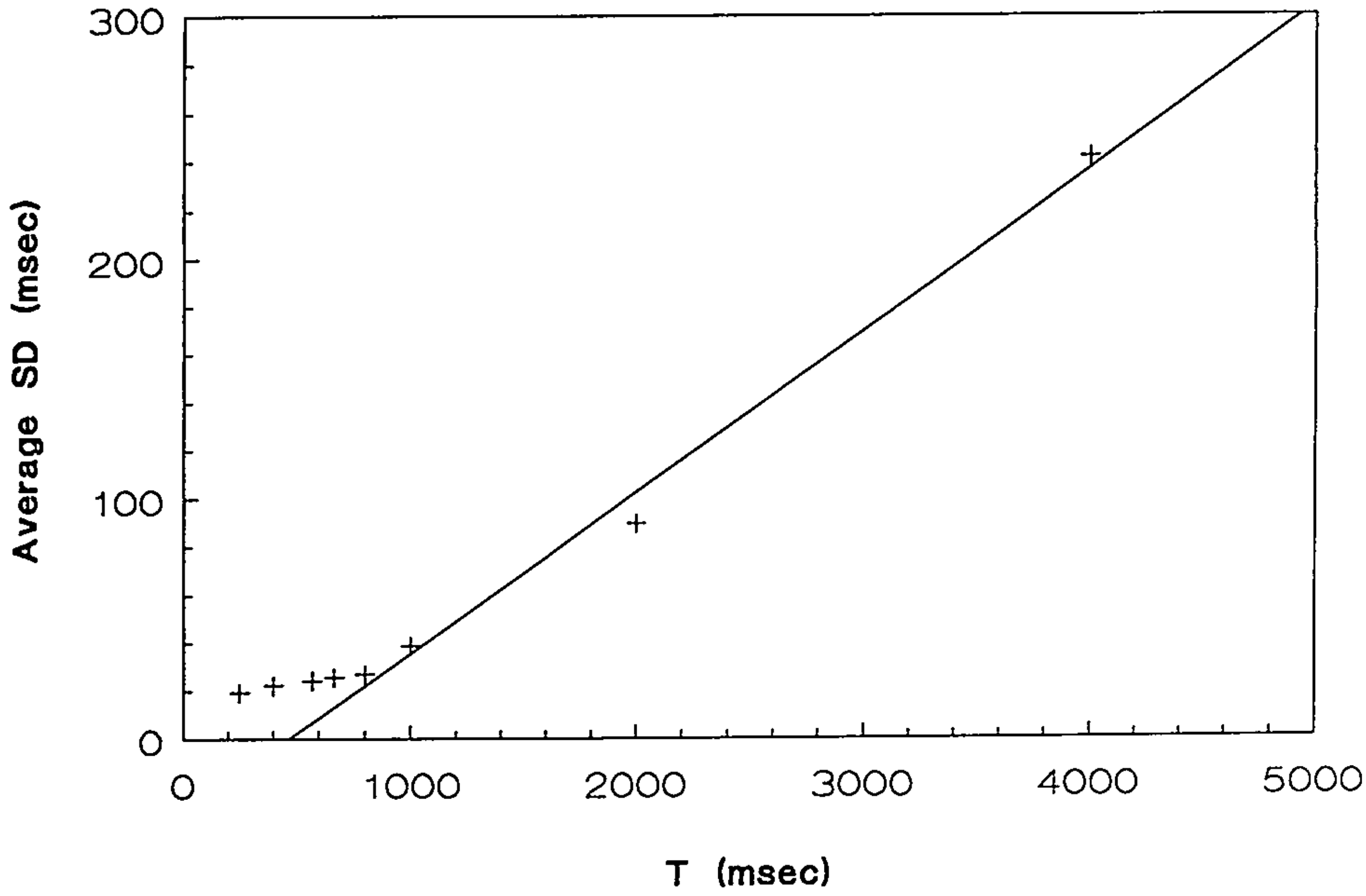
TABLE 1.1

Data from Woodrow's (1932) experiment (Table III).

T (msec)	SD(msec)
250	19.5
400	22.5
571	24.4
667	25.9
800	27.1
1000	39.0
2000	89.8
4000	242.0

FIGURE 1.10

The relationship between the SD of the distribution of reproduction times and T. T is the time between adjacent pulses in a train of isochronously spaced pulses. Data from Woodrow's (1932) synchronization experiment. The data are reproduced in Table 1.1. The slope of the least squares fit straight line regressed on the upper four points equals 0.067.


300
200
100
0
0
1000
2000
3000
4000
5000
Average SD (msec)
T (msec)

When these data are compared to Kristofferson's (1980) quantal step function, the almost flat segment between 400 and 800 msec corresponds closely to the q = 50 msec tread. Between 800 and 4000 msec, the function increases linearly with slope = 0.067 (r = 0.996). It is interesting to note that the slope coefficient for the linear segment of the function is just slightly higher than that found by Getty (1975), for a similar range in a DD experiment, and about twice that when compared to Kristofferson's (1976) linear segment obtained in an R-SS experiment.

The difference between these slope coefficients may be due to various methodological differences. For example, Getty's (1975) Ss received more practice at each T than Woodrow's. Woodrow's (1932) Ss ran only 8 sequences of 40 seconds each at each ISI. Perhaps if his Ss were given more practice the slope of the rising segment of the function would reduce. This becomes even more plausible when it is considered that Woodrow's (1932) Ss received decreasing levels of practice with increasing values of T. This was the case because each sequence duration was held constant regardless of the value of T. Kristofferson's Ss received by far the most practice at each T which probably contributed to the lower slope coefficient.

Even more important is the remarkable similarity in shape of the three functions - a relatively flat segment at low values of T changing into a linearly increasing segment at higher values. These similarities suggest that there may be a common timing mechanism underlying the three tasks.

Although synchronization techniques provide useful information about the temporal abilities of human Ss they are limited in how much information they can provide about motor timing. The problem is the complexity introduced by the presence of the exogenous stimuli. It is not clear how S uses the information about the relationship between the stimulus and his responses to time subsequent responses. At least two possibilities exist. Voillaume (1971) and Fraise and Voillaume (1971) (cited in Wing, 1973) suggest that Ss may use the error of synchrony to adjust the subsequent delay and/or they may use the perceived duration between pulses, T. Their studies suggest that both strategies are used, thereby making the development of mathematical models exceedingly complex. To circumvent the problem of direct sensory influences on motor timing some investigators have employed other methods. In the next subsection one of those methods is described.

THE CONTINUATION METHOD

The "continuation" method was initially developed by Stevens (1886) and later used by Michon (1967), Wing (1973), Wing and Kristofferson (1973a), Wing and Kristofferson (1973b), Wing (1980), Kolers and Brewster (1982), Collyer, Broadbent, and Church (1992), and others. Like the repetitive sensorimotor synchronization paradigm described above it involves the presentation of a series of auditory pulses, equally spaced in time (T msec between the onsets of two adjacent pulses). S must attempt to synchronize a response to each pulse. Following a predetermined number of pulses, the pulse train stops and S must continue to respond in an attempt to maintain the same rate of responding that was established during the pulse train. The synchronization phase (SP) is employed in an attempt to set Ss motor clock to time out intervals of T msec in duration. Thus, from an examination of the interresponse intervals in the continuation phase (CP) we should be able to infer the characteristics of the motor timekeeper.

One of the most salient features of interresponse interval (IRI) timing using the continuation paradigm was first reported by Stevens (1886) and later by Michon (1967) and Wing (1973). It is the observation that there is an alternating or "zig-zag" pattern in IRI responses in the continuation phase. Not every shorter than average IRI is followed by a longer one and vice versa, but that general trend is clearly evident in IRI response sequences (e.g., see Stevens' (1886) graph on p. 398).

Stevens (1886) discussed that observation and interpreted it to "...indicate that an interval is judged more correctly after it is completed than before, and that correction is made for its error in the next reproduction..." (p.401). In other words he thought that the pattern reflected a compensatory, or corrective, timing process based on a sensory feedback mechanism. Stevens' interpretation, then, is consistent with the peripheral control hypothesis.

The term "closed-loop" process is often used synonymously with a sensory feedback process based on the peripheral control hypothesis (e.g., Wing, 1977 ; Schmidt, 1988). A simple closed-loop model for interresponse timing is shown in Fig. 1.11. It is called closed-loop because there is a cyclic relationship between the timing of responses and the stimulation (feedback) provided by the response that is used to time the following response.

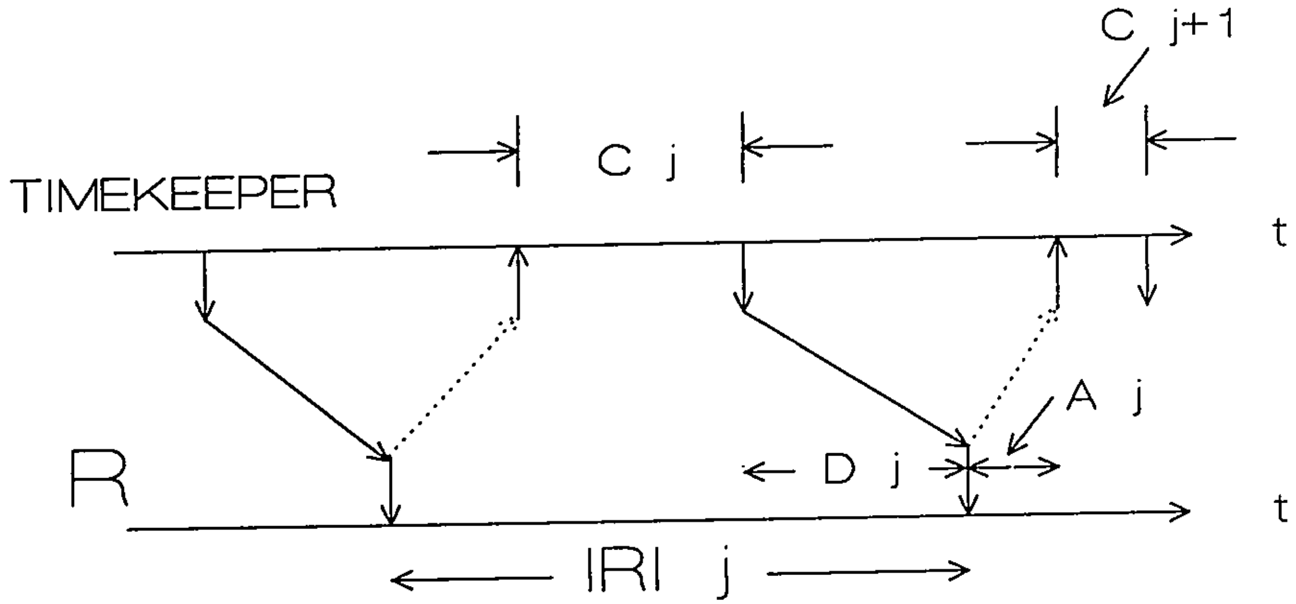
The zig-zag pattern of responding in interresponse interval times may be caused by a process that has nothing to do with error correction or sensory feedback from responding. In contrast to the closed-loop processes, processes not dependent on sensory feedback are often categorized as "open-loop". A model based on an open-loop process is consistent with the central control hypothesis because the central timekeeper times out and triggers responses independent of any sensory feedback from those responses. Although it is not immediately apparent how an open-loop model would predict the observed zig-zag pattern of IRIs, the open-loop based Two Process Model (TPM) (Wing, 1973; Wing and Kristofferson, 1973) does just that.

WING AND KRISTOFFERSON'S MODEL

Wing (1973) and Wing and Kristofferson (1973) developed the TPM to account for the timing of IRIs in the CP. A schematic representation of the TPM is shown

FIGURE 1.11

A simple three-stage, closed-loop model of IRI timing (Wing, 1977). Each IRI is composed of three time intervals; Aj-1, Cj, and Dj. Aj is the afferent delay, Cj the timekeeper interval, and Dj the response delay associated with the response. R is the response time line.


C j+1
C j
TIMEKEEPER
t
A j
R
D j
t
IRI j

in Fig. 1.12. Their model is based on the assumptions that motor timing is a stationary process and that two mutually independent random variables contribute to IRI timing; the timekeeper variable C, which produces a series of independent, centrally timed intervals with mean μ_C and variance σ_C^2, and the motor delay variable D which produces a series of independent delay intervals with mean μ_D and variance σ_D^2. Turning to Fig. 1.12, it can be seen that C_j is the centrally timed interval, and D_j and D_{j-1} are the motor delays for response j and the immediately preceding response respectively. Each IRI is equal to the difference between the motor delays associated with the two responses defining it plus the intervening timekeeper interval between the central triggers of the two response delays.

$$I_j \quad = \quad C_j - D_{j-1} + D_j. \qquad (1.23)$$

In order to evaluate the TPM, Wing (1973) used the interresponse interval autocovariance function, $\gamma_I(k)$. $\gamma_I(k)$ is defined at lag k as;

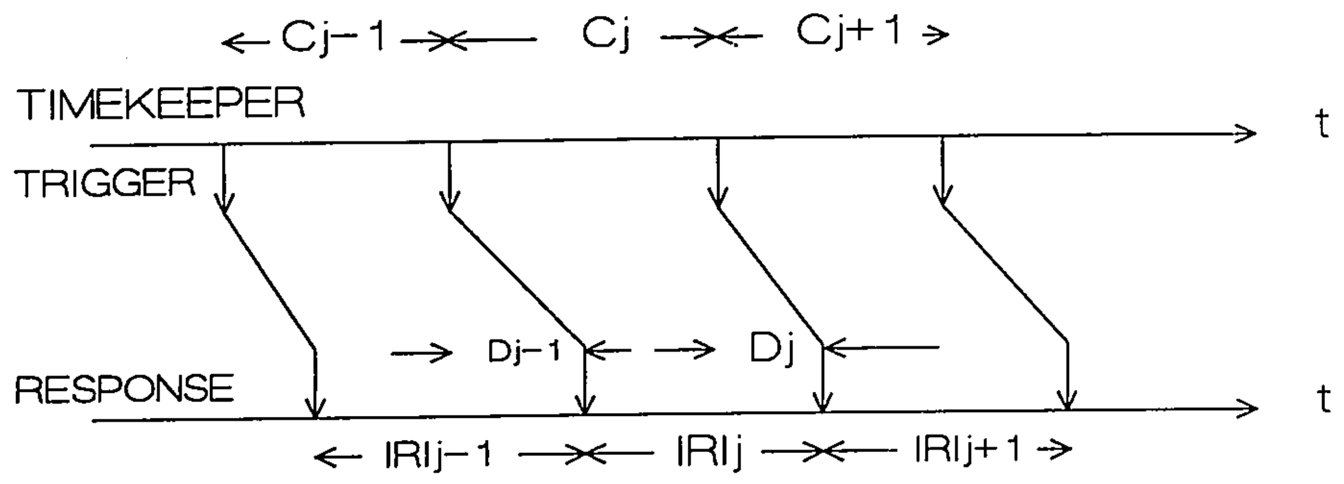
$$\gamma_I(k) \quad = \quad E[(I_j-\mu_I)(I_{j-k}-\mu_I)], \qquad |k| = 0,1,2,... \qquad (1.24)$$

where μ_I represents the theoretical mean of the IRIs and m_I an estimate of it. The computational formula used to estimate $\gamma_I(k)$ is;

$$G_I(k) \quad = \quad \sum_{j=1}^{N-k} (I_j-m_I)(I_{j+k}-m_I)/(N-k-1), \qquad k = 0,1,2,...N-1. \qquad (1.25)$$

FIGURE 1.12

Wing and Kristofferson's (1973) two-stage, open-loop model of IRI timing. C_j is the timekeeper interval and Dj the response delay. The upper horizontal line is the internal time line and the lower line is the response time line. The time between two adjacent responses is the interresponse interval (IRI_j).


Cj−1
Cj
Cj+1
TIMEKEEPER
t
TRIGGER
Dj−1
Dj
RESPONSE
t
IRIj−1
IRIj
IRIj+1

For the TPM it can be shown that (see Wing, 1977 eq. 2)

$$\gamma_I(k) = \begin{cases} \sigma_C^2 + 2\sigma_D^2, & k = 0 \\ -\sigma_D^2, & k = 1 \\ 0, & k > 1. \end{cases} \tag{1.26}$$

Thus, $-G_I(1)$ provides an estimate of σ_D^2 and $G_I(0) + 2\,G_I(1)$ an estimate of σ_C^2.

From the mathematical presentation above it is apparent that Wing and Kristofferson's (1973) model provides a method to estimate the portion of s_I^2 that is due to variance in D_j. More significantly, from that estimate the portion of variance attributable to C_j may then be estimated. I know of no other model that offers a rationale and the technique to partition s_I^2 in this way. The ability to do so is perhaps the single most important contribution arising from the development of the TPM.

Although the TPM offers a way to estimate σ_C^2 and σ_D^2 it does not offer further guidance as to how to partition each of those major sources into their contributing subsources. The central source of variance may originate from variability in the CPG which may have many of its own contributing subsources. Likewise, variance originating from a peripheral source may arise from variability in transmission times in the efferent nervous system and/or from variability in effector movement. Factors such as response force (Keele, Ivry, & Pokorny, 1987; Semjen, Garcia-Colera, & Requin, 1984) or movement requirements (Wing, 1973) may further contribute to effector movement variability. However, the inability of the TPM to partition central and efferent variance components into their subsources is not an important restriction at present because the main point of interest is to compare the two estimates that it does provide with equivalent estimates obtained from other experimental paradigms.

According to the TPM, lag 1 autocorrelation, $\rho_I(1)$, which equals $\gamma_I(1)/\gamma_I(0)$, is predicted to be negative, falling somewhere in the range $-.5 \leq \rho_I(1) \leq 0$. Thus, the TPM, which is a member of the open-loop class of models, predicts that successive IRIs should be negatively correlated. The magnitude of $\rho_I(1)$ depends on the relative contribution of each of the two variance sources. If all variance is due to the motor delay process (i.e., a deterministic central delay) then $\rho_I(1)$ should equal -1/2. On the other hand, as the variance contribution from the delay process approaches zero, so too should $\rho_I(1)$ approach zero. Thus, values of $\rho_I(1)$ smaller than -1/2 or greater than zero are not predicted by the TPM and an $\rho_I(1)$ value between these two limiting bounds reflects the relative contribution of variance from each source. Furthermore, all non adjacent IRIs are predicted to be stochastically independent and therefore should not covary (i.e., $\rho_I(k) = 0$ for $k > 1$).

Wing (1973) and Wing and Kristofferson (1973) tested the predictions of the TPM and were rewarded by the results. Estimates of $\rho_I(1)$ were in the predicted range for data collected for T between 170 and 400 msec inclusive. Furthermore, it turns out that this result is also incompatible with a closed-loop model based S-R chaining. Consider that, logically, motor timing might be accomplished by linking small motor movements together by chain reflexes with sensory feedback eliciting each subsequent movement. Varying the number of such movement units could be one way to vary the interval timed. An increase in the number of units would probably manifest itself by a change in the course of the overt motor response. As Wing (1973) points out, if longer movements are temporally more variable than shorter ones, then there should be a monotonic increasing relationship between the means and variances of timed intervals. That does appear to be the case. But if the elements in the chain are mutually independent random variables then the distribution of timed intervals will also be independent. That is, $\rho_I(k)$, for k greater than zero, should not differ from zero (Wing, 1973). Because estimates of $\rho_I(1)$ were negative, the closed-loop model was rejected.

In summary, Wing (1973) and Wing and Kristofferson (1973) found evidence to confirm the role of an open-loop process in which a central timekeeper times out a delay independent of sensory feedback. They found no evidence to support the idea that sensory feedback from the response plays a role in response timing.

Wing (1973) and Wing and Kristofferson (1973) went on to obtain estimates of σ_D^2 and σ_C^2. It should be kept in mind, however, that valid estimates will be obtained only if all assumptions of the model are met, including the assumption of stationarity. In order to evaluate whether or not there were trends in the sequences of 30 IRIs in the CP, Wing (1973) compared the mean of the first 15 IRIs to the mean of the last 15 IRIs. He argued that if the means were statistically different that there would be reason to doubt that the assumption of stationarity was valid. That analysis provided conflicting results - for approximately half of the cases the 95% confidence intervals about the change in the mean of the first and the last 15 IRIs did not include zero. Consequently, for those values of T, the assumption of stationarity was rejected. However, because the changes in the means, when averaged over all T, was typically less than 1 percent of the mean, Wing (1973) did not consider detrending the data. Thus, although the effects of non-stationarity were statistically significant their magnitude was thought not to be psychologically significant. Because the trends were so small relative to the mean the application of the TPM was considered to be appropriate.

In another continuation experiment Michon (1967) used a much wider range of T spanning from 333 msec to 3333 msec. He found that non-stationarities in the CP IRIs became more significant in absolute and relative terms as T increased. Michon (1967) interpreted that to mean that as the interval to be timed increases, storage efficiency of the internal standard decreases. But he offers no reason why storage inefficiency should lead to non-stationarity as opposed to just an increase in variability. Unlike Wing (1973), Michon (1967) chose to detrend the CP IRI to eliminate the effects of non-stationarity.

The detrending procedure involved the method of least squares to find the highest order best fitting polynomial that significantly reduced residual variance. His IRI data were then reduced to the residuals to either side of that best fitted function. As expected detrending in this manner reduced s_I^2 for the majority of sequences analyzed and did so to a greater extent for longer Ts. But, it is a mystery to me why the detrended data provided slightly higher s_I^2 estimates in five instances and why positive overall $G_I(1)$s sometimes remained.

The existence of non-stationary CP IRI sequences must be considered very seriously when the TPM is being used to model the CP IRI. However, I think that fundamentally altering the data (i.e., detrending it) without adequate justification can only lead to the misrepresentation of the processes involved. For example, Michon's (1967) finding suggests that the applicability of the TPM may not be justified for T greater than an upper limit. However, detrending the data to force it to comply with the assumption of stationarity can lead to the misleading conclusion that the TPM is valid. For this reason data collected in the present experiment will not be detrended should they contain non-stationarities.

In Wing's (1973) study, the average value of s_D^2 was reported to be 16.2 msec^2 for a Morse key finger tapping task with estimates ranging between a low of 10 to a high of about 50 msec^2. These estimates correspond nicely with others reported in the literature. For example, Hopkins and Kristofferson (1980) found that total response variance for S1-S2 intervals in the 170 to 550 msec range was no greater than 50 msec^2. Thus, it appears that efferent delay variance must be at most 50 msec^2. According to a model fitting procedure carried out on R-SS data by Hopkins (1984), the estimate of motor delay variance was on the order of 13 msec^2 for an S1-S2 interval equal to 460 msec. Thus, because several independent sources provide corroborating estimates of delay variance it appears that those based on the TPM are valid.

Estimates of σ_C^2 derived from the Morse key tapping procedure appear to increase monotonically with m_I from a low of approximately 20 msec^2 for the shortest interval, to approximately 70 msec^2 for the longest interval. Upon application of the method of orthogonal comparisons to the mean estimates of σ_C^2, Wing (1973) reports that the linear component is significant but the quadratic component is not. The functional relationship between s_C^2 and m_I for the averaged data was; $s_C^2 = 0.20\ (m_I - 62)$, (Wing, 1973). Although slightly different parameters were found for different responses, this basic linear relationship was maintained. This result supports the notion that the timekeeper is based on a simple stochastic process in which the variance of the timed interval increases in proportion to the mean. However, we must keep in mind that the range of Ts investigated in Wing's (1973) morse key finger tapping experiment was very narrow, spanning from 170 to 350 msec only.

Curiously the range of durations employed by Wing (1973) is fully contained within the range of durations over which other investigators have found evidence of invariance in the timekeeper (e.g., for R-SS, Kristofferson, 1976; Hopkins & Kristofferson, 1982 and for DD, Kristofferson, 1980; Schulze, 1989; and Halpern & Darwin, 1982). For those tasks it is only above a point somewhere between 400 and 550 msec that the function starts to rise in accord with Weber's law. Thus, in order to gain a better understanding of the nature of the tapping function, and to directly compare the tapping function with functions based on other tasks, a much wider range of intervals needs to be studied.

As mentioned above, the TPM was evaluated in the context of several response requirements (e.g., finger flexion, wrist flexion, and forearm elevation, Wing, 1973). According to the model an alteration in response requirements should change σ_D^2 and not change σ_C^2 if T is held constant across conditions. Contrary to these expectations, Wing (1973) found that changes in response movements resulted in changes in s_C^2 but not in s_D^2. Thus, in order to maintain the integrity of the TPM the model itself needed to be modified.

It turns out that the necessary modification was to make the independence assumptions less stringent. Wing (1973) noticed that the autocovariances for lags greater than one were non-zero, a result that is not predicted by the original TPM but one that is predicted by modified versions allowing dependence among either D_j or C_j. As a result, Wing (1973) tested two generalizations of the TPM in which there was either a first-order autoregressive (AR(1)) process in timekeeper intervals or motor delays.

GENERALIZATIONS OF THE TPM

The defining characteristic of an AR(1) process is that successive deviations of a random variable from its mean equals the sum of a proportion of the immediately preceding deviation plus a random variable that is distributed about a mean equal to zero. If an AR(1) process is operating on C_j then

$$C_j - \mu_C \quad = \quad x_j + \phi(C_{j-1} - \mu_C), \qquad |\phi| < 1. \qquad (1.27).$$

x_j are independent and identically distributed with mean equal to zero and variance equal to σ_x^2 and ϕ is the lag one serial correlation coefficient among timekeeper intervals. Wing (1973) shows that the resulting IRI autocovariance function for this generalization is

$$\begin{aligned} \gamma_I(k) &= [\sigma_x^2/(1-\phi^2)] + \sigma_D^2, && k = 0 && (1.28) \\ &= [\phi\sigma_x^2/(1-\phi^2)] - \sigma_D^2, && k = 1 \\ &= \phi^2\sigma_x^2/(1-\phi^2), && k = 2. \\ &= \phi\gamma_I(k-1), && k > 2 \end{aligned}$$

The autocovariance function can be of three forms depending on the value of ϕ. If ϕ is negative $\gamma_I(k)$ oscillates in sign - it is negative for all odd k, positive for k = 0 and all even k, and it damps down toward zero as k increases. For ϕ positive the entire function is positive and it too approaches zero as k increases. Thus, regardless of the sign of ϕ the function is always positive for even k. For the unique case when ϕ equals zero the function is identical to that of the TPM with full independence assumptions because that is formally equivalent to independence in C_j. In keeping with Wing's (1977) terminology this generalization will be called Model I.

If the independence assumption for the D_j variable is relaxed such that there is an AR(1) process in D_j, we arrive at Wing's (1973) second generalization (Model III, Wing; 1977). Successive deviations of D_j about its mean, μ_D, are based on some proportion, θ, of the previous deviation plus some new random variable, y, with mean $\mu_y = 0$, and variance σ_y^2. The mathematical representation of this process is;

$$D_j - \mu_D \quad = \quad y_j + \theta(D_{j-1} - \mu_D), \qquad |\theta| < 1. \qquad (1.29)$$

Once again, if θ equals 0 then $\gamma_I(k)$ is identical to that of the TPM. For θ less than zero, $\gamma_I(k)$ oscillates to either side of zero as it did for the generalization presented above. When θ is greater than zero however, $\gamma_I(k)$ diminishes in magnitude as k increases and it is predicted to be negative in value for all positive k. $\gamma_I(k)$ for this process is;

$$\begin{aligned} \gamma_I(k) &= \sigma_C^2 + [2\sigma_y^2/(1+\theta)], && k = 0 \qquad (1.30) \\ &= -[(1-\theta)/(1+\theta)]\sigma_y^2, && k = 1 \\ &= \theta\gamma_I(k-1), && k > 1. \end{aligned}$$

When the best fitting parameter estimates were determined for each Model according to a least squares criterion, Wing (1973) found that Model III provided the best fit to the autocovariance functions over the entire range of temporal intervals (T = 220 to 490 msec) studied. For the best fitted case, estimates of θ were negative so the autocovariances oscillated around zero. However, as T increased so did θ even to the extent that θ became positive on some occasions.

In a follow-up investigation, Wing (1977) evaluated two generalizations of the TPM in addition to Models I and III. Each of these was an instance in which the independence assumptions were relaxed such that a first-order moving average (MA(1)) process is introduced among either timekeeper intervals or efferent delays. Again, the main assumption that timekeeper intervals and motor delays are independent was maintained. In contrast to the AR(1) generalizations, MA(1) generalizations state that each successive deviation of a random variable (i.e., either C_j or D_j for our purposes) from its mean is equal to a weighted sum of two variables. If the MA(1) process is in C_j (Model II, Wing, 1977) then the mathematical statement of it is

$$C_j - \mu_C = x_j + \phi x_{j-1}, \qquad |\phi| < 1. \qquad (1.31)$$

Once again x_j are independent and identically distributed with mean, μ_x, equal to zero and variance equal to σ_x^2. Wing (1977) gives the IRI autocovariance function for Model II as

$$\begin{aligned} \gamma_I(k) &= (1+\phi^2)\,\sigma_x^2 + 2\sigma_D^2, && k = 0 \qquad (1.32)\\ &= \phi\sigma_x^2 - \sigma_D^2, && k = 1\\ &= 0, && k > 1. \end{aligned}$$

This function equals zero for all $k > 1$, but for $k = 1$ it is negative unless $\phi > 0$ and $\sigma_D^2 < \phi\sigma_x^2$.

Finally, the MA(1) process in D_j (Model IV; Wing, 1977) was defined by

$$D_j - \mu_C = y_j + \theta y_{j-1}, \qquad |\theta| < 1. \qquad (1.33)$$

The IRI autocovariance function for it is

$$\begin{aligned} \gamma_I(k) &= \sigma_C^2 + 2[1 + \theta\,(\theta - 1)]\,\sigma_y^2, && k = 0 \qquad (1.34)\\ &= -(1-\theta)\,\sigma_y^2, && k = 1\\ &= -\theta\sigma_y^2, && k = 2\\ &= 0 && k > 2. \end{aligned}$$

From the expressions above it can be seen that this function is always negative for $k = 1$ and zero for $k > 2$. For $k = 2$ it is negative when θ is positive and positive when θ is negative.

Wing (1977) used the autocovariance functions to determine whether the data supported any of the four TPM generalizations. Model III proved to fit the obtained autocovariance functions the best (Wing, 1977) when T = 400 msec. However, unlike the previous analysis (Wing, 1973), the best estimate of θ was positive.

The conclusion that emerges from these studies is that there is an AR(1) process in response delays for short IRIs (e.g., shorter than 500 msec) and that there appears to be a transition point somewhere between 400 and 500 msec below which θ is negative and above which it is positive. Autocovariance functions for a series of T greater than 500 msec have not been reported for highly practiced Ss using the continuation paradigm so it is not known whether the TPM or any of its generalizations can be used to model the process timing responses at those durations. The absence of such an investigation, in part, motivates the second experiment presented in this thesis.

BIAS IN AUTOCOVARIANCE FUNCTIONS

There is a potentially serious problem with the use of autocovariance functions to evaluate the TPM and its four generalizations - a problem of bias in $G_I(1)$. Anderson (1971) shows that the degree of bias in $G_I(1)$ is on the order of 1/N, where N is the number of IRIs in a sequence. Thus, the shorter the sequence the more bias is introduced into $G_I(1)$.

Taking bias into account, the expected value of the estimator $G_I(k)$ according to Anderson (1971) is expressed in Eq. 1.35 below;

$$E[g_I(k)] = \gamma_I(k) - 1/(N(N-k)) \sum_{n=1}^{N-k} \sum_{m=1}^{N} (\gamma_I(n-m) + \gamma_I(n+k-m)) + 1/(N^2) \sum_{n=1}^{N} \sum_{m=1}^{N} \gamma_I(n-m)$$

where $\gamma_I(k)$ is the theoretical autocovariance function. To complicate matters further, Vorberg (1978) states that bias changes the geometric shape of the function such that the shape of the biased function is different from that of the unbiased theoretical function.

Therefore, any attempt to model obtained functions should be carried out after first removing the contribution due to bias.

One approach taken to account for the bias in estimates of $\gamma_I(k)$ was suggested by Vorberg (1978) and adopted by Vorberg and Hambuch (1977) and Wing (1979). Because the theoretical autocovariance functions are not known they must be estimated from the obtained biased functions. Best fitting parameters that describe the obtained autocovariance function are taken as estimates of the parameters of the theoretical function. These estimates are inserted into Eq. (1.35) to generate biased theoretical estimates of $\gamma_I(k)$ which are then compared to the biased $G_I(k)$ to determine if differences between autocovariance estimates of the two functions are statistically significant. If they are, the model that is used to generate the theoretical autocovariance function must be rejected.

Based on a comparison between unbiased theoretical autocovariance functions and biased obtained autocovariance functions, Wing (1977) concluded that of the four generalizations of the TPM only Model III could not be rejected. However, when the effect of bias in $G_I(k)$ was taken into account, for those $G_I(k)$ in which the corresponding $\gamma_I(k)$ equals zero, Wing (1979) concluded that, in addition to Model III, the rejection of Model IV in Wing (1977) was unjustified. Thus, while it appears that successive response delays are correlated, the evidence does not allow one to conclude whether that correlation reflects an AR(1) or an MA(1) process.

Unfortunately modeling of the autocovariance functions by Wing (1973), Wing and Kristofferson (1973), and Wing (1977) was carried out withoug taking account of bias in $G_I(1)$. Fortunately, relatively long sequences were used in all of those studies so the degree of bias should be small. However, even though long sequences were used, the reanalysis of Wing's (1977) data by Wing (1979) illustrates the serious implications the effect of bias has on modeling.

In summary, it appears that the TPM is valid for the timing of IRIs in the CP. However, modeling of the autocovariance functions suggests that the assumption of independence among D_j does not hold but it remains an open question as to whether D_j are correlated according to an AR(1) or MA(1) process.

Wing and Kristofferson's TPM provides a way to estimate σ_C^2 and σ_D^2 from s_I^2 but it does not offer guidance as to the fundamental nature of the timekeeper (i.e., a discrete or continuous mechanism). In this regard Michon (1967) reports that the distribution of IRIs are multi-modal for T above 1000 msec. He interpreted this characteristic of the distributions as being strong evidence for the existence of a time quantum similar to that offered by Stroud (1955). The peaks were separated by about 100 msec, an interval that Michon (1967) interpreted as an estimate of the time quantum. This was the first time empirical evidence was presented to suggest that the mechanism underlying the timing of continuation IRI was quantal in nature.

Collyer et al. (1992) conducted a continuation experiment in which 27 values of T ranging from 175 to 825 msec in steps of 25 msec were used. They too report evidence supporting a discrete internal timekeeper hypothesis but their evidence comes from an approach very different to Michon's (1967). Rather than analyzing the variance of IRIs their evidence is based on an analysis of the difference between mean IRI and T, a term they call bias. Bias was partitioned into linear and residual components, where the latter was defined as the difference between mean IRI and the predicted mean IRI based on a linear regression of mean IRI on T. The evidence for discrete timing comes from the fact that residual bias was non-randomly related to T. Furthermore, it was related to T in a way that is consistent with a discrete timekeeper. The term oscillator signature was used to refer to the form of the relationship between residual bias and T.

It is possible that oscillator signatures are determined by the physical requirements of the response. Collyer et al. (1992) ruled out that possibility because the oscillator signatures of finger and wrist tapping responses did not differ significantly. The similarity between finger and wrist tapping oscillator signatures was taken to suggest that they are not produced by biomechanical requirements of the efferent end of the system but rather, are the result of the operation of a central timekeeper.

In summary, only a couple studies have reported evidence favouring a discrete timekeeper hypothesis for the timing of motor responses. Michon's (1967) investigation and the insightful approach taken by Collyer et al. (1992) both suggest that while timing is continuous in that mean IRI approximates T very closely they also suggest that the underlying mechanism is discrete in its operating characteristics.

THE STIMULUS AS CLOCK MODEL

The TPM was developed to account for timing of CP IRI but there is no reason why it can not be applied to IRI of the SP. In this section one possible application of the TPM to model SP responding is presented.

Woodrow (1932) studied the IRIs in a series of attempts to synchronize responses to a train of stimuli. His analysis was at a descriptive level and no attempt was made to model internal processes. Several other investigators have use the method of continuation (e.g., Stevens, 1886; Wing, 1973; Wing & Kristofferson, 1973; Wing, 1977; Wing, 1979; Wing, 1980; Kolers & Brewster, 1985) to study the timing of IRIs in the CP but none have systematically studied the timing of IRIs in the SP. The Stimulus as Clock Model (SCM) which is developed below, is a first attempt to fill that gap.

It is generally thought that the central timekeeper, in the context of the TPM, is located inside the subject where it generates a series of internal events. However, there is no reason to believe that the locus of the timekeeper must be internal. This distinction is an important one for the development of the SCM for tapping in the SP.

The essential feature of the SCM is that the pulses of the external pulse train are timekeeper pulses. Thus, according to SCM the timekeeper is exogenous, located outside of S. Each external pulse triggers a delay, D_j, which terminates at the response which is made in an attempt to synchronize to the next pulse. Thus, the SCM is similar to traditional R-SS models in that it is a stimulus-response, rather than a response-response model.

The essential characteristics of the SCM are shown in Fig. 1.13. The beginning of the timed interval I_j is defined by the terminus of delay D_{j-1}, and the end by the terminus of delay D_j. Immediately successive I_j are related because the termination of one delay ends one response and begins the next. Symbolically, the relationship between these components is

$$I_j \quad = \quad T + D_j - D_{j-1} \qquad (1.36)$$

where T is equal to the duration of the interpulse interval.

Although the external pulse train is the clock under the SCM, that does not rule out the existence of an internal central processor. If D_j subsumes all components in the chain of events between the onset of the external pulse and the moment the overt response is registered then the central processor simply may be a part of D_j. We know from R-SS models (e.g., Kristofferson, 1976; Hopkins & Kristofferson, 1980; Hopkins, 1984) that the interval between pulse onset and the registration of a response has been partitioned into three subcomponents; the afferent subcomponent, A_j (with mean μ_A and variance $\sigma_A{}^2$), the central subcomponent, C_j (with mean μ_C and variance $\sigma_C{}^2$), and the motor subcomponent, M_j (with mean μ_M and variance $\sigma_M{}^2$). If that convention is incorporated into the SCM then D_j is simply the sum of those three subcomponents;

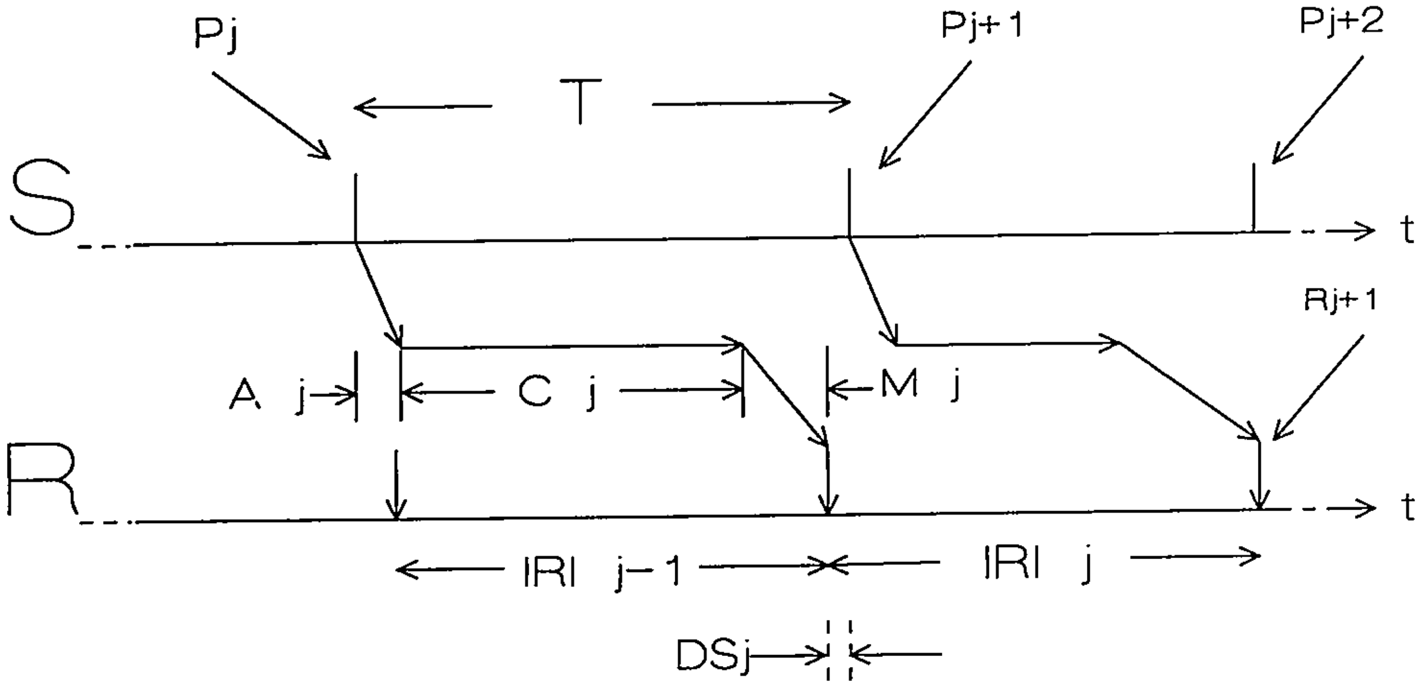
$$D_j \quad = \quad A_j + C_j + M_j. \qquad (1.37)$$

Inserting this modification into Eq. (1.36) yields the following expansion;

$$I_j \quad = \quad T + (A_j + C_j + M_j) - (A_{j-1} + C_{j-1} + M_{j-1}). \qquad (1.38)$$

FIGURE 1.13

The SCM for the timing of synchronization phase IRIs. T is the inter pulse interval, M_j the motor delay, A_j is afferent latency, and C_j is timekeeper interval. $D_j = A_j + C_j + M_j$. S is stimulus time line and R is response time line. P_j is pulse j and DS_j is deviation from synchrony from pulse P_{j+1}.


Pj
T
Pj+1
Pj+2
S
t
Rj+1
A j
C j
M j
R
t
IRI j−1
IRI j
DSj

Because of the high degree of temporal control afforded by modern computer technology it is assumed that T is a fixed constant. Since the pulses act as clock triggers it follows that there is no variability associated with the response triggers. Consequently, all s_I^2 will arise from variability in the subcomponents that make up D_j. If it is assumed that those subcomponents are mutually independent then σ_I^2 equals $2\sigma_D^2$.

The A_j delay is equal to the time between the onset of the external pulse and the time of occurrence of the internal event that marks the transferrence of the sensory information to the central processor. Some lines of evidence suggest that while A_j is greater than zero, σ_A^2 is negligible (e.g., see Hopkins, 1984).

Following A_j, the internal signal enters the central processor. Numerous theories about the nature of that process, and models about the distribution of central processing times have been offered. For present purposes it will be sufficient to assume that s_C^2 is greater than zero. After the signal has been completely processed by the central processor, the response processor is activated, and following a variable motor delay, M_j, the overt response is made. It is usually assumed that the Gaussian distribution adequately describes the shape of the distribution of M_j (Hopkins, 1984).

If we assume that σ_T^2 and σ_A^2 each equal zero and distribute the resulting covariances, the following interresponse interval autocovariance distribution is obtained for the SCM;

$$\begin{aligned} \gamma_I(k) &= 2(\sigma_C^2 + \sigma_M^2), && k=0 && (1.39) \\ &= -(\sigma_C^2 + \sigma_M^2), && k=1 \\ &= 0, && k>1. \end{aligned}$$

This distribution states that $-\gamma_I(1)$ equals s_D^2, which in turn equals $\sigma_C^2 + \sigma_M^2$. In general, $-\gamma_I(1)$ will equal the sum of the variances of all components that comprise D_j.

Only immediately adjacent I_j are expected to covary since $\gamma_I(k)$ for all $k > 1$ equal zero. Furthermore, it can be seen that both $-\gamma_I(1)$ and $\gamma_I(0)/2$ are equal to σ_D^2.

Two predictions arise out of the autocovariance distribution. The first is that $\rho_I(1)$ (which is equal to $\gamma_I(1)/\gamma_I(0)$), equals -0.5. The second is that all $\rho_I(k)$ and $\gamma_I(k)$ for k greater than 1 should equal zero. If the data are consistent with these predictions then the SCM will receive general support.

Assuming that the SCM will be supported by data then two estimates of σ_C^2 can be obtained if an estimate of σ_M^2, s_M^2, is first obtained. One estimate of σ_C^2 equals $(-G_I(1) - s_M^2)$ and the other equals $(G_I(0)/2 - s_M^2)$. However, the validity of either estimate of σ_C^2 depends directly on the estimate of σ_M^2.

DURATION DISCRIMINATION EXPERIMENT

INTRODUCTION

The central issue concerning the PTDD experiment is the functional form of the relationship between the variance and mean of the psychometric function. At a general level of analysis the goal is to determine whether it is the variance or the standard deviation that is better described as being a linear function of the mean. This will be carried out fitting a set of mathematical models and rank ordering them in terms of how well they fit the functions. This analysis will provide the necessary information upon which the bulk of theoretical implications will be based. Closely linked to this issue is one of the shape of the psychometric function. This too is a matter of theoretical significance because of the implications that the shape of the function has on the underlying temporal processes. In this regard an attempt will be made to determine which of the normal or isosceles triangle distribution has a cumulative form that better represents the shape of the psychometric function.

Finally, the issue of how practice affects variability at each value of T, and consequently how the variance vs mean function changes as a result of practice, will be investigated. First we wish to determine if extensive practice leads to an improved level of performance. If it does, and we expect that it will, we will further analyze how variability is affected by practice. In particular we wish to determine if performance stabilizes with experience. If it does, we would like to know the degree to which it is affected and the amount of practice necessary to reach the asymptotic level.

Based on findings reported by Kristofferson (1980) we expect that practice will not improve discriminability equally for all base durations. Thus the shapes of the post-practice variability versus mean functions should be different from their pre-practice counterparts if explicit standard DD (i.e., PTDD) is similar to implicit standard DD (i.e., MFDD). Specifically, we expect that practice will have little effect on discriminability for those base durations corresponding to values at the low end of each tread on the quantal step function, and that it will have an increasing effect for those base durations approaching the high end of the tread. As a final comparison, the models that are fitted to the pre-practice functions will also be fitted to the post-practice functions. The parameter estimates and the rank ordering of how well those models fit will form the basis of the comparison.

METHOD

SUBJECTS

Three highly motivated subjects participated in this experiment. LL, an adult female technician in the laboratory, was well practiced in DD experiments. She was paid five dollars per session for her time. The other two subjects, AK and GF, are adult males. AK served as a subject in previous experiments on R-SS (Kristofferson, 1976), DD (Kristofferson, 1977, 1980, 1984), and numerous other projects. GF, the author, had very little prior experience as a subject in psychophysical experiments.

PROCEDURE

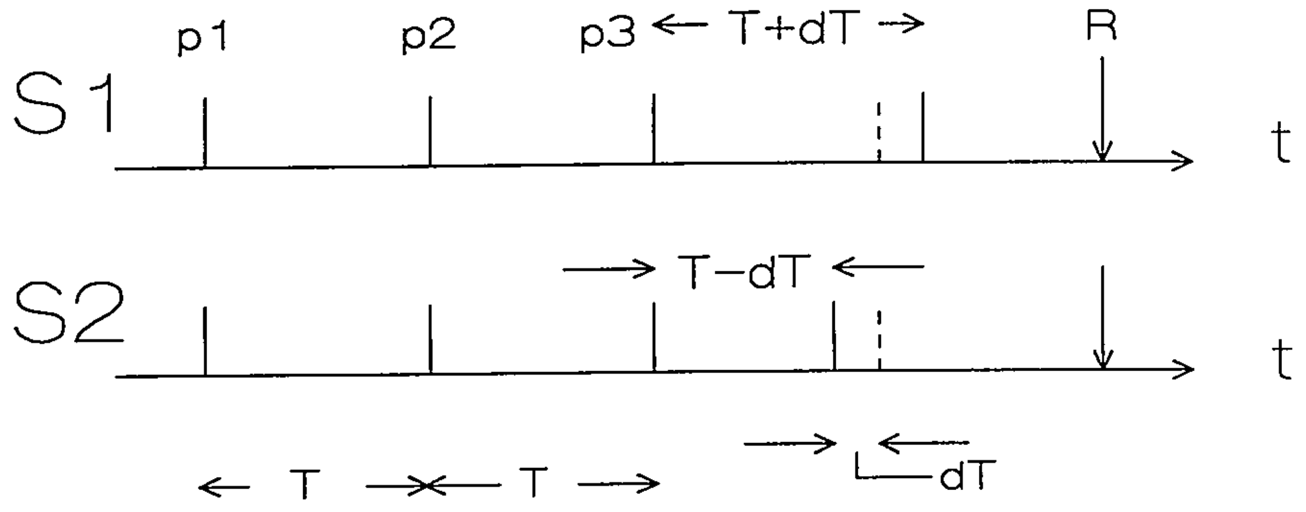
Each session of the PTDD experiment is composed of four blocks of 96 trials each, with a one minute break between blocks. A computer beep initiates each trial. After a delay of two seconds the first of a train of four auditory pulses is binaurally presented to the subject through headphones. The interval between the onsets of the first and the second and the second and the third pulses is equal to T msec in duration. The interpulse interval defined by the interval between the onsets of the third and fourth pulses is the test stimulus. The test stimulus differs from T by an amount equal to ± δT msec. There are 48 "long" (T + δT) and 48 "short" (T - δT) test stimuli in a block that are pseudorandomly distributed throughout it. Fig. 2.1 shows the structure of each trial and session.

On every trial, the subject is required to judge whether the variable interval is longer or shorter than T. A "longer" judgment is indicated by pressing "L" on the computer console, and a "shorter" judgment is indicated by pressing "S". Speeded responding (Kristofferson, 1977), the technique which requires subjects to respond as fast as possible, was not used in the present experiment. Instead, subjects were encouraged to respond as accurately as possible. If a key other than "S" or "L" was pressed the message "Press either L or S", which is displayed on the computer monitor and the computer waited for another response. Only after one of these two keys was pressed does the trial end and progress to the next trial. No provision is made to repeat a trial. As soon as an acceptable response is made, S receives immediate feedback indicating whether his response was correct or not. Between trials, a visual display of the trial number and a cumulative count of total errors made to that point in the block are presented on the monitor.

A set of eight values of T are used in this experiment. They are: 100 (for AK and GF), 110 (for LL) and, 175, 233, 367, 466, 734, 932, 1468 msec for all three subjects. They were chosen such that their values correspond closely to the lower and higher ends of each step on Kristofferson's (1980) step function and so their range spans the range previously identified to be in the Weber's law range of base durations (e.g., Kristofferson, 1980; Getty, 1975). Subjects continue at one value until performance does not noticeably improve over a five session span.

FIGURE 2.1

Stimulus and response time lines for each trial of the PTDD method. pj marks the pulses in which p_4 is presented T + δD msec following p_3 in stimulus train S1 and T - δD msec following p_3 in stimulus train S2. The enclosed box represents a typical session. Bj, for j = 1 to 4 represents the four blocks.


p1
p2
p3
T+dT
R
S1
t
T−dT
S2
t
T
T
dT


B1
rest
B2
rest
B3
rest
B4
end
ONE SESSION

APPARATUS

An Apple IIe computer, in conjunction with an Interactive Structures DI09 card and an assembler program, controls the timing of events in a session. The accuracy of stimulus timing is plus or minus one half of one msec. Each pulse of the pulse train is a 2000 hertz, 10 msec (from pulse onset to offset) square wave signal generated by an EICO Audio Generator (Model 377) with the amplitude setting fixed at 20. The auditory pulses are comfortable and clearly audible for all subjects who sit alone in a well ventilated sound attenuating booth during a session. Responses, as indicated above, were registered by pressing either the "S" or the "L" key on the computer keyboard.

RESULTS AND DISCUSSION

The presentation order of T was the same for AK and LL but it differed for GF, and the duration of the variable interval, $T \pm \delta T$ generally differed across Ss. The value of δT initially was set by trial and error in order to ensure imperfect discrimination. Table 2.1 shows the values of T encountered by each subject, the order in which they were presented, the number of sessions run at each, and the final value of δT at each.

THE PSYCHOMETRIC FUNCTION

The cumulative form of the normal and isosceles triangle distributions describe the obtained DD psychometric functions extremely well and it is extremely difficult to judge which one does so better. Allan et al. (1971) found that these two distributions represented the DD psychometric function equally well.

Because the issue of whether the psychometric function is better represented by the normal or the isosceles triangle distribution remains unresolved, estimates of the mean, μ, and the variance, σ^2, of the psychometric function will be calculated twice. They will be calculated once assuming that the function represents the cumulative form of a normal distribution and again assuming that it represents

TABLE 2.1

Details of the Pulse Train Duration Discrimination Experiment

LEGEND:

SYMBOL	DESCRIPTION
O	sequential order of T
#S	number of sessions
δT	final deviation from T for last interval of pulse train

Tms	O	#S	δT	O	#S	δT	O	#S	δT
100	5	30	6				7	25	4
110				5	20	5			
175	6	27	6	6	26	5	4	16	5
233	7	35	6	7	41	5	5	20	7
367	8	45	6	8	25	5	1	25	7
466	1	30	8	1	20	8	6	15	8
734	2	20	20	2	20	15	8	20	10
932	3	30	20	3	20	15	2	12	20
1468	4	40	40	4	40	30	3	17	25

the cumulative form of an isosceles triangle distribution. The algorithms that were used to calculate these estimates are presented below.

When estimates of σ^2 and μ are based on the isosceles triangle distribution, they will be represented by s_{it}^2 and m_{it} respectively. If $P(R_L \mid S_S)$ and $P(R_L \mid S_L)$ respectively represent the probabilities of S_S and S_L being called long, where S_S represents a stimulus of duration T-δT and S_L a stimulus of duration T+δT, then s_{it}^2 and m_{it} can be calculated as follows;

$$s_{it}^2 = q^2/6 \qquad (2.1)$$

where $$q = (S_L - S_S)/(A + B), \qquad (2.2)$$

$$A = 1 - (2P(R_L \mid S_S))^{1/2}, \qquad (2.3)$$

and $$B = 1 - (2(1-P(R_L \mid S_L)))^{1/2}. \qquad (2.4)$$

$$m_{it} = T - \delta T + Aq. \qquad (2.5)$$

Fig. 2.2 shows a picture of the relationships among these variables.

Estimates of μ and σ^2 will be represented by m_n and s_n^2 respectively when it is assumed that the underlying distribution is normal. The internal representation of S_S should be located below m_n by some proportion, Z_b, of s_n. Similarly, the internal representation of S_L should be located above m_n by a proportion, Z_a, of s_n. The areas under the distribution to the left of these markers correspond to the probability of the respective stimulus being called "long" (i.e., $P(R_L \mid S_S)$ and $P(R_L \mid S_L)$). Fig. 2.3 shows the relationships among these variables.

According to the algorithm outlined in Abramowitz and Stegun (1970);

$$Zb = t - (C_1 + C_2t + C_3t^2)/$$

$$(1 + D_1t + D_2t^2 + D_3t^3) \qquad (2.6)$$

where $$t = (\ln(1/P(L \mid S_S)^2))^{.5} \qquad (2.7)$$

FIGURE 2.2

The relationships among the variables used to estimate σ^2 and μ when based on the isosceles triangle distribution. $P(R_L|S_S)$ and $P(R_L|S_L)$ respectively represent the probabilities of S_S and S_L being called long, where S_S represents a stimulus of duration T-δT and S_L a stimulus of duration T+δT. A represents the distance in standard deviation units of the triangular distribution the internal representation of S_S lies below m_{it} and B represents the distance in standard deviation units of the triangular distribution the internal representation of S_l lies above m_{it}.

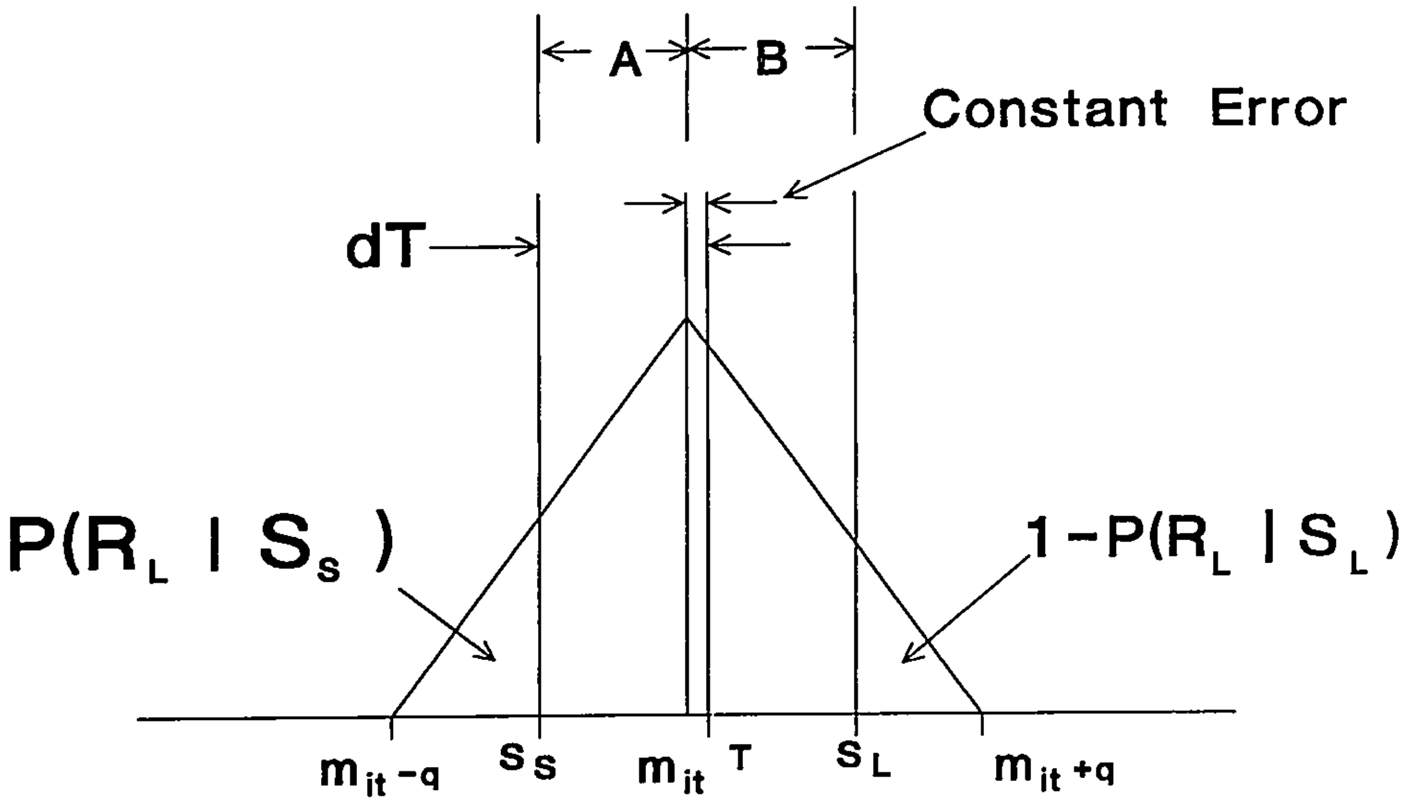
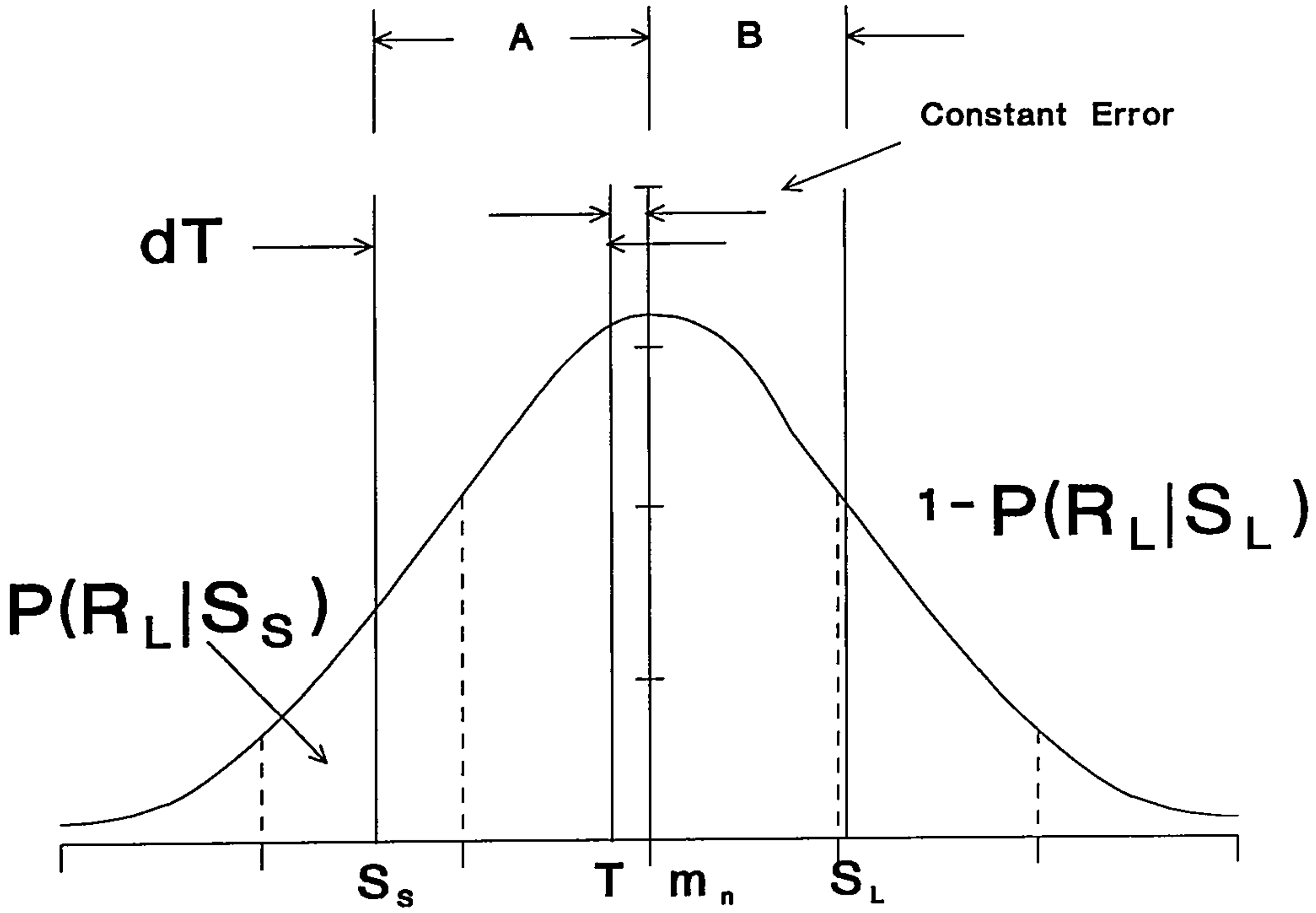

A
B
Constant Error
dT
$P(R_L \mid S_s)$
$1-P(R_L \mid S_L)$
$m_{it}-q$
s_s
m_{it}
T
s_L
$m_{it}+q$

FIGURE 2.3

The relationships among the variables used to obtain s_n^2 and m_n when based on the Gaussian distribution. $P(R_L|S_S)$ and $P(R_L|S_L)$ respectively represent the probabilities of S_S and S_L being called long, where S_S represents a stimulus of duration $T-\delta T$ and S_L a stimulus of duration $T+\delta T$. A represents the distance in standard deviation units of the Gaussian distribution the internal representation of S_S lies below m_n and B represents the distance in standard deviation units of the Gaussian distribution the internal representation of S_l lies above m_n.


A
B
Constant Error
dT
1 - P(R_L|S_L)
P(R_L|S_S)
S_S
T
m_n
S_L

and

$C_1 = 2.515517$ $D_1 = 1.432788$

$C_2 = 0.802853$ $D_2 = 0.189269$

$C_3 = 0.010328$ $D_3 = 0.001308$

An estimate of Z_a may be obtained in a similar manner if

$$t = (\ln(1/(1-P(L \mid S_L))^2))^{.5} \tag{2.8}$$

is substituted into equation 2.6. The sum of Z_a and Z_b indicates how far the two physical stimuli are apart in s_n units. The magnitude of one s_n may then be estimated because the difference between the two physical stimuli is known (i.e., $2\delta T$).

$$s_n = (2\delta T)/(Z_a+Z_a). \tag{2.9}$$

Similarly, the mean may be estimated as;

$$m_n = T-\delta T + Z_a. \tag{2.10}$$

These two procedures yielded highly similar estimates of σ and μ. In fact, when mean m_{it} and m_n are compared over sessions at each T, no statistically significant differences emerged for any S. However, a similar comparison of s_{it} and s_n indicates that s_{it} tends to be smaller than s_n. For the most part that difference was not statistically significant but in a few cases it did reach statistical significance. Table 2.2 shows the results of these comparisons.

Not surprisingly, when the Pearson correlation statistic, r, is used to evaluate whether there is a significant correlation between s_n and s_{it} over sessions, r reaches significance at every base duration. See Table 2.3 for the details of this analysis. Furthermore, when s_n is regressed on s_{it} for each T, the slope coefficients differ little from unity and from one T to another. In addition, the intercepts are, on average, within milliseconds of the origin. These results indicate that the difference between estimates based on the two distributions is not a function

TABLE 2.2

Comparison of estimates obtained assuming timekeeping of the internal clock is triangularly versus normally distributed.

LEGEND:

SYMBOL	DESCRIPTION
μ	mean
σ	standard deviation

	μ			σ		
T	AK	LL	GF	AK	LL	GF
100	-0.177		-0.339	-1.378		1.279
110		0.757			1.521	
175	-0.088	0.462	0.1673	-1.878	-1.762	-1.565
233	-0.036	0.437	0.077	**-2.878	-2.003	-1.229
367	-0.036	0.005	0.105	*-2.507	-1.916	-0.462
466	0.005	0.155	-0.006	-2.037	*-2.194	-1.390
734	0.313	0.183	-0.024	-0.824	-1.559	-1.325
932	-0.003	0.008	-0.030	-2.017	-2.077	-1.792
1468	-1.379	-0.023	-0.158	-1.654	**-2.800	-1.168

* $p \leq .05$
** $p \leq .01$

TABLE 2.3

Regression analysis and correlations between standard deviation estimates derived from assuming the triangular and normal distributions.

LEGEND:

SYMBOL	DESCRIPTION
T	base temporal interval
N	number of sessions
SLOPE	slope of best fit line
INTERCEPT	intercept of best fit line
r	correlation coefficient

	T	N	SLOPE	INTERCEPT	r
AK					
	100	30	1.1444	-0.872	0.99596*
	175	27	1.1686	-1.254	0.99725*
	233	35	1.2095	-1.951	0.99918*
	367	45	1.1730	-1.114	0.99970*
	466	30	1.1454	-0.380	0.99978*
	734	20	1.1608	-13.567	0.99950*
	932	30	1.1545	-11.374	0.99950*
	1468	40	1.1209	20.060	0.99945*
MEAN			1.1596	-1.307	0.99879
LL					
	110	20	0.4558	5.138	0.97746*
	175	26	1.2168	-1.497	0.99957*
	233	41	1.2125	-1.476	0.99908*
	367	25	1.1350	0.172	0.99992*
	466	20	1.1459	-1.106	0.99795*
	734	20	1.1630	-7.022	0.99850*
	932	20	1.1522	-2.644	0.99984*
	1468	40	1.1256	16.177	0.99982*
MEAN			1.07585	0.9678	0.99652
GF					
	100	25	0.7970	1.3048	0.98070*
	175	16	1.0327	2.3252	0.97972*
	233	20	1.1956	-2.3555	0.99951*
	367	25	1.0834	2.0079	0.99989*
	466	15	1.1420	-0.1282	0.99987*
	734	20	1.1235	1.8631	0.99977*
	932	13	1.1365	-1.0746	0.99884*
	1468	17	1.0743	76.4240	0.99992*
MEAN			1.0731	10.0458	0.99478

---

* (p ≤ .05)

of T. That fact means that the use of either distribution will provide estimates of s that can be readily transformed into estimates based on the other distribution. To obtain an accurate value of s_n from s_{it} one need only to multiply s_{it} by the appropriate slope coefficient provided in Table 2.3.

The above analyses indicate that either method will provide similar estimates of the parameters of the psychometric functions and that one estimate can be readily transformed into the other with a high degree of accuracy. But they do not offer guidance as to whether it is the normal or the isosceles triangle distribution that more accurately represents the true nature of the psychometric function. Unfortunately that issue cannot be addressed with the present data because only two points are available on each psychometric function (i.e., only two values of δT were used for each value of T). However, there are several reasons why the isosceles triangle distribution will be used for the purposes of modelling the PTDD psychometric function. First, because the DD psychometric function is represented very well by either distribution, there appears to be no empirical basis upon which to decide between them. The present analysis shows that estimates based on either distribution are highly correlated and not significantly different for the most part. Because one of the main goals of the present experiment is to evaluate Kristofferson's (1967) quantal theory of timing in combination with the RTCT (Kristofferson, 1977) in the context of PTDD, the isosceles triangle distribution will be used to model the PTDD psychometric functions.

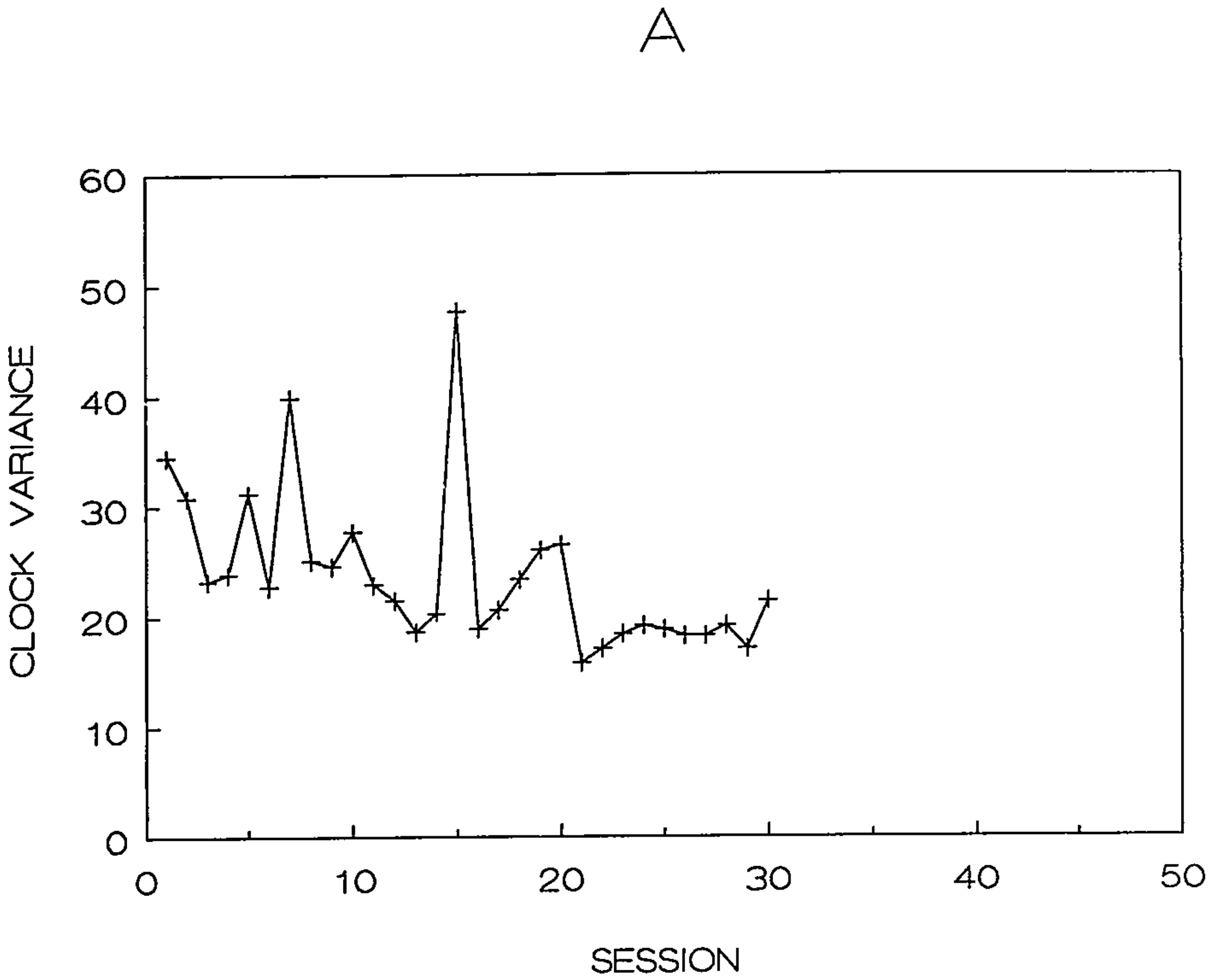
VARIANCE: ESTIMATES AND PRACTICE EFFECTS

Figs. 2.4a through 2.4x show a detailed representation of s_{it}^2 as a function of session number for each value of T and for each subject. These curves will be referred to as the PTDD variance practice curves. Each point represents an estimate of variance based on all judgments in a session - no data are excluded.

FIGURE 2.4

PTDD variance practice curves: s_{it}^2 shown as a function of session number for each value of T and for each subject.

PANEL	SUBJECT	T (msec)
A	AK	100
B	AK	175
C	AK	233
D	AK	367
E	AK	466
F	AK	734
G	AK	932
H	AK	1468
I	LL	110
J	LL	175
K	LL	233
L	LL	367
M	LL	466
N	LL	734
O	LL	932
P	LL	1468
Q	GF	100
R	GF	175
S	GF	233
T	GF	367
U	GF	466
V	GF	734
W	GF	932
X	GF	1468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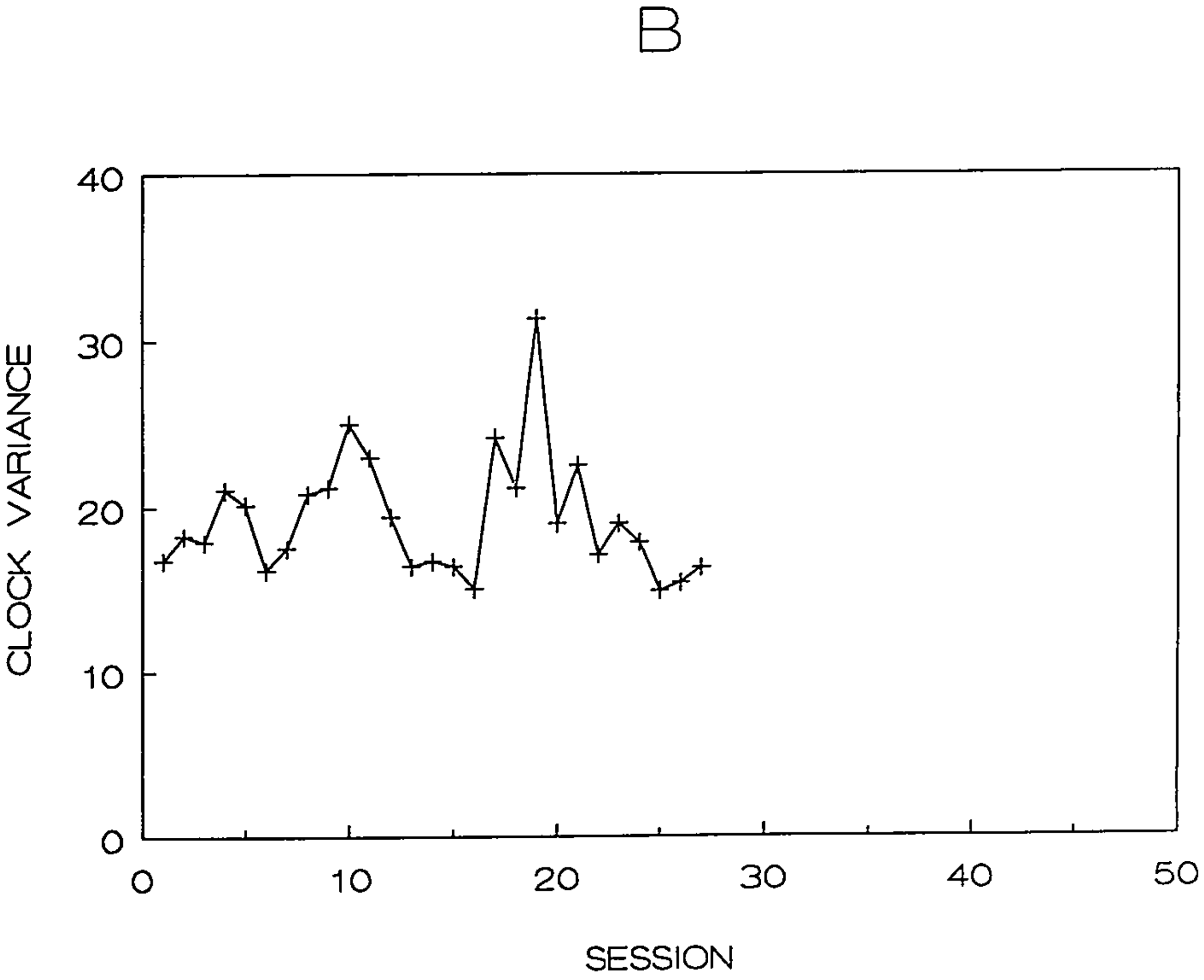
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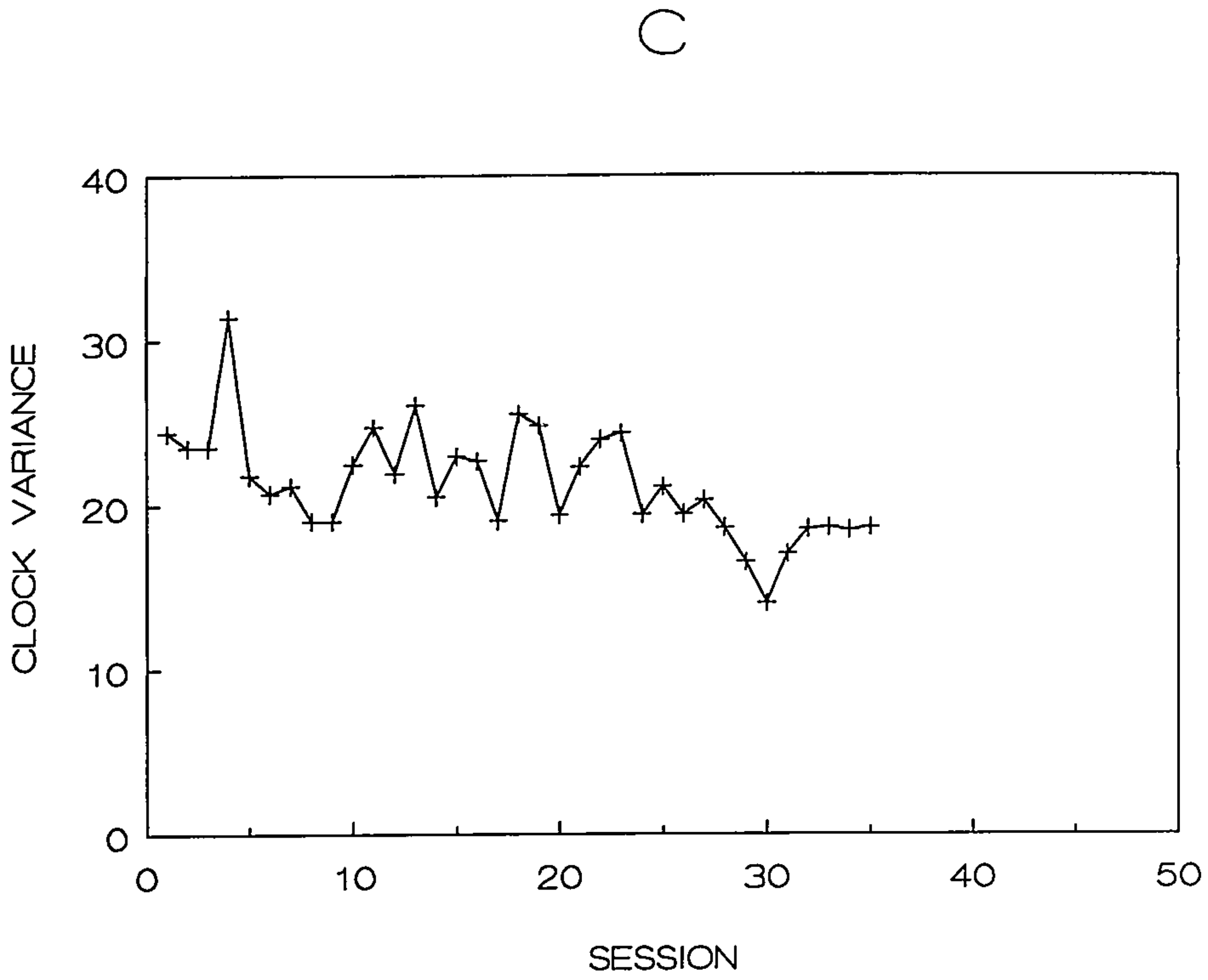
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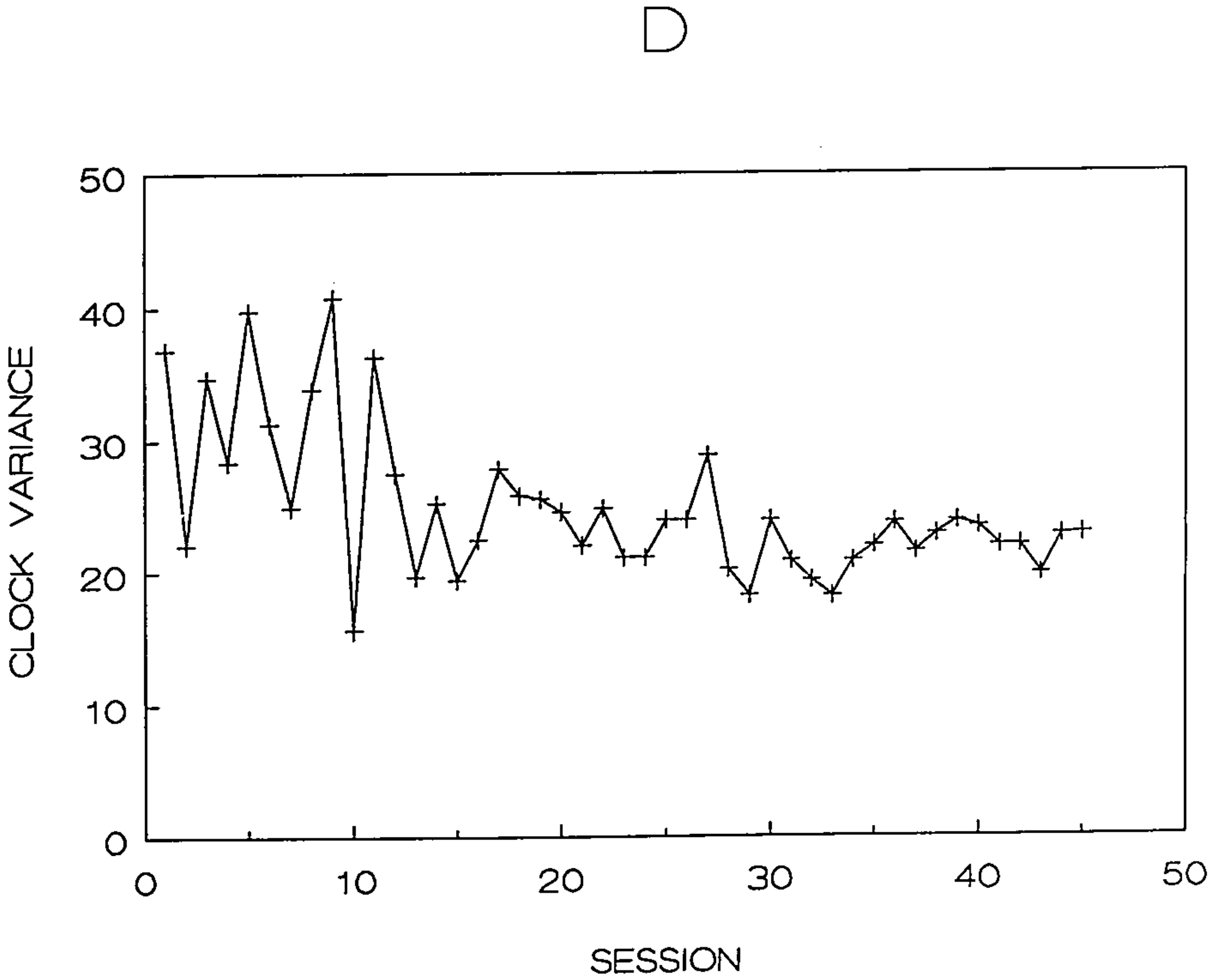
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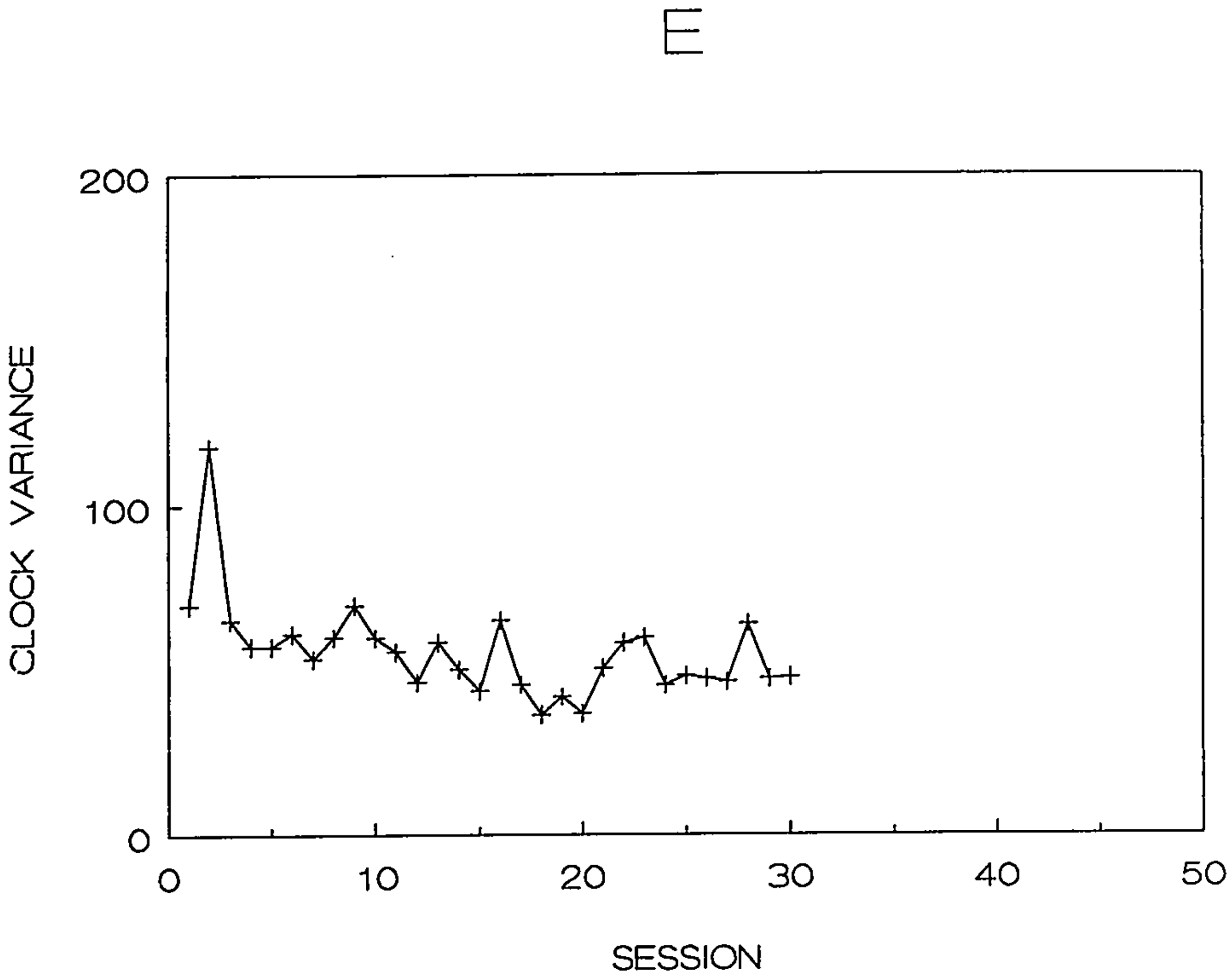
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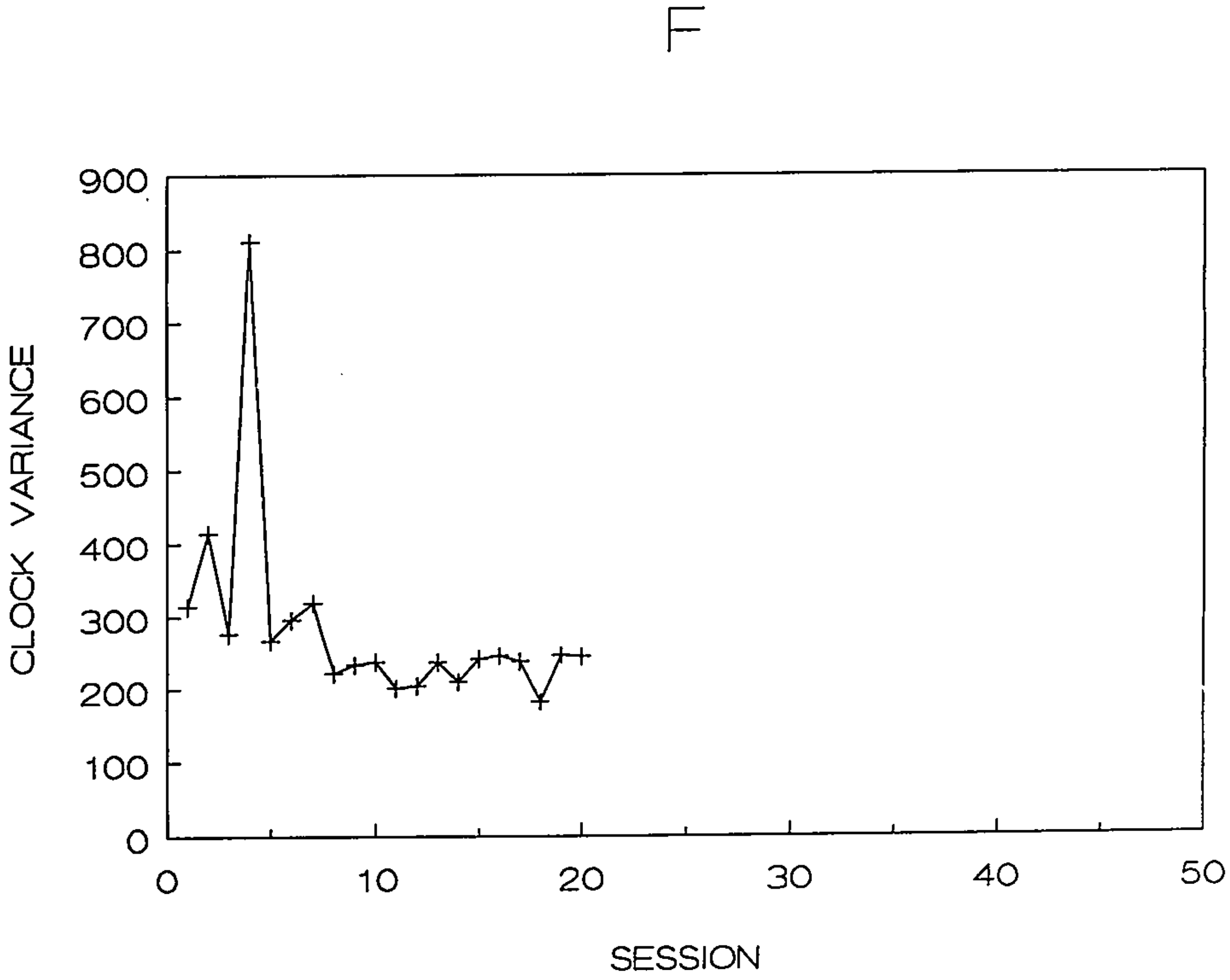
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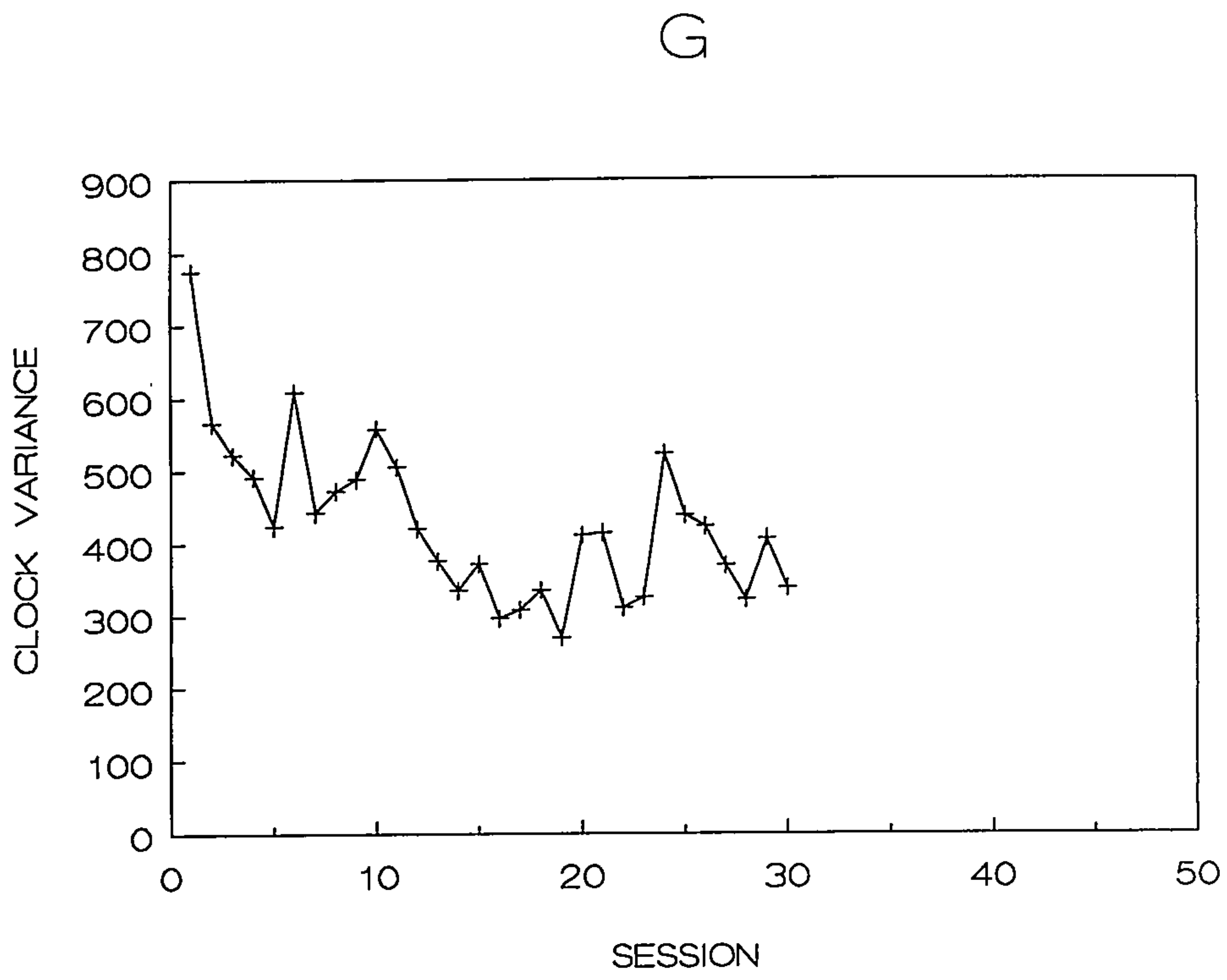
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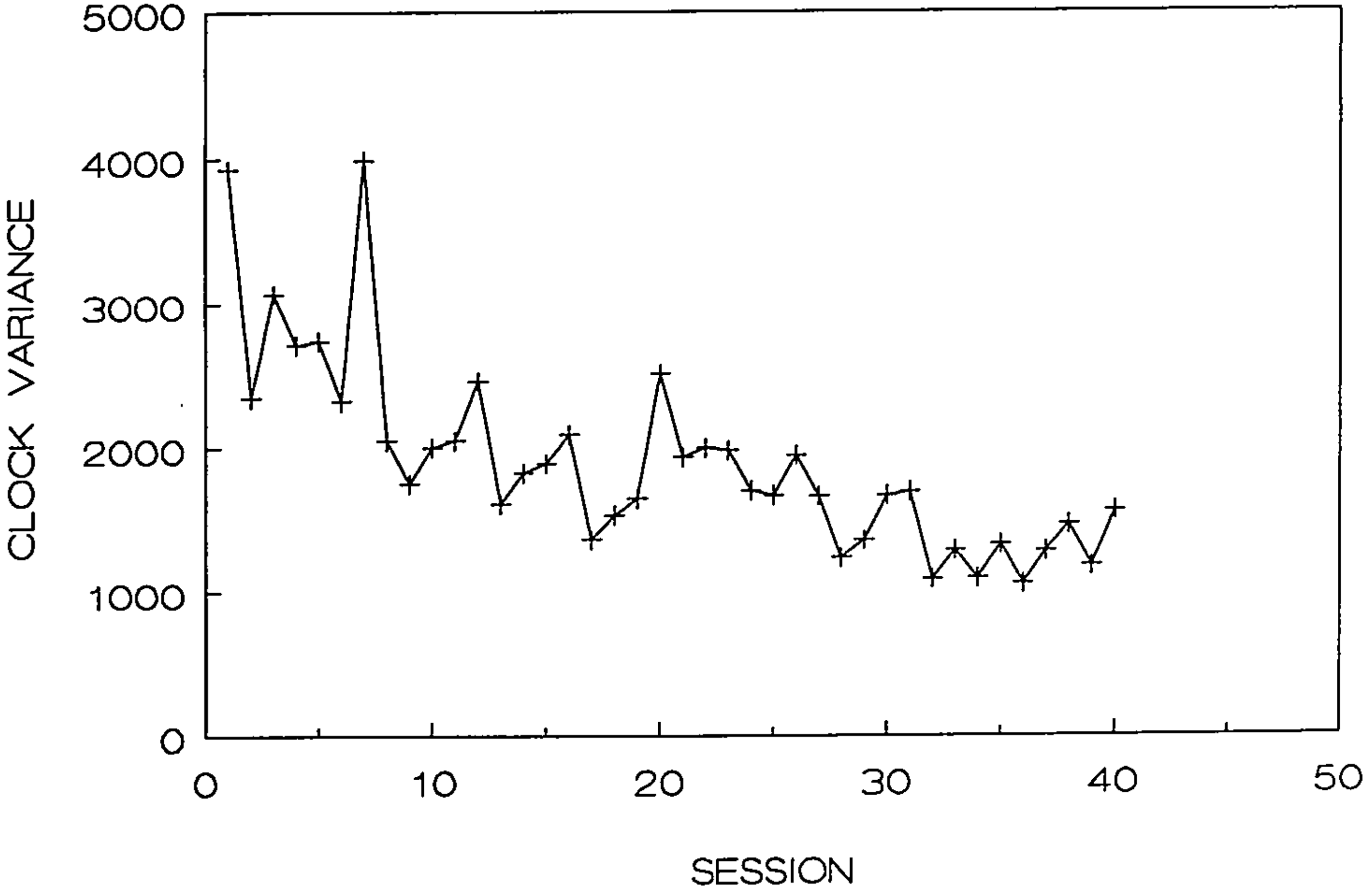
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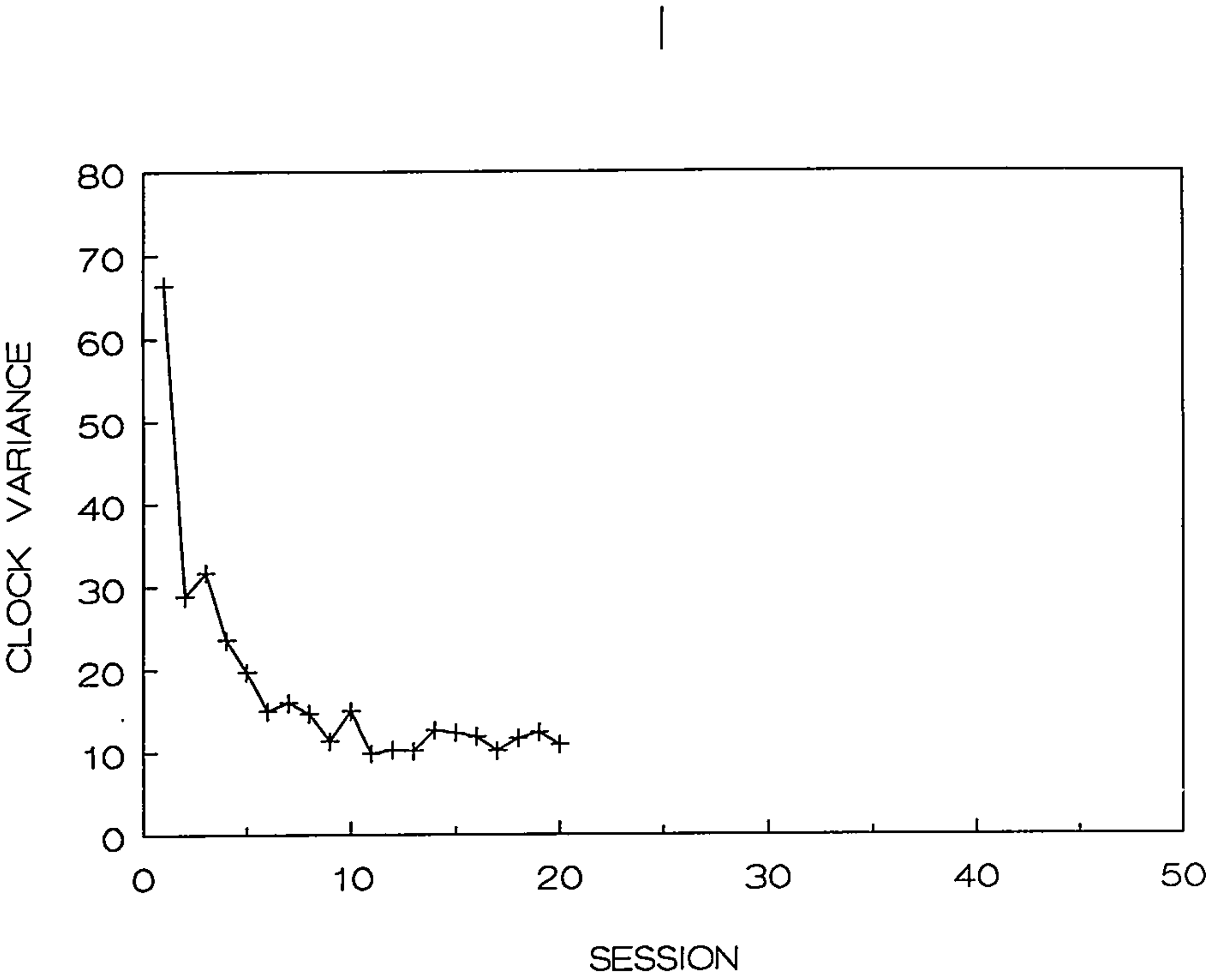
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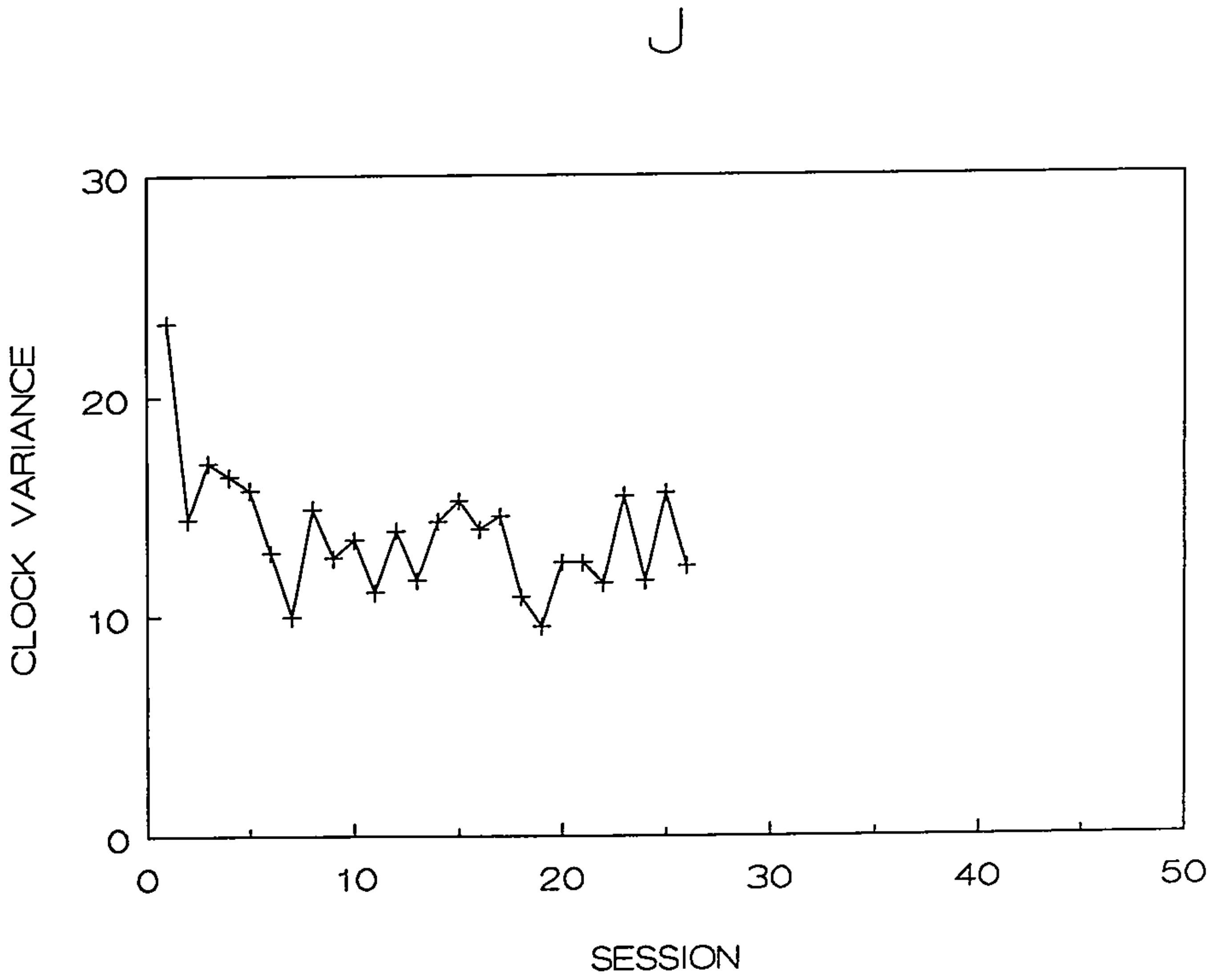
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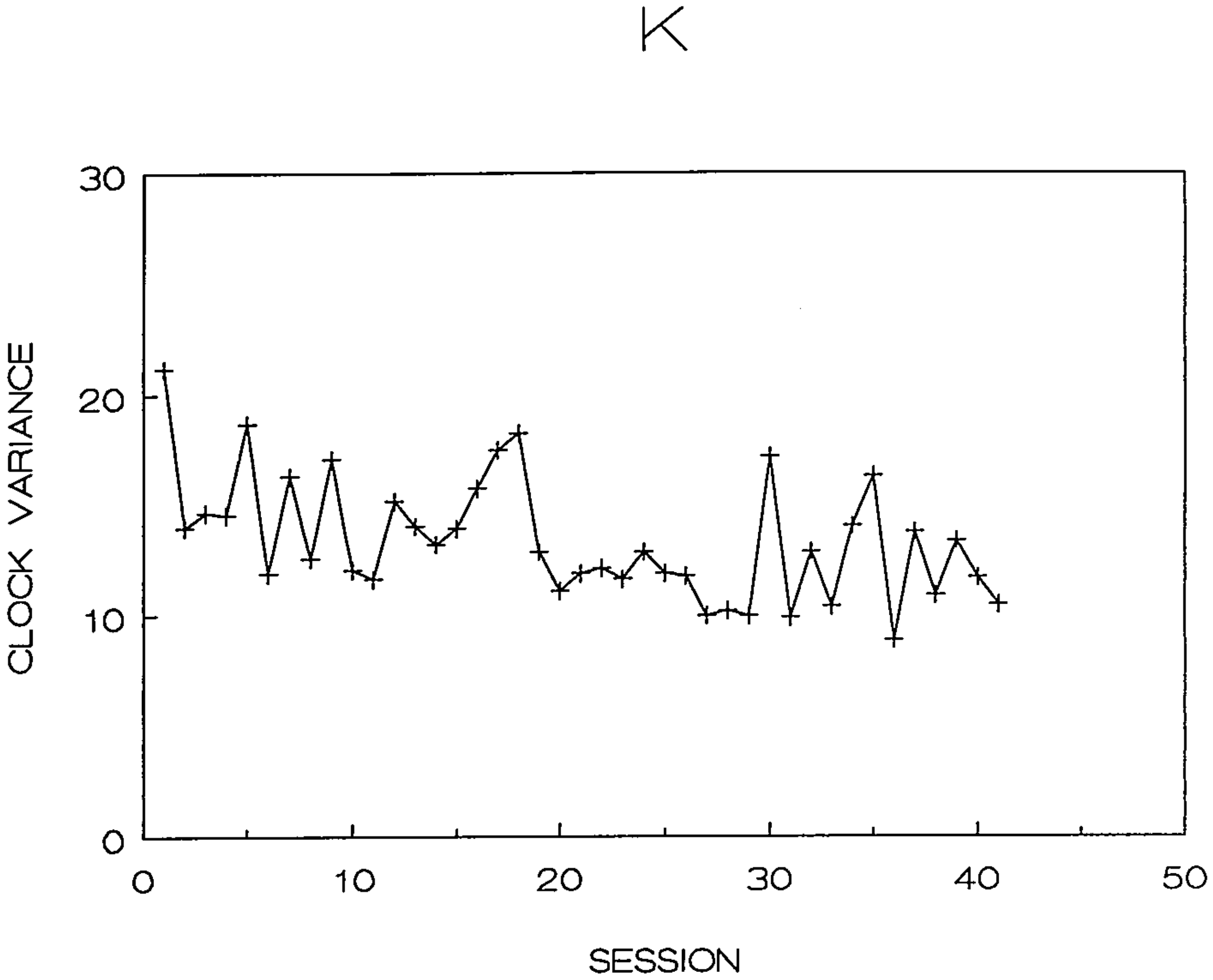
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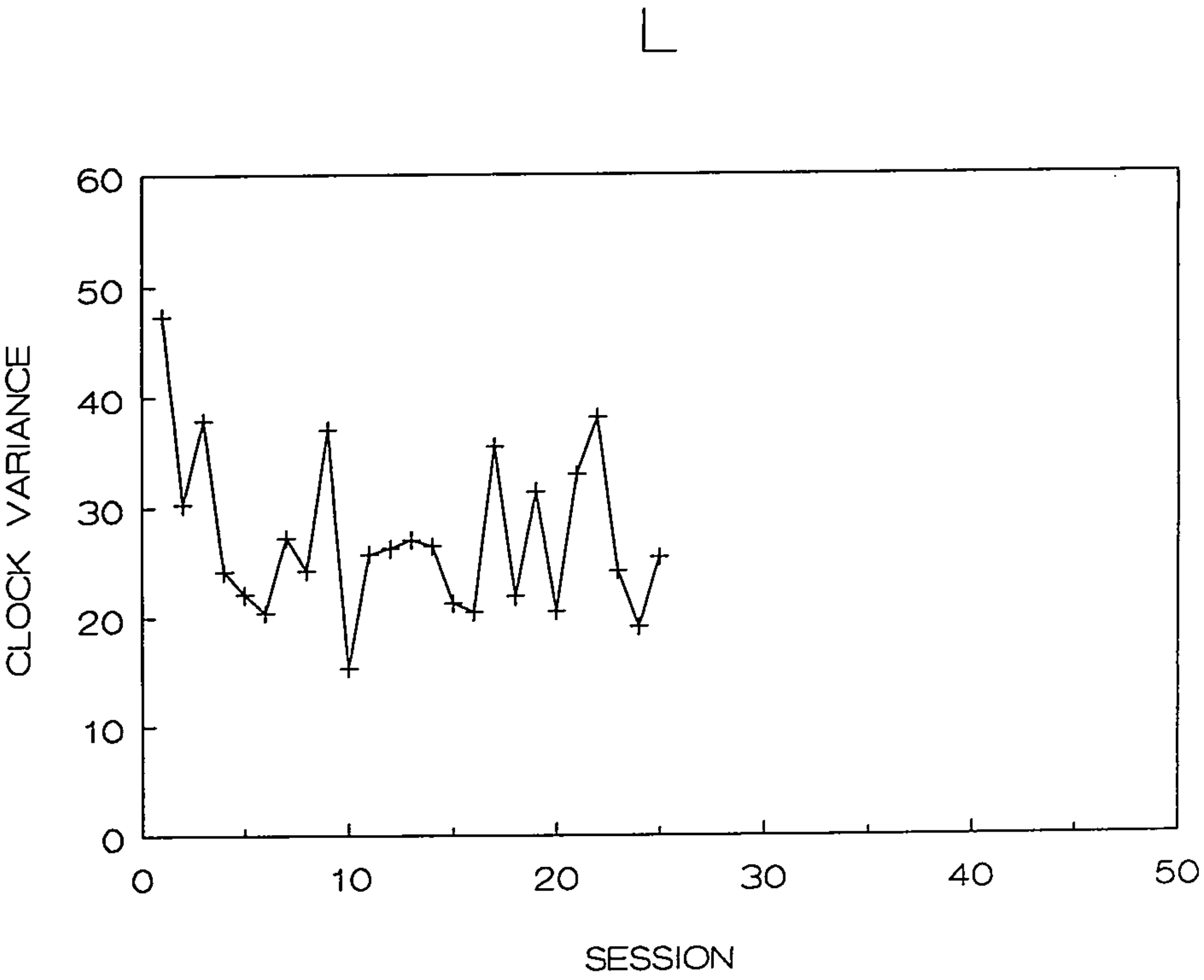
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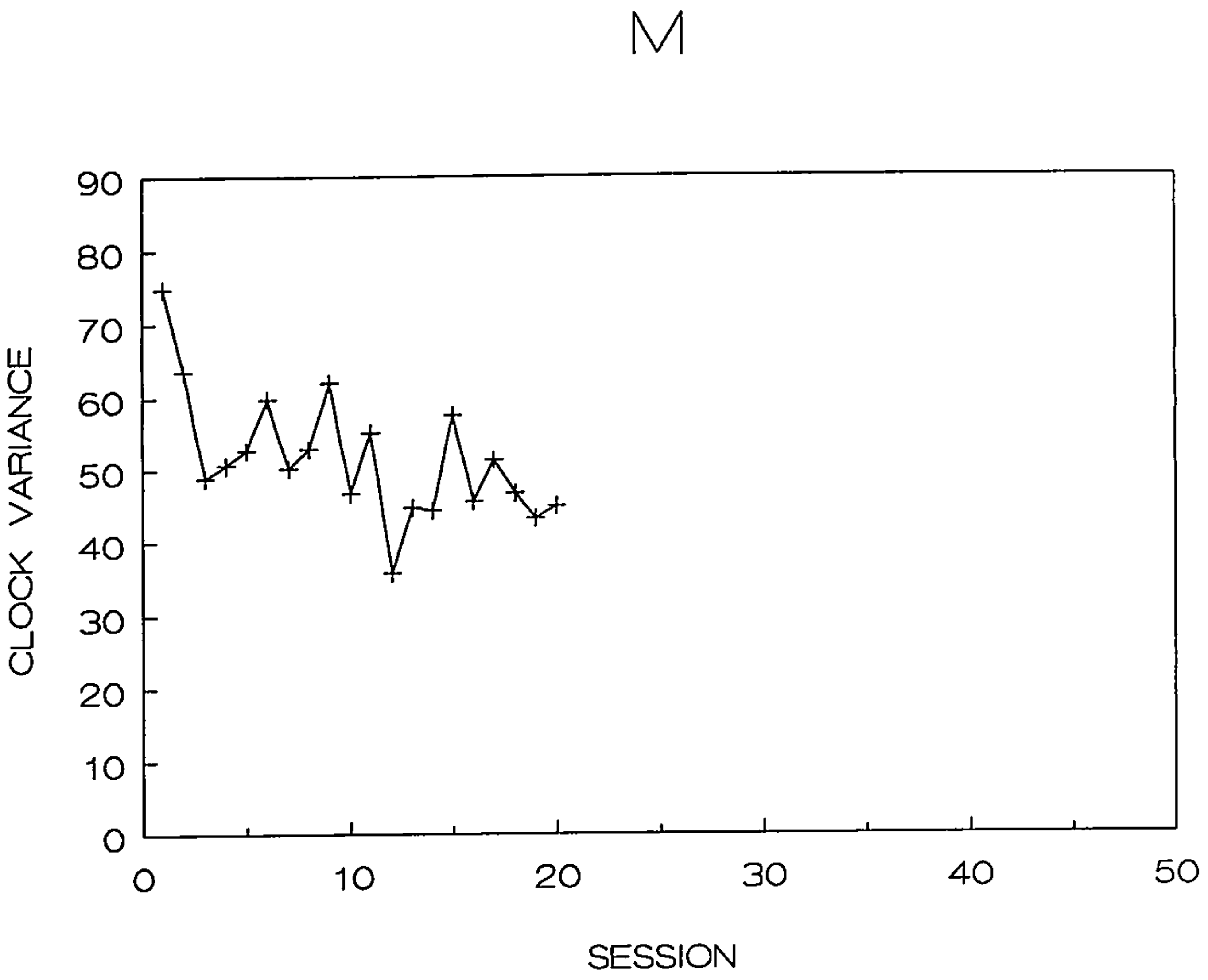
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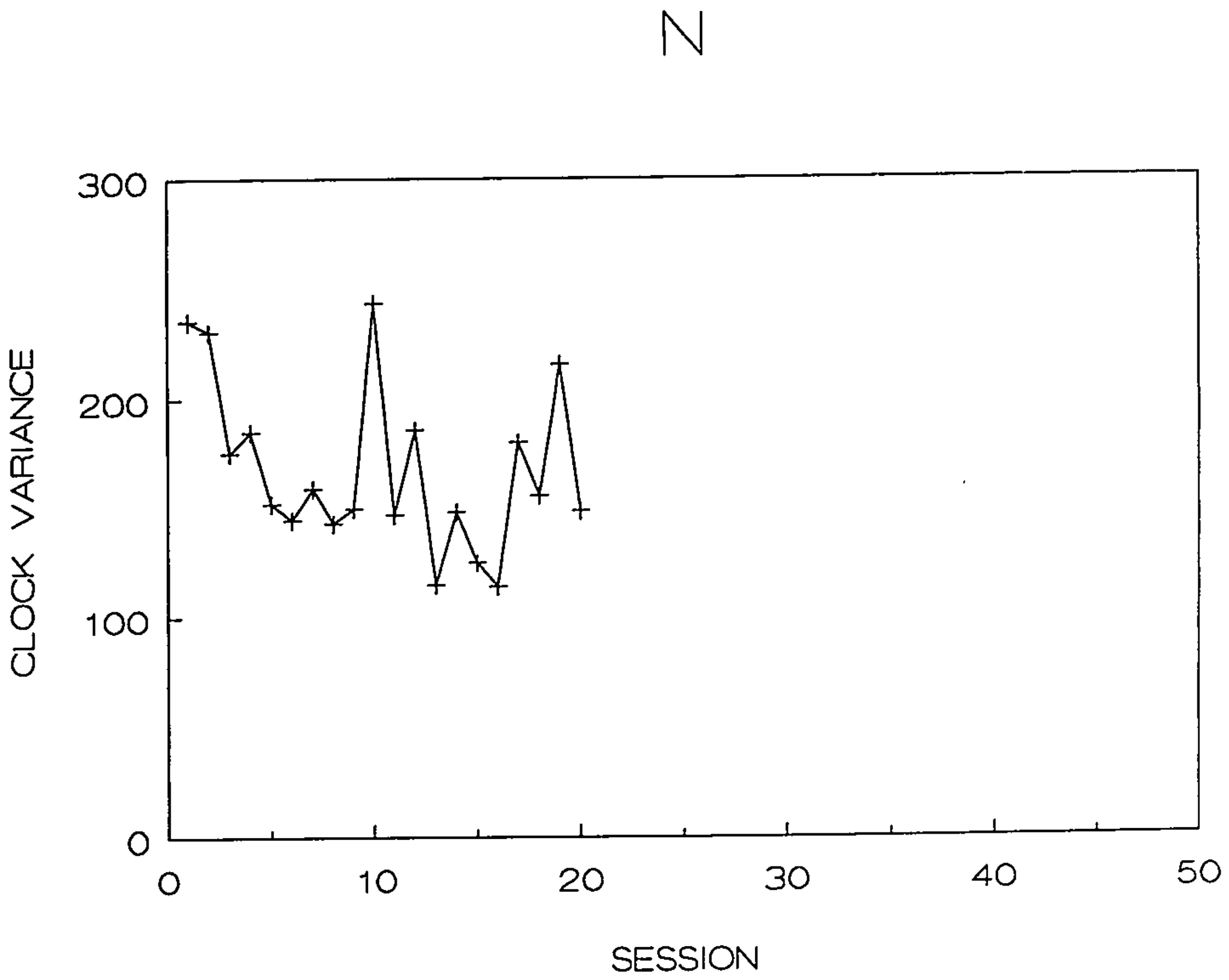
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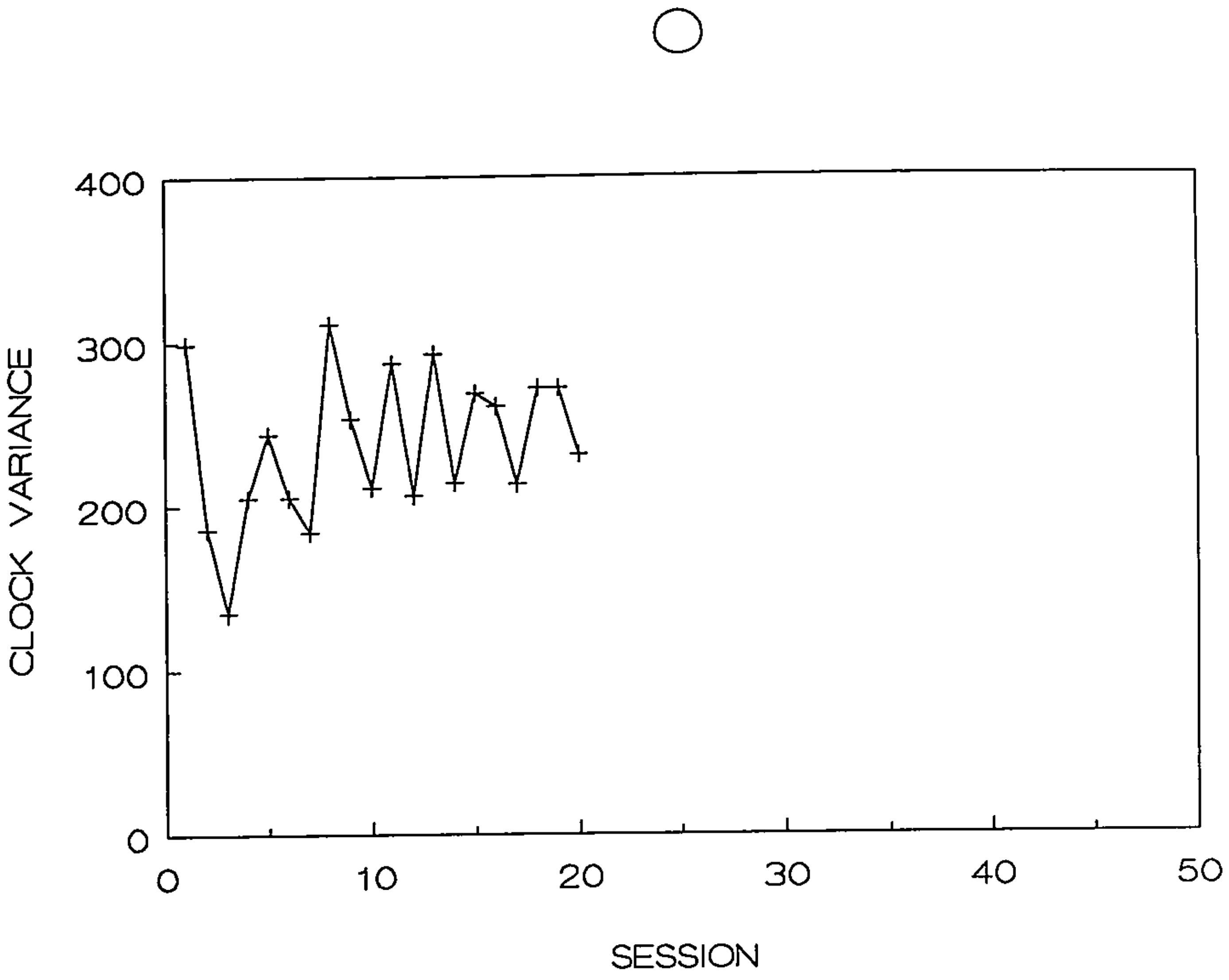
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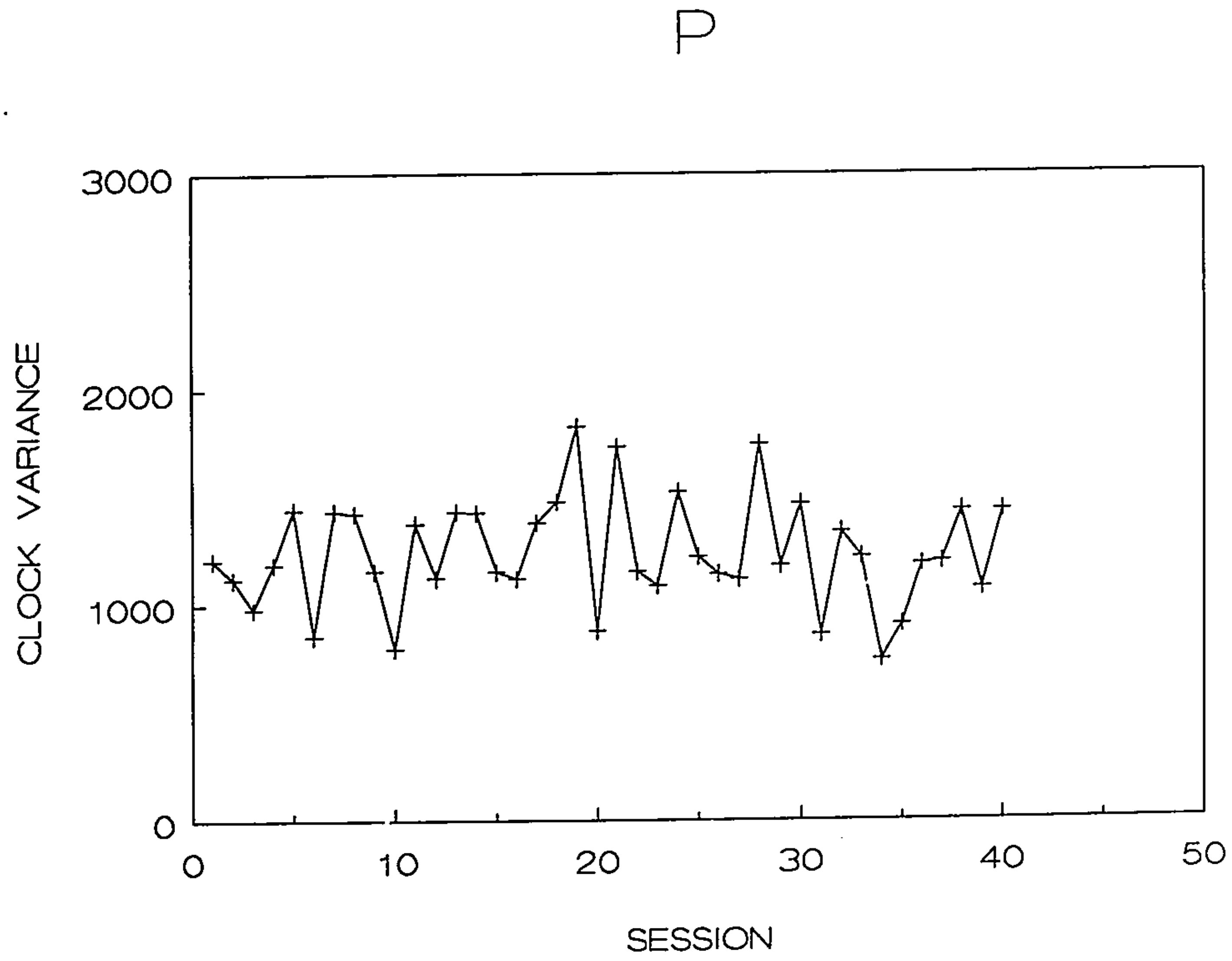
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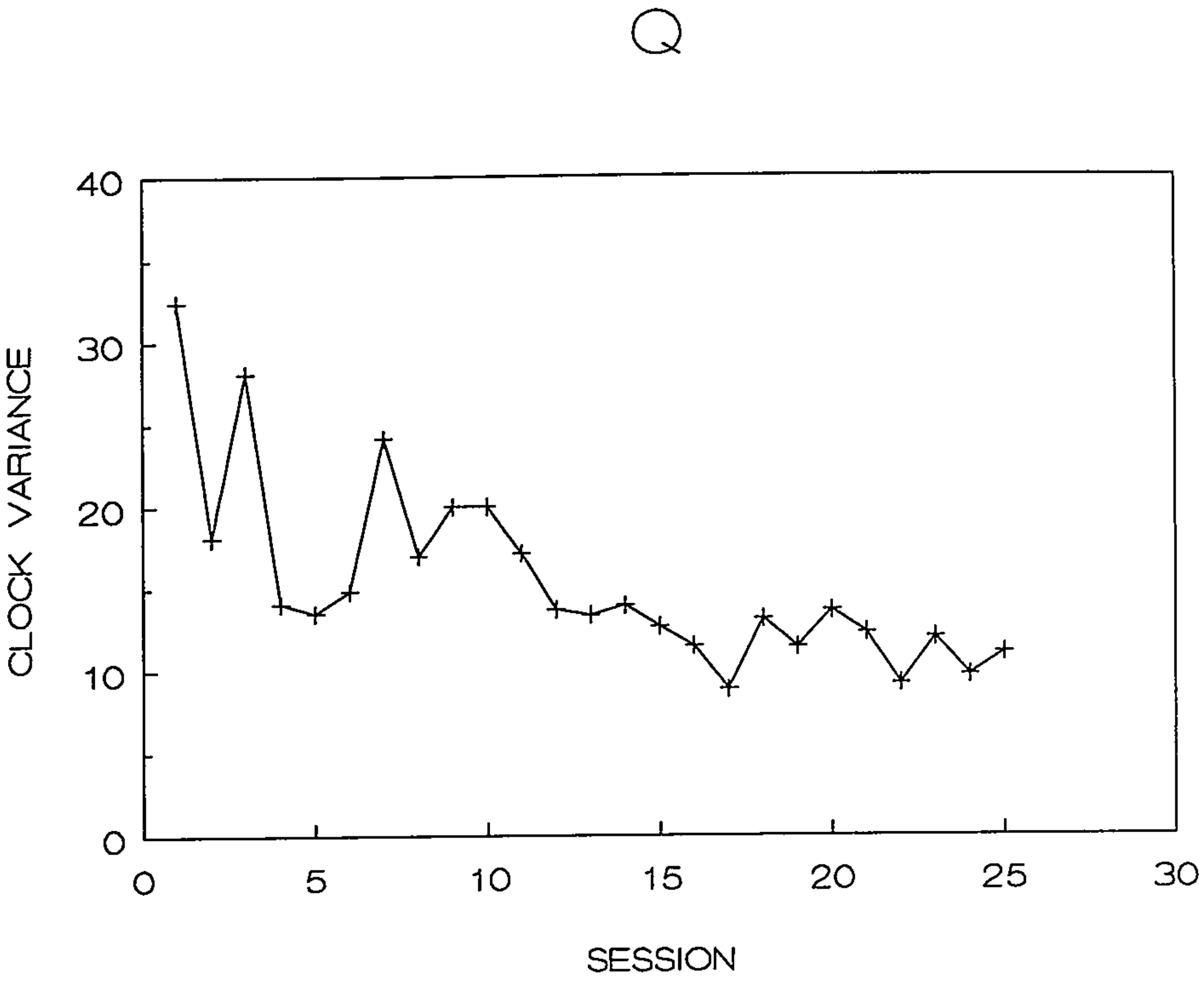
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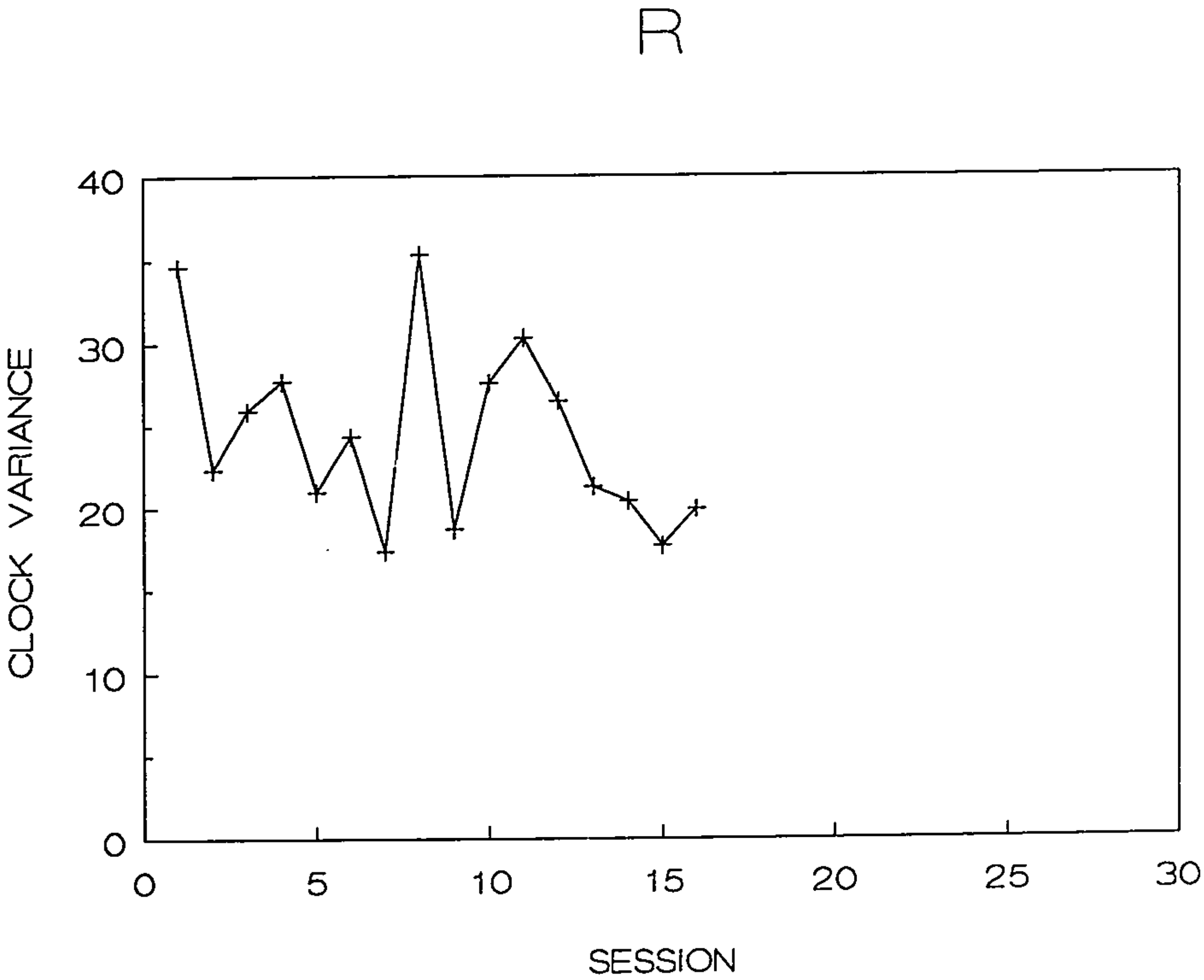
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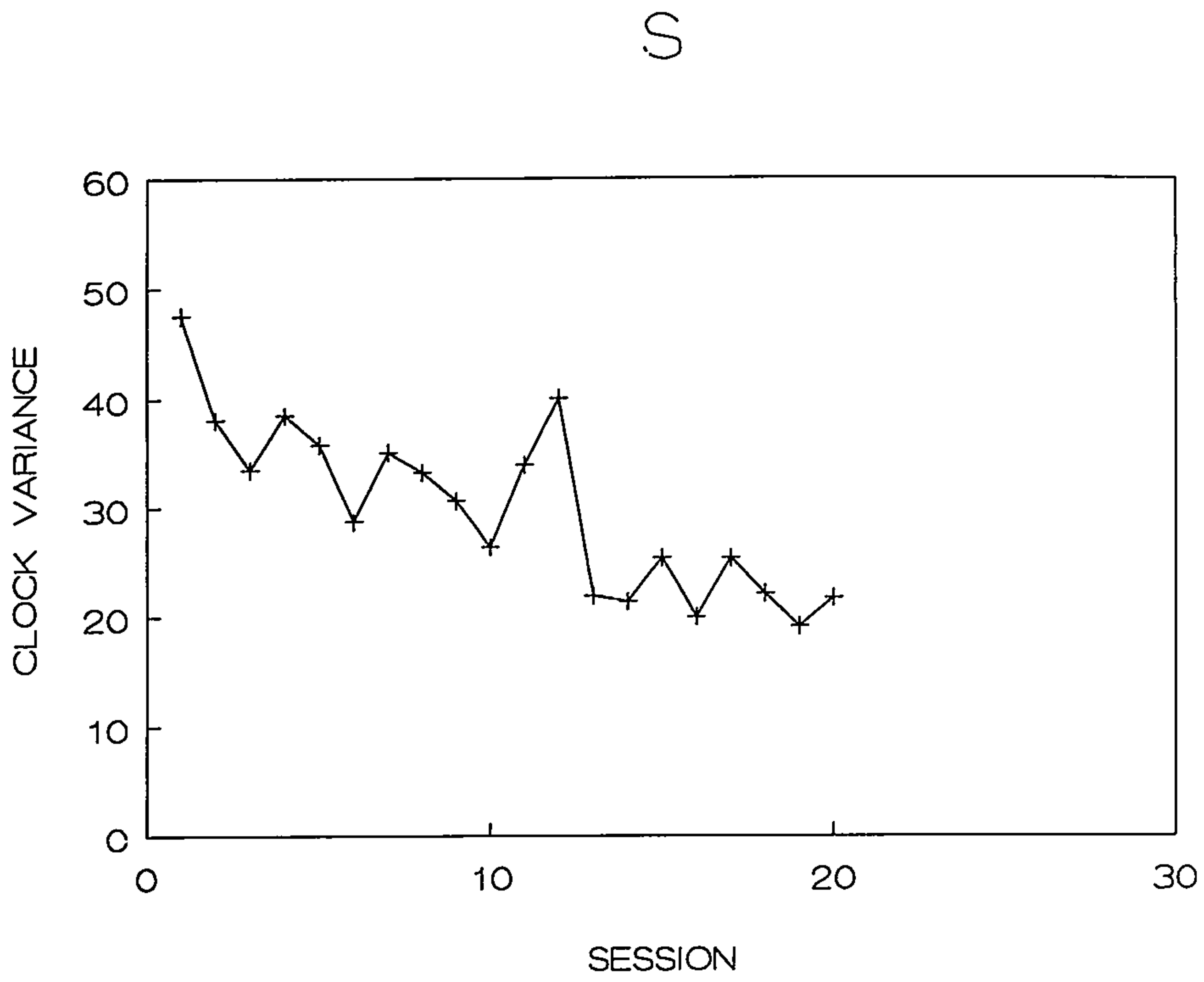
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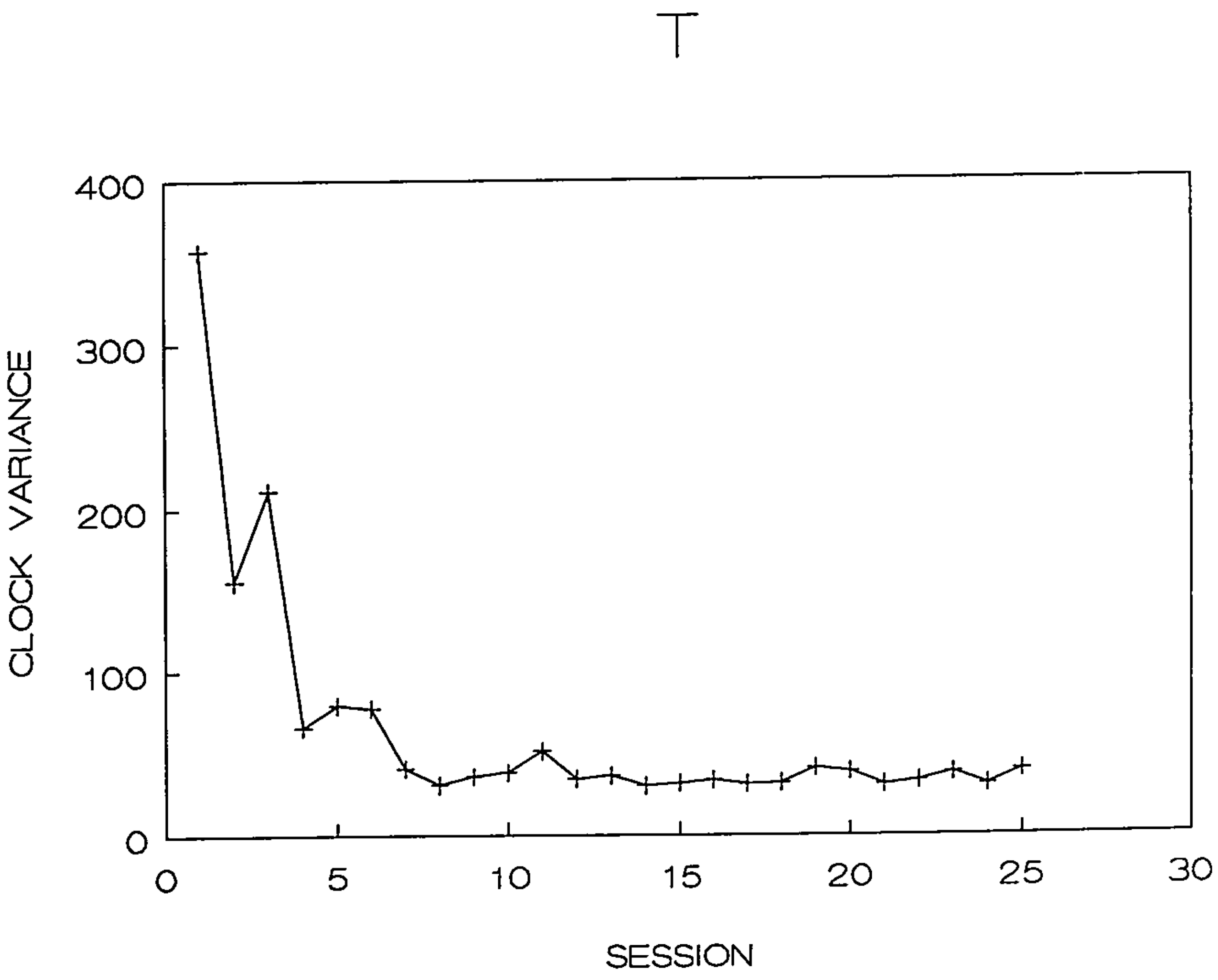
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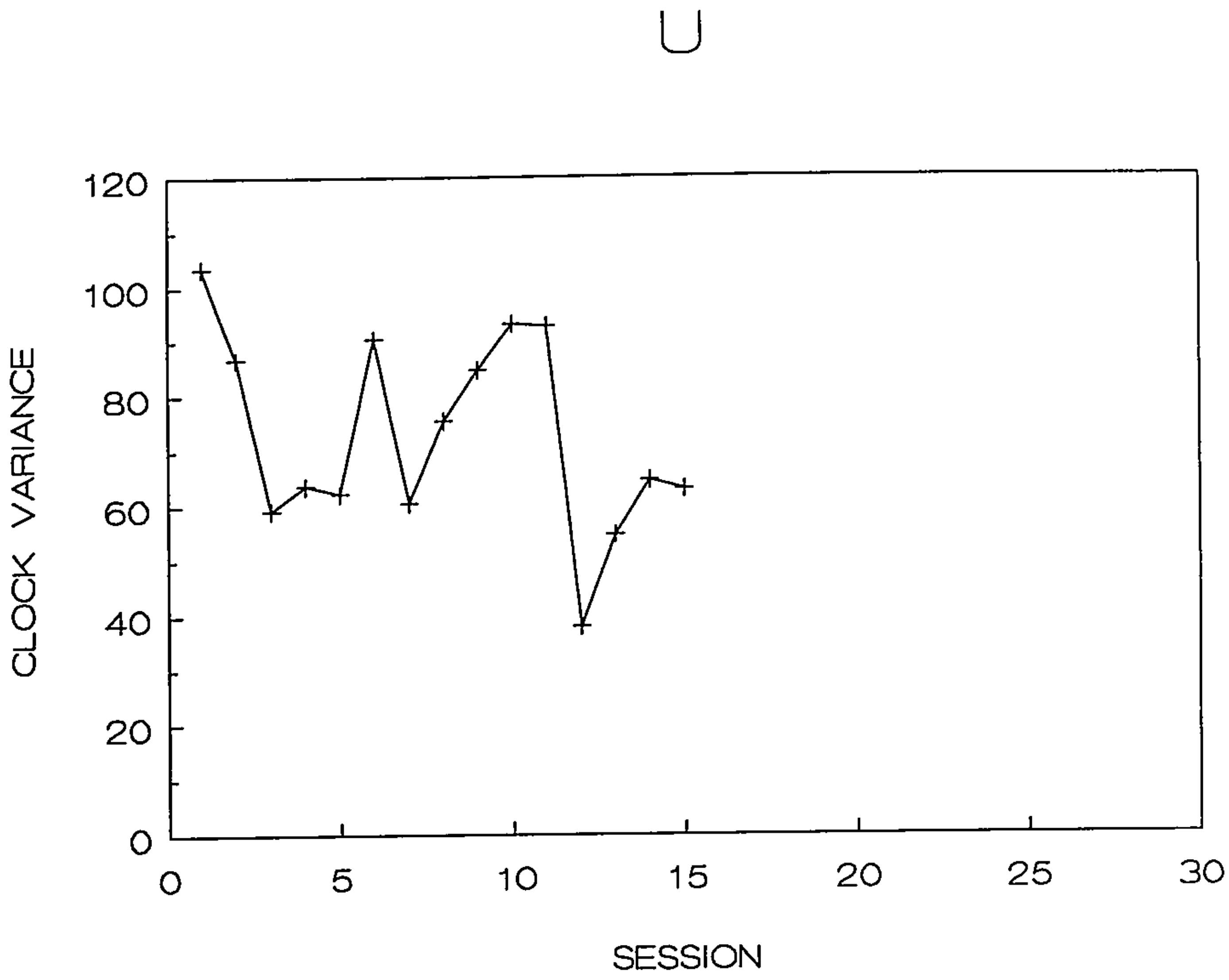
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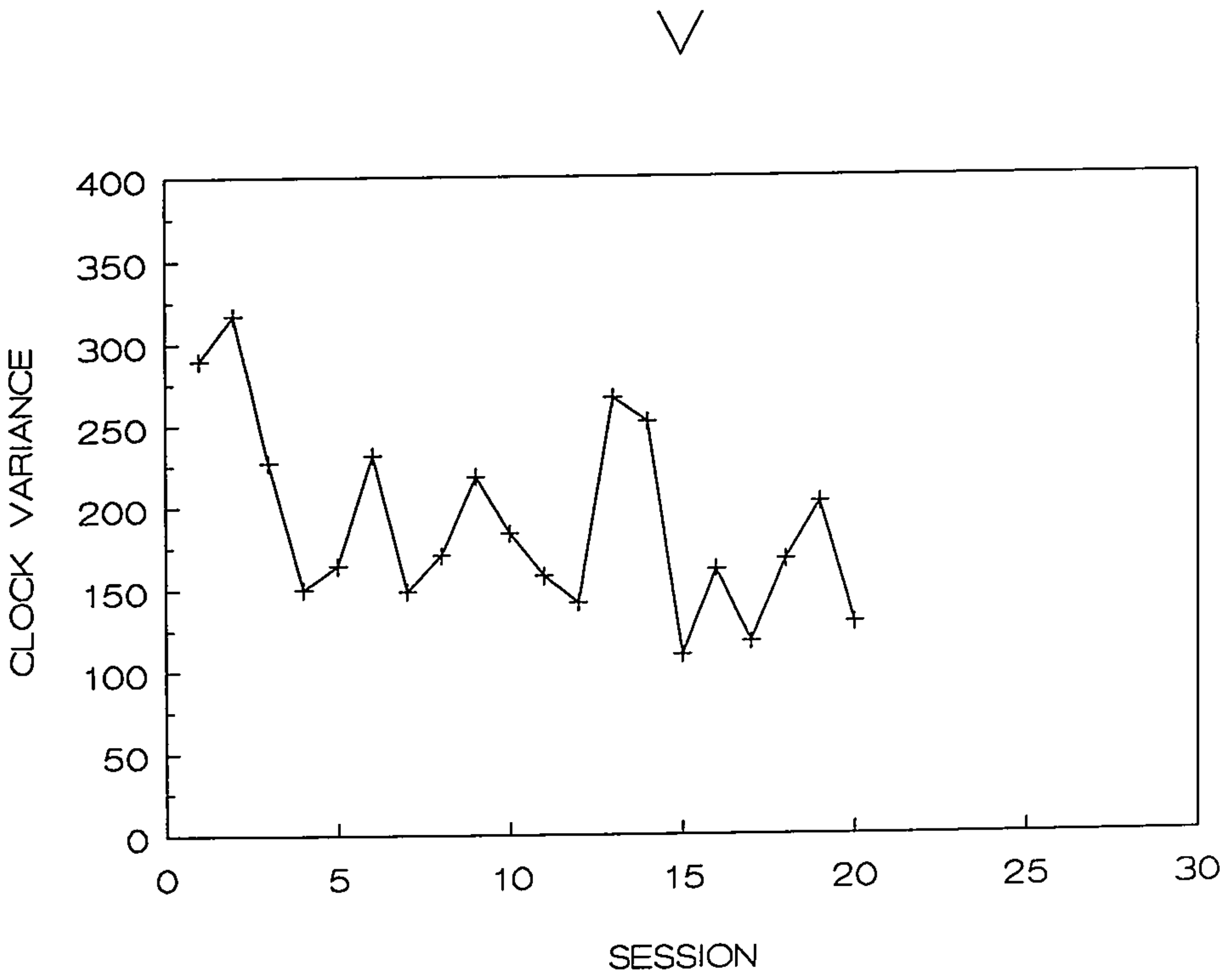
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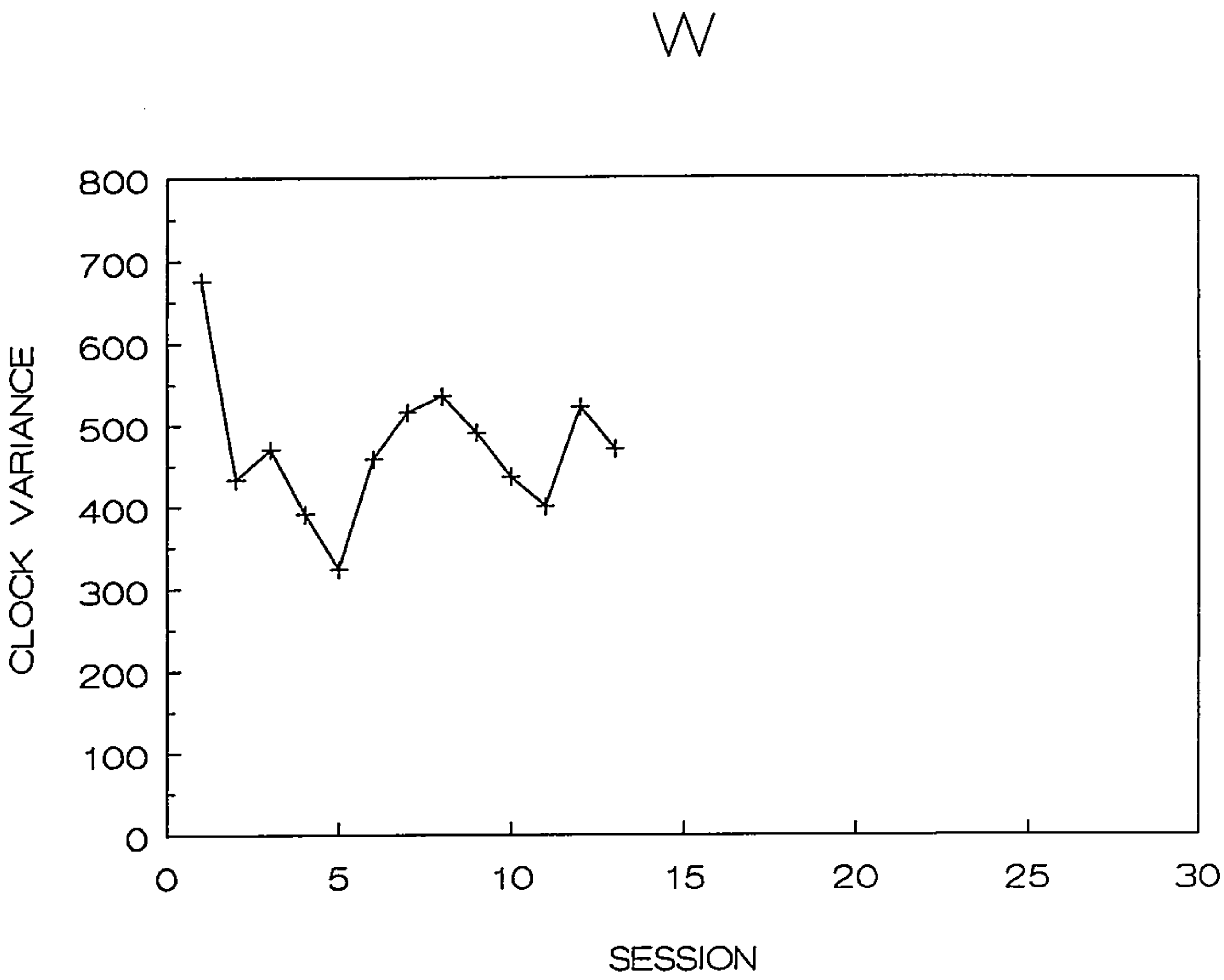
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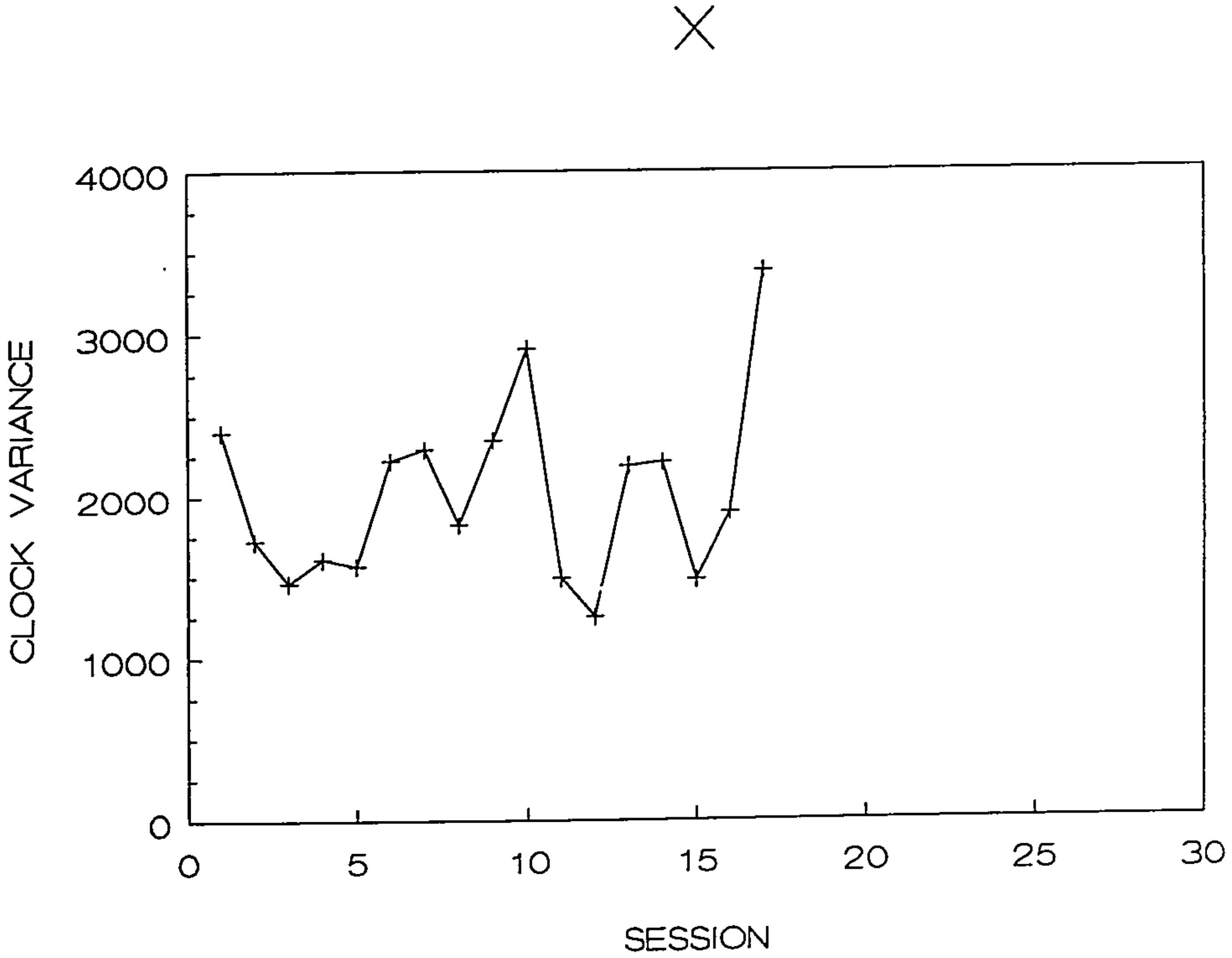
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SESSION

Practice clearly affects variance estimates. By way of a general description, most of the practice curves appear to be negatively accelerating, monotone decreasing functions. Variance estimates of all three subjects usually decrease as a function of session at each T. This generalization is most readily depicted by AK's practice curves. Sometimes however, variance remains constant throughout training and little practice effect is observed.

GF's data are well described by the general description above. However, his data show an unusually fast decline in variance over the first few sessions at T = 367 msec. Also, there appears to be a slightly negative practice effect for him at T = 1468 msec and perhaps at 932 msec. While GF's practice curves show an improvement in performance at most base durations, in comparison to AK that improvement is small.

For LL's data, there is also a gradual decline in s_{it}^2 with practice for most values of T. In common with GF, LL appears to show a negative practice effect at the two highest base durations. Her data indicate a very large positive practice effect at T = 110 msec.

The significance of the practice effect was assessed by testing the practice curves for a monotone trend. Several tests based on the number or length of runs (Gibbons, 1985) in the data sets, or on the strength of association between time points and a series of time-ordered observations (Gibbons, 1985) were considered for this purpose. But Kendall's Tau (τ) was chosen because, unlike simple run's tests, it considers the relative magnitude of each score relative to every subsequent score, not just the single immediately subsequent score. When τ is adapted to test for a trend it is sometimes called the Mann test for trend (Gibbons, 1985).

The significance of τ will be assessed according to Table L (Gibbons, 1985) for N ≤ 30 and by transforming τ to Z according to the following formula provided by Gibbons (1985) for N > 30;

$$Z = [3\tau(N(N-1))^{.5}]/[(2(2N+5))^{.5}] \tag{2.11}$$

where $\tau = 2S/(N(N-1))$ (2.12)

and S is computed as follows: If s_{it}^2 for session i (i = 1 to N-1) is less than that for session i+k (k = 1 to N-1), then S is incremented by one otherwise it is decremented by one unless the two estimates are equal, in which case S remains unchanged. The results of this analysis are presented in Table 2.4 and would be identical should the s_{it} practice curves be analyzed instead.

Most (15 of 24, or 62.5%) of the variance practice curves contain a significant negative monotone trend and all the rest except four have a tendency toward negative monotonicity. Thus, from this analysis it appears that practice significantly reduces s_{it}^2. This pattern of change in variability with the number of sessions of exposure presents a problem in terms of how to estimate initial and final (i.e., post-practice) levels of variance. There are a number of procedures that could be used to estimate initial and final variance levels. An averaging procedure could be used to compute the mean of s_{it}^2 over several of the first sessions to arrive at an estimate of the initial variance level. However, that would almost always lead to an underestimate of the true initial level of variance because of the rapid decrease in s_{it}^2 over those sessions. As an alternative the value of s_{it}^2 obtained on the first session could be used as the estimate of the initial level of variability. That option was ruled out because that would mean basing the estimate on a single session. To avoid these two problems, several common functions that can readily represent monotone decreasing or increasing curves were fitted to each practice curve. Several functions were used as I know of no apriori reason for choosing one over another. Also it is hoped that the use of several functions may provide insight into the nature of the practice effect if one function fits the practice curves unequivocally better than the others.

TABLE 2.4

Test for monotone trends in the s_{it}^2 vs session practice functions. Values in the table are the statistic τ.

T	AK	LL	GF
100	**-0.480		**-0.650
110		**-0.611	
175	-0.123	*-0.277	-0.300
233	**-0.429	**-0.361	**-0.653
367	**-0.371	-0.123	**-0.453
466	**-0.382	**-0.421	-0.162
734	*-0.332	-0.253	*-0.316
932	**-0.440	0.258	0.051
1468	**-0.623	0.022	0.074

---

* $p \leq .05$
** $p \leq .01$

For each practice curve the best fitting cases for the logarithmic (i.e., $a\ln(x)+b$), the power (i.e., ax^b), and the exponential (i.e., ae^{bx+c}) functions were determined according to a least squares criterion.

Of the 24 data sets analyzed the logarithmic function provided the best fit for 15, with the exponential function being best for five, and the power function being best for four. The interpretation of this curve fitting analysis is complicated by the fact that when the logarithmic function proved to fit better than the other functions, it was only marginally superior to the next best fitted function in many cases. Also when it did not provide the best fit, it often proved to be a very poor fit. Because no one of the three functions unequivocally represents the practice effect better than the others, little insight regarding the nature of the practice effect has been gained. In general the practice curves are well represented by a negatively accelerating monotonic decreasing function that most often is logarithmic.

Because none of the three functions was clearly better than the others at representing the practice effect, estimates of initial and final levels of variance will be made using the function that best fitted each data set. The predicted value for session 1 (s_F^2, F for first) and session L (s_L^2, L for last, where L equals the number of sessions run at a given T) respectively were taken as estimates of these effects. This procedure is preferred to the averaging procedure mentioned earlier because it makes use of the data of all sessions to arrive at the desired estimates. It is better especially for estimates of the initial level of variability because it is over the first few sessions that practice affects performance the most. Obtained values of s_F^2 and s_L^2 using this procedure are presented in Table 2.5 for all subjects and for all values of T.

TABLE 2.5

s_F^2 and s_L^2 variance estimates for AK, LL, and GF.

	AK		LL		GF	
T	s_F^2	s_L^2	s_F^2	s_L^2	s_F^2	s_L^2
100	29.8	17.7			28.2	10.5
110			50.3	9.4		
175	19.6	18.4	18.7	11.9	30.1	21.9
233	24.6	18.1	18.2	11.8	41.5	20.2
367	36.1	21.2	35.6	24.1	245.6	25.5
466	82.6	46.1	67.5	45.1	90.0	64.7
734	431.0	216.6	217.3	147.3	279.9	153.4
932	671.9	339.5	212.8	261.9	534.6	441.5
1468	3640.2	1319.4	1175.0	1265.5	1796.3	2241.9

MEAN: ESTIMATES AND PRACTICE EFFECTS

If m_{it}-T were plotted as a function of session number for each value of T it would confirm that m_{it} slowly becomes a better approximation to T with practice for each subject. Regardless of whether m_{it} is initially greater than or less than T, it tends to become closer to T with increased practice. This generalization is true for all three subjects. The difference between m_{it} and T, which is called the constant error (CE), is generally a negatively accelerating monotone function of session number with the value of the function approaching T in the limit.

The above general description is accurate when describing the data for AK. When m_{it} is less than T, it approaches T in a negatively accelerating monotone increasing function of session and when it is greater than T it approaches T in a negatively accelerating monotone decreasing function of session. Positive values of CE are common for AK at small values of T (e.g., 100, 175, and 233 msec), CE oscillates around zero for him at values of T equal to 367 and 466 msec, and CE is predominantly negative for values of T greater than 466 msec.

As was the case for AK, the absolute value of CE usually becomes smaller as a function of session number for GF and LL. However, CE is almost always negative for both of them at all levels of T.

Practice appears to improve timing precision. To determine if practice significantly improves a subjects ability to precisely match T, each m_{it} vs session practice function will be tested for a monotone trend. The results of that analysis are presented in Table 2.6.

Only 9 of 24 (37.5%) practice curves show a statistically significant monotone trend, and for every one of those the trend is in the expected direction. That is, the difference between m_{it} and T reduces regardless of whether it is initially positive or

TABLE 2.6

Test for monotone trends in the m_i vs session practice functions. Values in the table are the statistic τ.

T	AK	LL	GF
100	**-0.352		-0.223
110		0.011	
175	-0.137	-0.031	-0.142
233	-0.168	**0.366	**0.411
367	-0.139	0.203	-0.133
466	0.182	**0.495	-0.124
734	0.132	**0.632	**0.495
932	*0.283	0.058	*0.487
1468	**0.579	0.140	0.015

* $p \leq .05$
** $p \leq .01$

negative. The results indicate a negative practice effect for a few practice curves, but in all those cases the trend was not statistically significant.

Because there is a monotone trend in many of the practice curves, the same three functions that were fitted to the variance practice data sets are fitted to the mean practice data sets according to the least squares criterion. The best of those, for each function, is shown as the solid line on the practice curve.

Unlike the variance practice curves, the power function fitted most of the mean practice curves the best. Of the 24 practice curves, the power function fitted 11 of them the best, the exponential function fitted eight curves the best, and the logarithmic function fitted the remaining five curves the best. Of the three base durations greater than or equal to 734 msec, eight of the nine practice curves were best fitted by the power function. From that result it appears that a theoretical understanding of the practice effect for the longer base durations might be gained. However, because the proportion of variance accounted for by the logarithmic function is trivially less than that accounted for by the power function for those eight practice curves, I will refrain from concluding that the fit of one function is unequivocally better than the other. Because no one function best represents the practice effect in general, I feel that the only justified conclusion is that the practice effect is not homogeneous across base durations.

From a practical point of view, the analysis serves as a basis to obtain initial and final estimates of m_{it}. Using the best fitted function for each data set the initial (m_F) and final (m_L) estimates of the mean are computed as the predicted value for session 1 and session L. These estimates are given in Table 2.7. A comparison between the values of m_F and T and m_L and T illustrates the fantastic precision with which Ss can match I, the internal interval in the RTCT, to T.

Can the strong relationship between m_{it} and T lead to insight about the nature of the underlying timekeeper? Recall that in the context of motor timing, Collyer et al.

TABLE 2.7

Initial (m_F) and final (m_L) estimates of m_{it} based on the practice functions.

	AK		LL		GF	
T	m_F	m_L	m_F	m_L	m_F	m_L
100	103.0	100			100.2	99.5
110			110.3	109.7		
175	175.2	174.9	174.7	174.6	174.5	174.7
233	233.2	233.0	231.9	232.9	231.7	233.1
367	367.8	366.9	366.4	366.7	368.2	366.0
466	465.6	466.5	463.4	465.2	465.5	464.9
734	727.5	730.9	728.0	732.7	730.4	733.7
932	928.7	932.8	929.8	930.8	923.1	929.5
1468	1435.9	1467.9	1459.9	1467.7	1461.0	1462.8

(1992) proposed a new method involving oscillator signatures to detect evidence of discrete timing. Oscillator signatures may be present in duration discrimination data and an analogous analysis could reveal new evidence for discrete timing in PTDD.

Unfortunately the present experiment was not designed with such an analysis in mind. The characteristic shape of the oscillator signature might not be detectable because the difference between successive values of T is too large. With this potential shortcoming in mind let us see if an oscillator signature emerges from the PTDD data.

In the context of PTDD, the term bias refers to m_{lt}-T, a difference which earlier was called constant error. To avoid confusion in the application of the oscillator signature analyses to the PTDD data the terminology set out by Collyer et al. (1992) will be used in the present discussion.

When m_L-T is plotted as a function of T we have the final bias function which is displayed in Figure 2.5. Figure 2.5 shows that the function is very different for each of the subjects, a fact that makes generalizeability impossible. There is a tendency for the function to oscillate to either side of zero for AK in a way that resembles the oscillator signature pattern described by Collyer et al. (1992). However, there are marked differences between the two patterns, differences which suggest that AK's function does not conform to the discrete timing hypothesis as it is outlined in Collyer et al. (1992). Finally, the patterns of the final bias functions do not oscillate about zero for LL or GF.

An analysis of bias functions will only be valid if there is an identity relation between m_L and T. In order to determine if that is the case, linear regression is used to generate slope and intercept coefficients for the m_L vs T functions. These regression coefficients along with the corresponding coefficients of determination are given in Table 2.8. The near perfect linear relationship between m_L and T is revealed by the high degree of common variance; the coefficient of determination equals 0.99999 for each S.

FIGURE 2.5

The final bias function: m_L-T plotted as a function of T for each subject.

LEGEND:

SUBJECT	SYMBOL
AK	crosses
LL	triangles
GF	circles

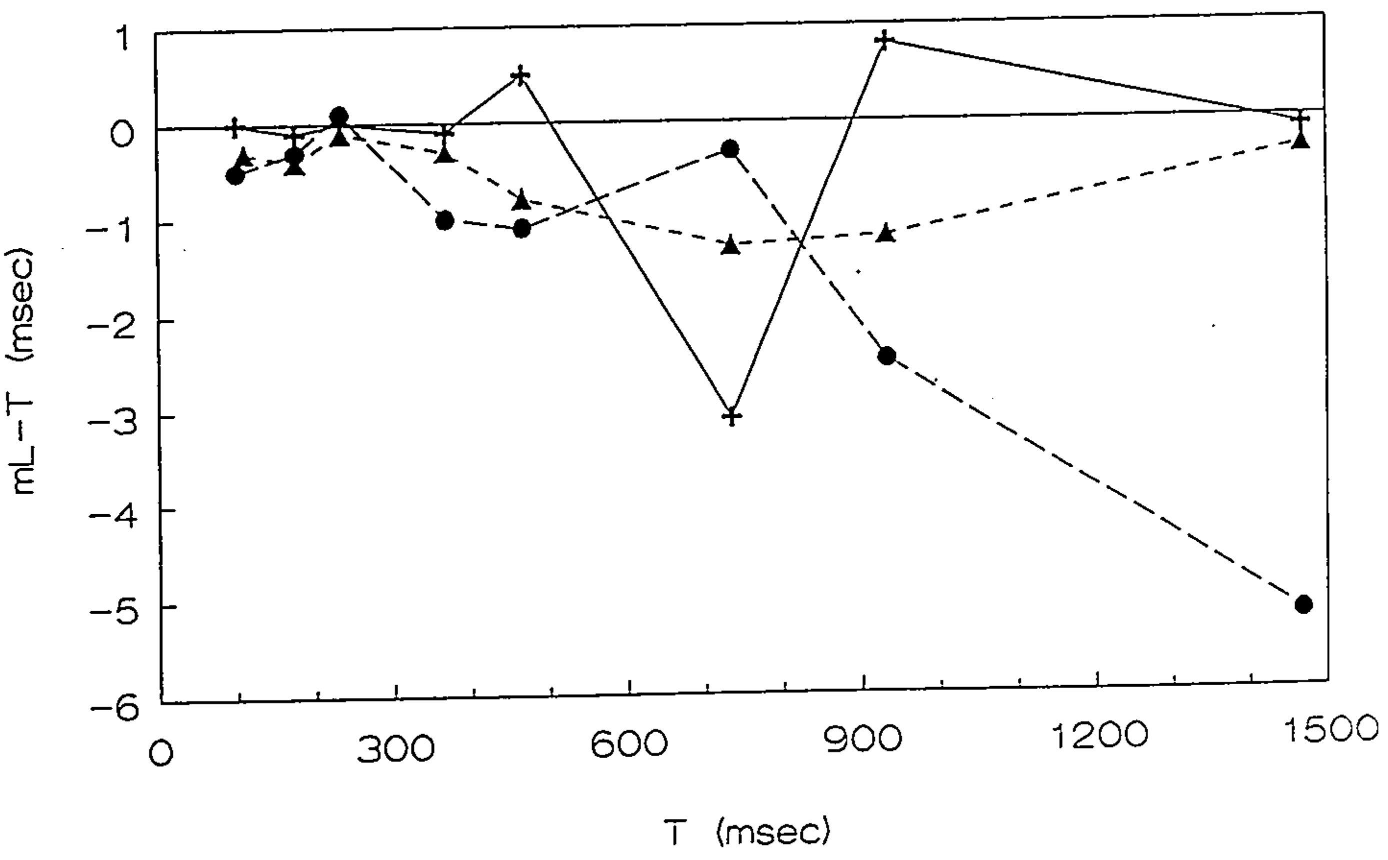

1
0
−1
−2
−3
−4
−5
−6
mL−T (msec)
0
300
600
900
1200
1500
T (msec)

TABLE 2.8

Regression analyses evaluating the relationship between m_L and T.

Subject	Slope	Intercept	r^2
AK	0.999785	-0.14248	0.99999
LL	0.999674	-0.40500	0.99999
GF	0.996612*	0.544849	0.99999

*significantly different from 1.0 for slope or from zero for intercept, $p \leq .01$.

The linear model fits almost perfectly but it does not rule out the possibility of linear bias. Linear bias is a term Collyer et al. (1992) used to indicate that either the slope of the best fit straight line differs significantly from one or the intercept differs significantly from zero. If either of these conditions occur then there is a non-identity relation between m_L and T, a condition referred to as linear bias. It can be seen that the slope coefficient differs significantly from one for GF but not for either of the other Ss, and in no instance does the intercept coefficient differ significantly from zero.

Collyer et al. (1992) detected linear bias in some of the functions they analyzed so they went on to analyze residual bias functions instead of the bias functions. Residual bias is a term used to refer to the difference between m_L and the predicted value of m_L based on the best fitting straight line.

Figure 2.6 shows the functions relating residual bias as a percentage of T to T. The data that are plotted in Figure 2.6 are presented in Table 2.9. One feature of these functions is very clear - there is no oscillator signature pattern in any of them. None of the subjects shows a pattern of residual bias that alternates between positive and negative with increases in T in a way that is consonant with Collyer's et al. (1992) discrete timekeeper hypothesis. At this level of analysis the absence of an oscillator signature fails to support the hypothesis that the underlying timekeeper is discrete. In conclusion, the analysis of the residual bias functions does not support the discrete timekeeper hypothesis. However, it should be kept in mind that this conclusion is not based on the appropriate experiment with closely spaced base durations so it should not be taken as critical evidence contrary to the discrete timekeeper hypothesis.

FIGURE 2.6

Residual bias, expressed as a percentage of T, plotted as a function of T

LEGEND:

SUBJECT	SYMBOL
AK	crosses
LL	triangles
GF	circles

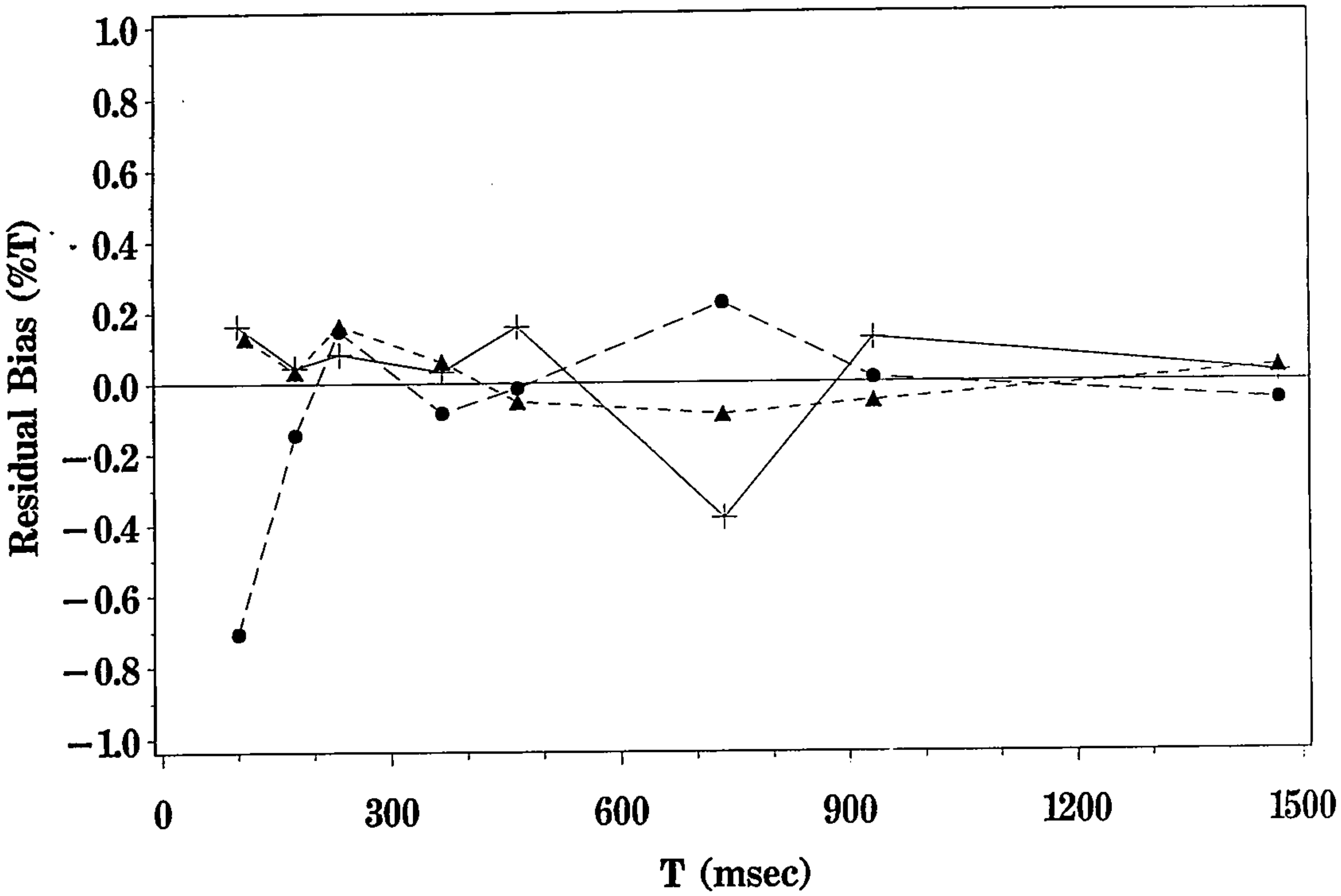

1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
Residual Bias (%T)
0
300
600
900
1200
1500
T (msec)

TABLE 2.9

Residual bias expressed as a percentage of T for each T.

T	AK	LL	GF
100	0.164		-0.706
110		0.128	
175	0.046	0.035	-0.144
233	0.083	0.163	0.148
367	0.033	0.061	-0.082
466	0.159	-0.052	-0.014
734	-0.381	-0.089	0.224
932	0.123	-0.053	0.012
1468	0.024	0.040	-0.053

THE WEBER FRACTION

It is important to determine how measures of variability and central tendency are affected by practice because that information will lead us to a better understanding of how practice affects discrimination of different intervals of time. However the relationship between variability and mean is of more theoretical importance in order to better understand the processes underlying duration discrimination. The Weber fraction, W, which equals s_{it}/m_{it}, will be used to study that relationship and is the topic of this section.

W was computed from initial (s_F/m_F) and final data (s_L/m_L) for each T. See Table 2.10 for these data. Using W as an index of overall performance, LL is the best discriminator. For her W is lower at each value of T, with only one exception, than those of either AK or GF. However, it should be emphasized that all Ss performed extremely well. The lowest value of W reported in the present data set is .0125, and in many instances it falls in the 0.013 to 0.017 range. These low ratios reflect the impressively good performance of all three subjects.

Getty (1975) reported a Weber fraction equal to about 0.055 (an average across two Ss) in his 2AFC DD experiment. By comparison, when averaged over the three subjects in PTDD W is equal to about half of that reported by Getty (1975). Some of this difference is due to the fact that Getty (1975) used the cumulative form of the normal distribution (s_n) rather than the isosceles triangle distribution (s_{it}) to model the psychometric function. We now know that W is smaller when it is based on s_{it} rather than s_n because estimates of s_{it} are smaller than estimates of s_n when both are based on the same data. That fact was established in an earlier section of this chapter. If the normal distribution were used to model the psychometric function, W would, on average, be about 15% higher for AK, and about 7.5% higher for LL and GF. When averaged across Ss, the s_F/m_F ratio

TABLE 2.10

Initial and final Weber fractions for each T and subject.

	AK		LL		GF	
Tms	s_F/m_F	s_L/m_L	s_F/m_F	s_L/m_L	s_F/m_F	s_L/m_L
100	0.0530	0.0421			0.0530	0.0326
110			0.0643	0.0279		
175	0.0252	0.0245	0.0248	0.0197	0.0315	0.0268
233	0.0213	0.0182	0.0184	0.0147	0.0278	0.0193
367	0.0163	0.0125	0.0163	0.0134	0.0426	0.0138
466	0.0195	0.0146	0.0177	0.0144	0.0205	0.0173
734	0.0285	0.0201	0.0203	0.0166	0.0229	0.0169
932	0.0279	0.0198	0.0157	0.0174	0.0250	0.0226
1468	0.0420	0.0247	0.0235	0.0242	0.0290	0.0324
Mean	0.0292	0.0221	0.0251	0.0185	0.0315	0.0227

equals 0.0286 in the present experiment. Were that ratio to be based on s_n it would change to 0.0315, which represents an increase of about 10%.

The quantity (0.0315 - 0.0286), which equals 0.0029, is an amount equal to the difference in W that is attributable to the use of the two variance estimation procedures. That difference accounts for only 11% of the difference between Getty's (1975) estimate of W and the present estimate (0.055 - 0.0286). Thus the difference that remains unaccounted for (approximately 89%) must be due to other considerations with the most likely candidates being the use of different experimental procedures (i.e., PTDD method with specific practice instead of the 2AFC method).

Halpern and Darwin (1982) used the PTDD procedure and found that W equals approximately 0.05 which is in close agreement with Getty's (1975) estimate. They too assumed that the shape of the psychometric function is normal. Thompson, Schiffman, and Bobko (1976) also report that W equals approximately 0.05 for stimuli over a very wide range of temporal intervals (250-3750 msec). They used the 2AFC DD method. Triesman (1963) however reports W to be 0.11, approximately double the other estimates and in good agreement with Snodgrass et al. (1967) and Woodrow's (1933) time estimation studies. In contrast, Wing and Kristofferson (1973) report W to be approximately equal to 0.023 in their continuation experiment. Kristofferson (1976) on the other hand reports Weber ratios that fall below 0.02 in R-SS, and Hopkins and Kristofferson (1980) were able to reduce that to less than 0.015 after special procedures were implemented into the R-SS procedure. In summary, the smallest Weber ratios obtained in the present experiment are as small as the smallest ratios previously reported in the literature evaluating timing and time perception, and much smaller than Weber ratios that have been reported when duration discrimination procedures were used. These new results indicate that the relationship between m_{it} and s_{it} needs to be investigated.

THE WEBER FUNCTION

The Weber function describes the relationship between the mean and standard deviation of the psychometric function. When the function is composed of s_F and m_F it will be referred to as the initial Weber function, and when it is composed of s_L and m_L it will be called the final Weber function. Initial and final Weber functions are shown in Figs. 2.7 through 2.9 for each subject. In order to facilitate between subject comparisons, Figure 2.10 shows all of the initial Weber functions plotted on the same graph and Figure 2.11 shows all three final Weber functions on the same graph.

In general it can be seen that the final Weber functions are remarkably similar in form and position for the three subjects. There is one region, over the smaller values of T within which s_L appears to remain constant. Above that region s_L appears to increase in proportion to T.

Several mathematical models of the Weber function were presented in the Introduction, all of which are based on various generalizations of Weber's Law. In this subsection each of those models will be evaluated in terms of how well it can describe the obtained PTDD Weber functions. The best fitted case of each model will be determined by fitting the model to the data for each subject according to an iterative procedure using the least squares criterion. This was carried out on a VAX 6420 computer with the use of the LMDIF1 subroutine (Garbow, Hillstrom, and More, 1980).

The LMDIF1 subroutine uses a modified Levenberg-Marquardt algorithm to quickly find the solution to several variables in several non-linear equations. Upon starting the program, an argument vector of length n contains a user provided initial estimate for each parameter in the functions. When the program terminates, the parameters that correspond to the minimum sum of squared errors (SSE) are returned in that same vector. The routine comes to a successful termination when the algorithm estimates 1) that

FIGURE 2.7

s_F plotted as a function of m_F (light crosses, dashed line) and s_L plotted as a function of m_L (bold crosses, solid line) for subject AK.

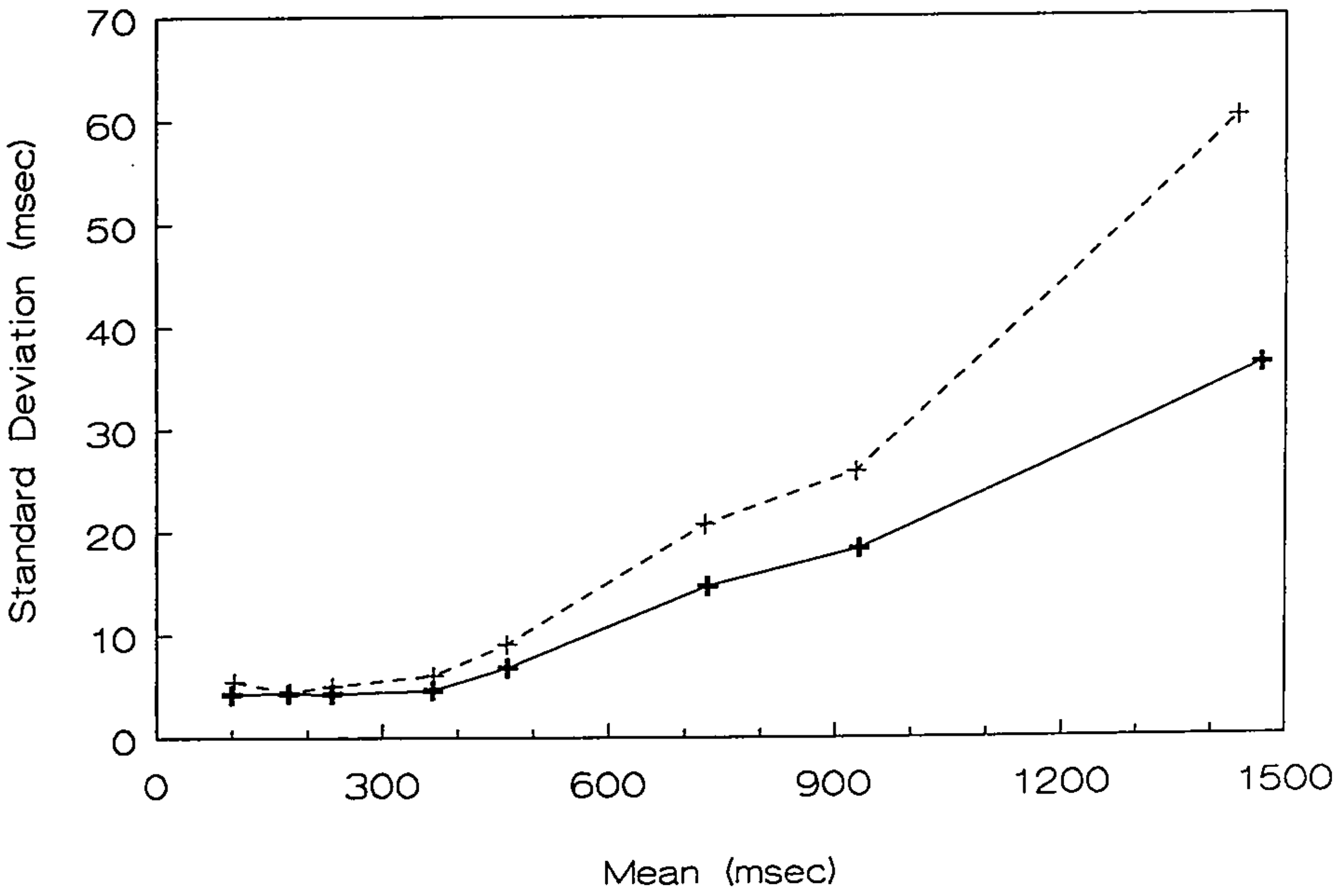

Standard Deviation (msec)
0
10
20
30
40
50
60
70
0
300
600
900
1200
1500
Mean (msec)

FIGURE 2.8

s_F plotted as a function of m_F (open triangles, dashed line) and s_L plotted as a function of m_L (filled triangles, solid line) for subject LL.

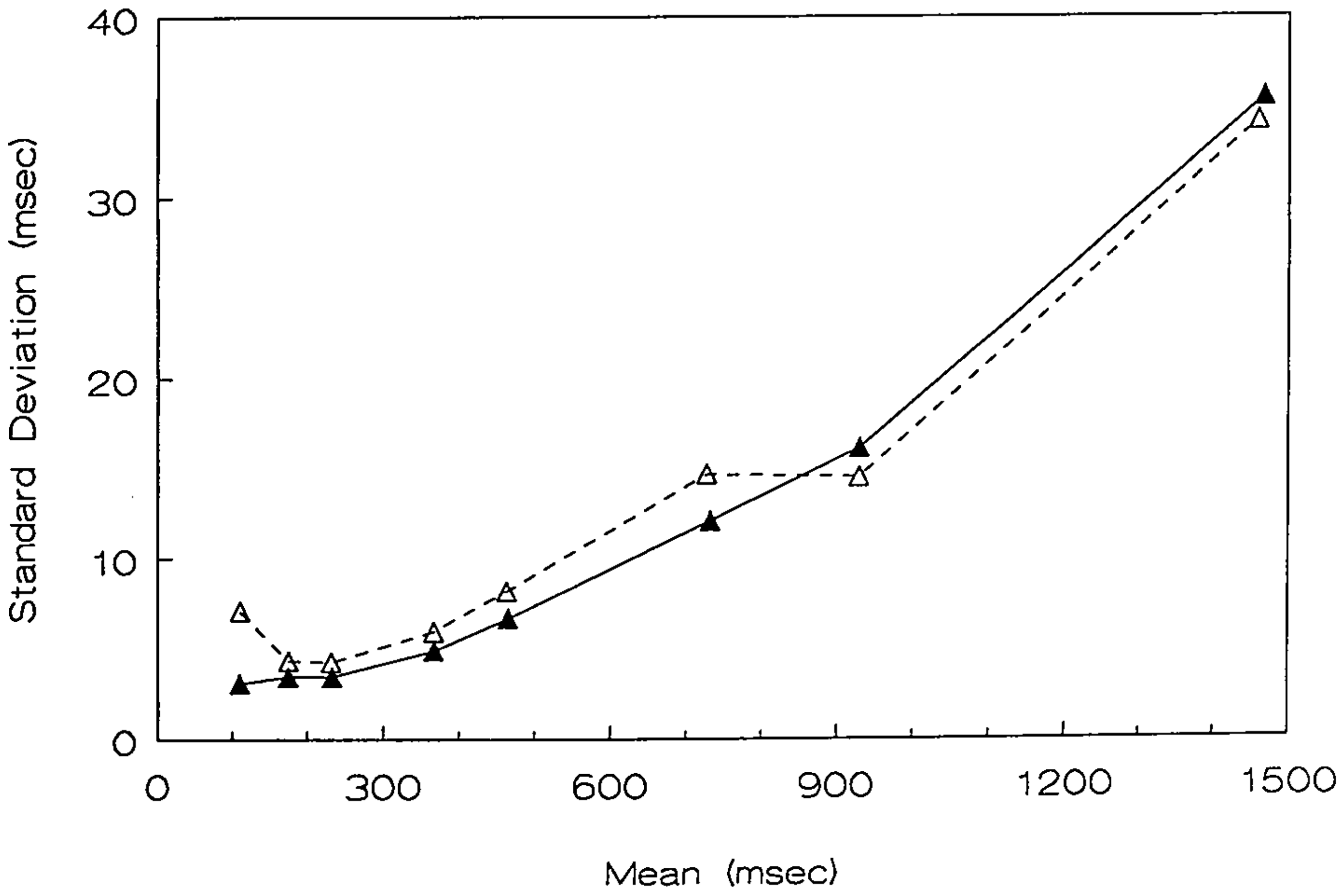

40
30
20
10
0
Standard Deviation (msec)
0
300
600
900
1200
1500
Mean (msec)

FIGURE 2.9

s_F plotted as a function of m_F (open circles, dashed line) and s_L plotted as a function of m_L (filled circles, solid line) for subject GF.

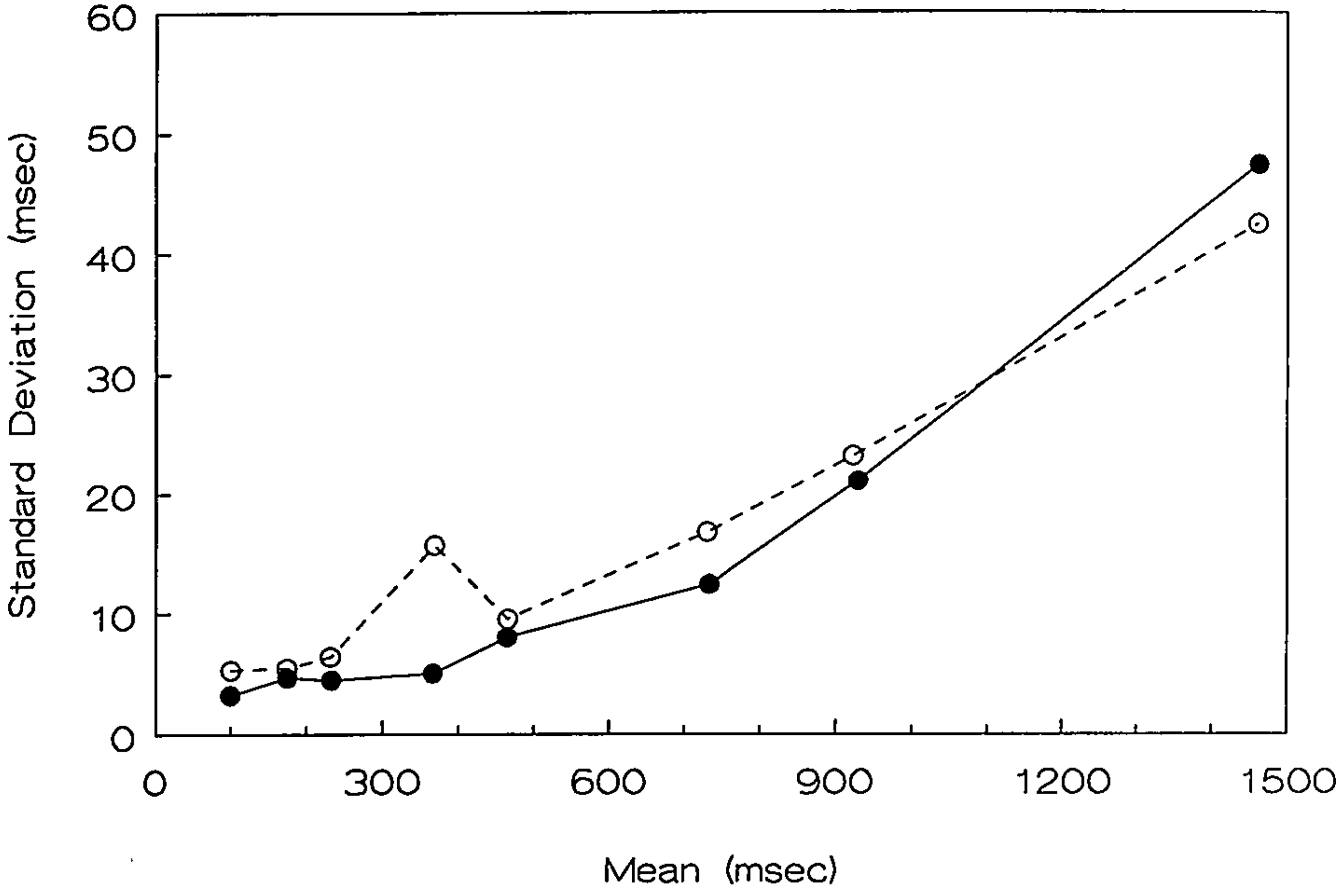

Standard Deviation (msec)
60
50
40
30
20
10
0
0
300
600
900
1200
1500
Mean (msec)

FIGURE 2.10

Initial Weber functions (s_F plotted as a function of m_F) for all three subjects.

LEGEND:

SUBJECT	SYMBOL
AK	crosses
LL	triangles
GF	circles

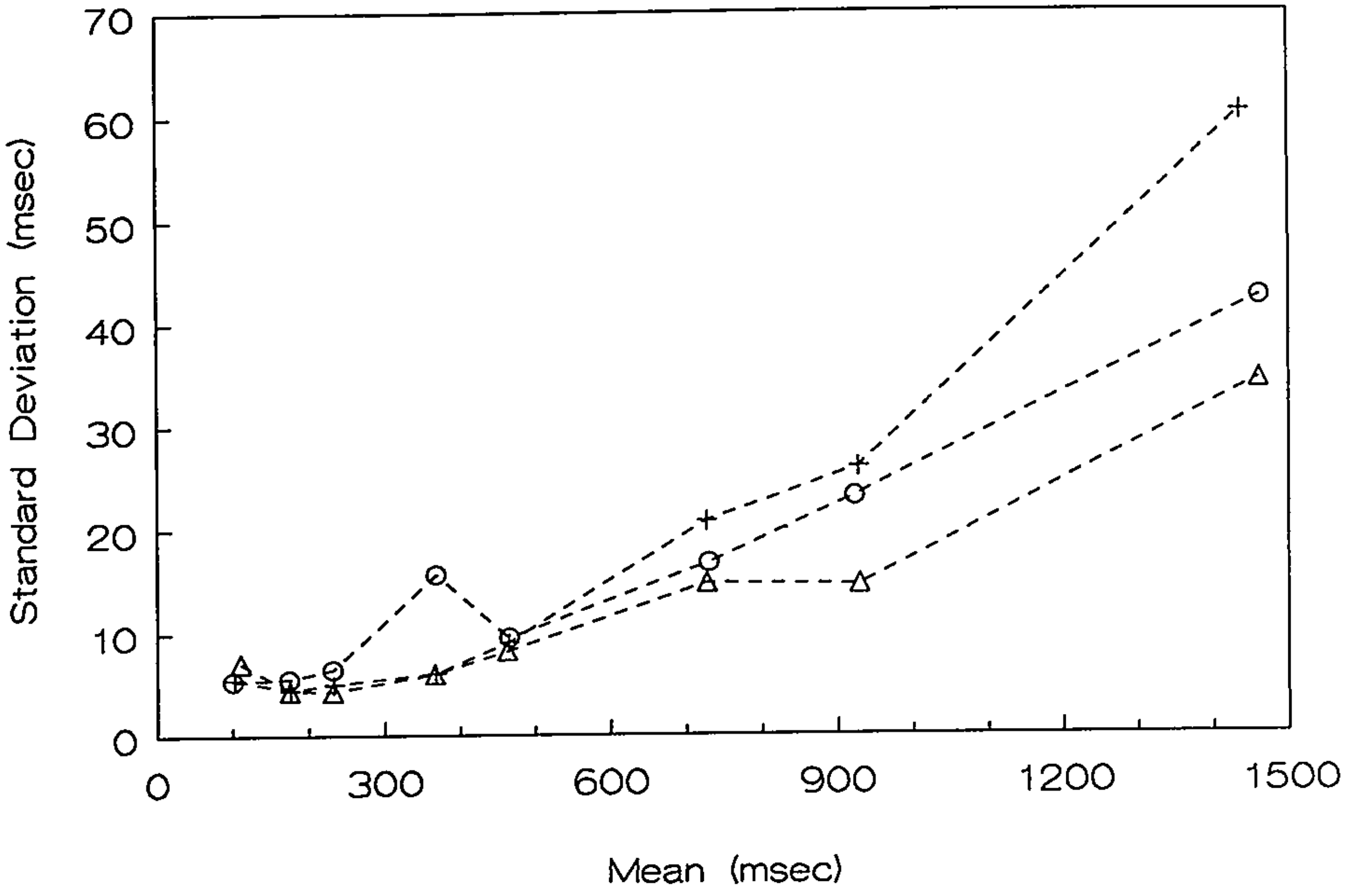
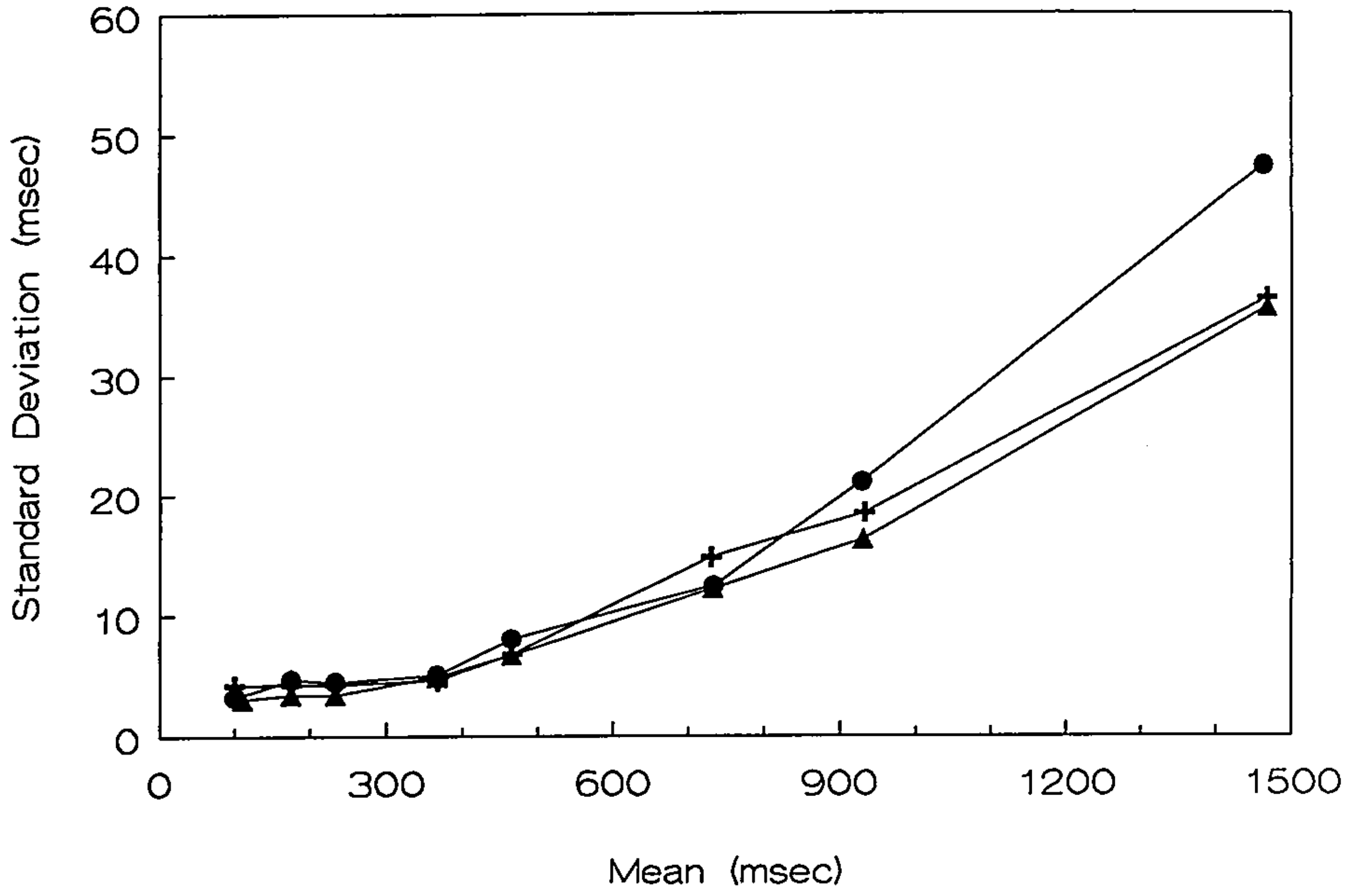

70
60
50
40
30
20
10
0
Standard Deviation (msec)
0
300
600
900
1200
1500
Mean (msec)

FIGURE 2.11

Final Weber functions (s_F plotted as a function of m_F) for all three subjects.

LEGEND:

SUBJECT	SYMBOL
AK	crosses
LL	triangles
GF	circles


60
50
40
30
20
10
0
Standard Deviation (msec)
0
300
600
900
1200
1500
Mean (msec)

the relative error in the SSE is at most equal to a pre-specified tolerance level, tol, or 2) that the relative error between the nth and the n-1 estimate of the solution vector is at most tol, or 3) that both 1 and 2 simultaneously occur. Tol was kept constant at 10^{-4} for all runs. Unsuccessful terminations occurred when the program halted for a reason other than those specified above. These were extremely rare and they occurred as a result of providing improper input parameters. Fortunately that problem was simple to correct by re-running the program with new input parameters.

When the parameters for each of the models had no range constraints imposed on them meaningful estimates of them were recovered for the Weber and the Kristofferson models only. For Creelman's and Getty's models, estimates of residual variance, V_r, for all subjects were negative. Because negative variances make no sense, the models that generate them must be considered to be inadequate representations of the data. But if the variance terms were constrained to non-negative values the solutions would be meaningful.

Unfortunately the routine does not provide an option to constrain the range of acceptable values for an argument. Such an option would be extremely useful under the present circumstances in which negative variances are being returned. Non-negative range constraints were imposed on an argument by squaring the argument in the function expressions and carrying out the same transformation on the parameter returned by the program. This technique was incorporated into a similar program used by Wing (1973).

When the non-negative range constraint was imposed on V_r during the evaluation of Creelman's and Getty's models, V_r equalled zero for all three subjects and both models. Remember that when V_r equals zero, Getty's model effectively reduces to the original Weber's law model. Under these circumstances, Weber's model must be considered to be superior to Getty's because while both models fit the data equally well

Weber's is the more parsimonious since it contains only one parameter as compared to two in Getty's model.

Getty (1975), however, used a different technique to estimate V_r. He initially fitted his model to only those data points corresponding to base durations of less than 400 msec to obtain an estimate of V_r. Defending this procedure Getty (1975) states that "...the effect of the residual variance is negligible beyond a duration of about 400 msec...." (p.6). Getty (1975) does not explicitly state how he arrives at the base duration of 400 msec for the initial V_r estimation procedure but upon inspection of his data variances for all base durations below 400 msec were roughly equal and smaller than variances for larger base durations.

In order to remain consistent with Getty's (1975) procedure, the same procedure is adopted in the present analysis in which V_r is determined by fitting Getty's model to the data corresponding to all Ts less than or equal to 466 msec (note: all variance estimates in that range are small and nearly equivalent). Once V_r is determined in this way, it is entered into the equation as a constant, rather than as a free variable when fitting procedures are applied over the entire range of durations. As expected, small and positive values of V_r are recovered when Getty's procedure is followed. Those are the values that are shown in Table 2.11, for the s_F vs m_F functions, and Table 2.12 for the s_L vs m_L functions. The statistics for the best fitted case of each of the other models being evaluated are reported in those Tables as well.

MODELLING THE s_{it} VS m_{it} FUNCTIONS

According to the original version of Weber's Law there should be a proportional relationship between s_{it} and m_{it} across the full range of durations. It is clear that that relationship does not adequately represent either the initial or the final functions - most of the obtained points

TABLE 2.11

Parameter estimates for the best fit case of the four models fitted to the s_F vs m_F functions.

LEGEND:

SYMBOL	DESCRIPTION
SSE	sum of squared errors

All other symbols are parameter estimates of the respective models.

Model: Creelman

Subject	SSE	C	V_r
AK	1078.1	.86942	0.0
LL	234.3	.34972	0.0
GF	289.7	.61900	0.0

Model: Getty

Subject	SSE	K	V_r
AK	321.3	.03407	22.5
LL	74.8	.01980	29.3
GF	65.2	.02662	23.9

Model: Weber

Subject	SSE	K
AK	281.8	.03454
LL	66.6	.02087
GF	69.7	.02740

Model: Kristofferson

Subject	SSE	K	V_o	L
AK	32.0	.05621	31.67	398.1
LL	25.9	.02827	30.68	310.2
GF	56.8	.02993	35.59	119.0

TABLE 2.12

Parameter estimates for the best fit case of the four models fitted to the s_L vs m_L functions.

LEGEND:

SYMBOL	DESCRIPTION
SSE	sum of squared errors

All other symbols are parameter estimates of the respective models.

Model: Creelman

Subject	SSE	C	V_T
AK	305.2	.3783	0.0
LL	321.2	.3249	0.0
GF	657.3	.5202	0.0

Model: Getty

Subject	SSE	K	V_T
AK	68.9	.0215	17.26
LL	73.8	.0204	7.60
GF	201.8	.0261	13.33

Model: Weber

Subject	SSE	K
AK	51.6	.0220
LL	64.0	.0207
GF	179.7	.0265

Model: Kristofferson

Subject	SSE	K	V_O	L
AK	2.9	.0306	18.2	301.0
LL	9.5	.0311	15.5	361.1
GF	12.8	.0493	26.1	510.1

fall below the line predicted by it and SSE is high relative to Kristofferson's model.

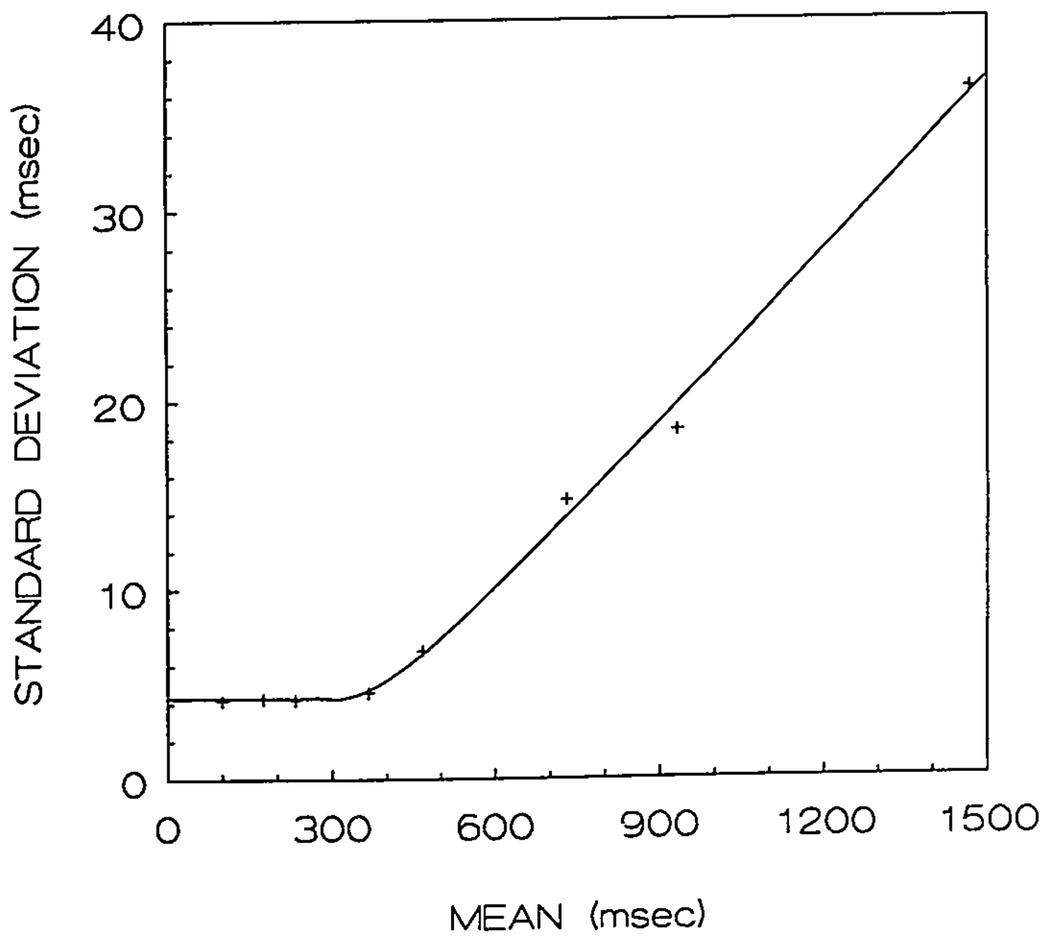
Even poorer are the best fitted functions generated by Creelman's and Getty's models. This is true in terms of SSE being larger and especially because negative values of V_r were recovered when that variable's range was not constrained. Not unlike the fit to the Weber's law model, most of the obtained points fall below the predicted points for both Creelman's and Getty's models. In summary, neither Creelman's nor Getty's models accurately represent the PTDD Weber functions.

The same, however, cannot be said of Kristofferson's model - it fits the data extremely well for all subjects and all parameter estimates fall within logically acceptable limits. Kristofferson's model fits the initial and final Weber functions the best; SSE is lower for every within subject comparison. Taken together the results provide strong support for Kristofferson's model as being the best description for both unpracticed and highly practiced PTDD results. Consequently the present discussion will focus on Kristofferson's model.

Based on a comparison between the total SSE generated by fitting Kristofferson's model to the initial and final Weber function, it can be seen that the model fits the post-practice functions substantially better. For every S SSE was much lower when the model was fitted to the final function than when it was fitted to the initial function. This is interesting because while practice improves performance it also leads to a better fit of the model that best represents it. Figs. 2.12 through 2.14 show the best fitting case of Kristofferson's model superimposed on the final Weber functions for each subject. Although Kristofferson's model describes these functions very well, the parameter estimates differ substantially among subjects within each level of practice and within subjects between levels of practice. These two considerations emphasize the need to discuss the analysis separately for each subject.

FIGURE 2.12

The best fitting case of Kristofferson's model superimposed on the final Weber function (s_L vs m_L) for AK.



40
30
20
10
0
STANDARD DEVIATION (msec)
0
300
600
900
1200
1500
MEAN (msec)

FIGURE 2.13

The best fitting case of Kristofferson's model superimposed on the final Weber function (s_L vs m_L) for LL.

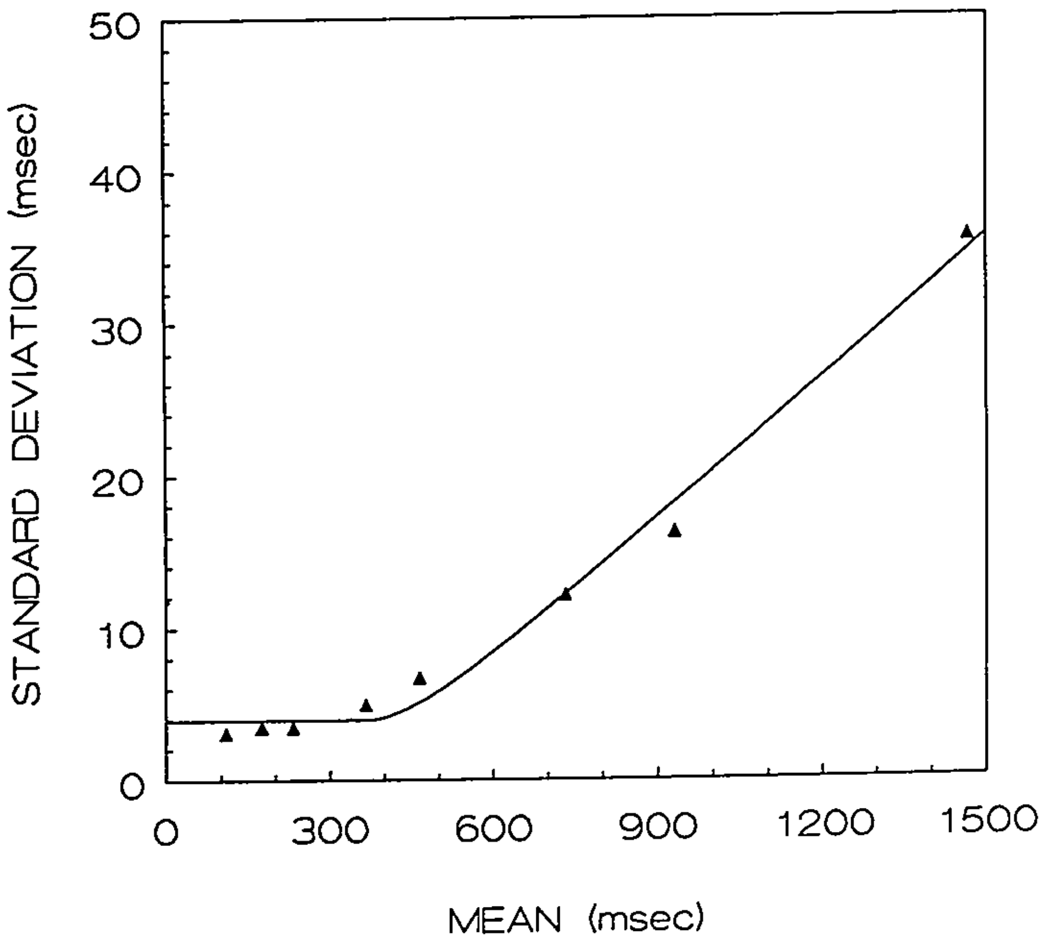
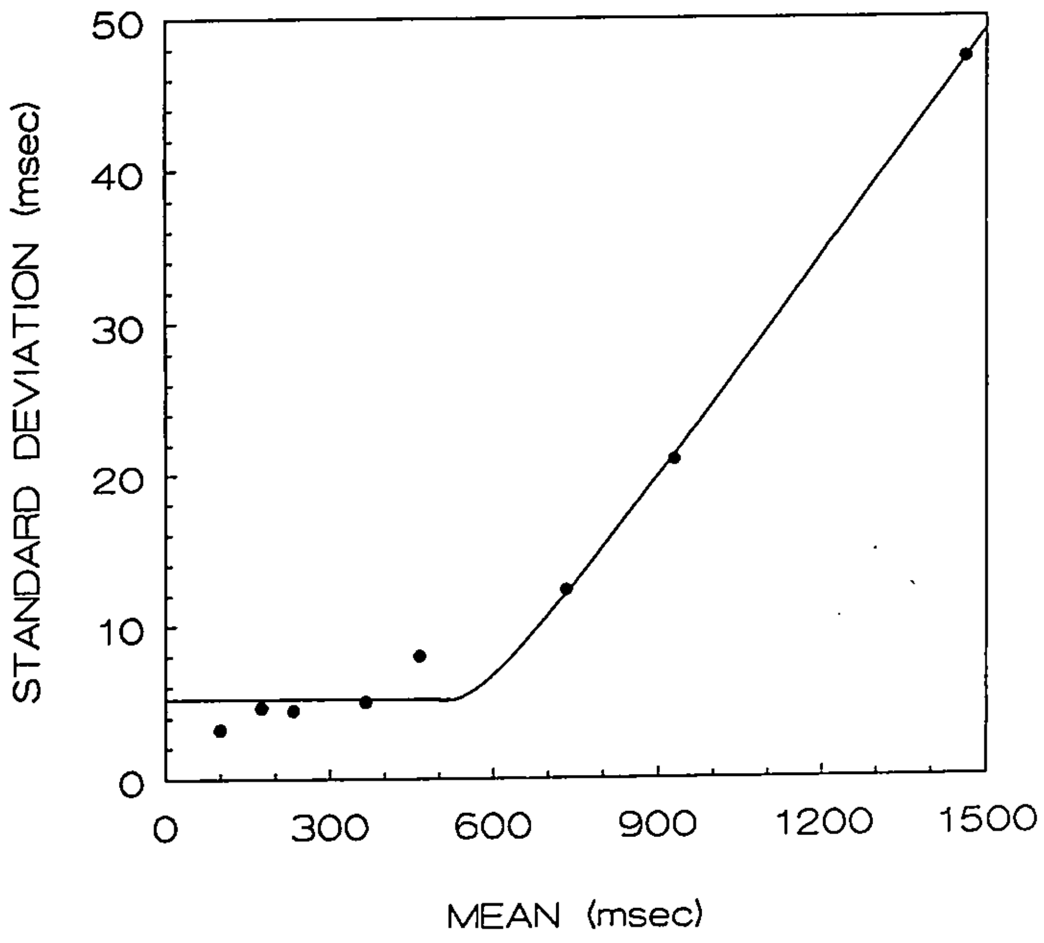

STANDARD DEVIATION (msec)
50
40
30
20
10
0
0
300
600
900
1200
1500
MEAN (msec)

FIGURE 2.14

The best fitting case of Kristofferson's model superimposed on the final Weber function (s_L vs m_L) for GF.



50
40
30
20
10
0
STANDARD DEVIATION (msec)
0
300
600
900
1200
1500
MEAN (msec)

For AK the initial level of performance indicates that V_o equals 32 msec^2 and L equals 400 msec. When compared to the initial level reported by Kristofferson (1976) for R-SS in which V_o was equal to 142 msec^2, the present estimate is very low. If V_o represents the sum of central and efferent component variances in R-SS and it represents only central variance in PTDD then the difference between these two estimates equals the variance associated with the motor end of the R-SS response. In that case R-SS motor variance equals 110 msec^2 (142-32; more will be said about this estimate in Chapter 3). Furthermore, if afferent variance equals or approaches zero, and the assumptions of tripartite variance partitioning and that the three components are mutually independent are valid, the minimum initial variance estimate of the central timekeeper for AK would be 32 msec^2. Interestingly, this estimate matches closely that reported by Hopkins (1984) in which V_o approximately equalled 35 msec^2 following extensive practice.

L, the upper limit of the proposed deterministic interval, has a value of 400 msec which is identical to the value of L reported by Kristofferson (1976) for R-SS after an estimate of simple reaction time has been removed. Such close correspondence between these two very different experimental paradigms on this parameter supports the idea that a 400 msec deterministic delay can be and is inserted into the temporal chain of events. However, results from these same two paradigms indicate that there is a difference in the Weber function for base durations greater than L. K, the Weber constant for increments in duration greater than L, equals 0.056 for AK's initial data but it equals 0.034 for R-SS data (Kristofferson, 1976). On the other hand there is a remarkably close similarity to the Weber fraction of 0.055 reported by Getty (1975) that was based on unpracticed 2AFC DD. This limited comparison between initial Weber functions of several experimental paradigms reveals important similarities and dissimilarities.

An analysis of AK's final Weber function tells a very different story. The magnitudes of V_o, L, and K each drop over the course of practice; V_o drops from 32 to

18 $msec^2$, L drops from 400 to 300 msec, and K drops from .056 to .031. How might these reductions be interpreted within the framework of the present approach? The most likely possibility is one in which the reduction in V_0 is caused by a reduction in temporal processing variability at the central stage because processing at the afferent stage is thought to be virtually variance free (e.g., Kristofferson, 1976; Hopkins, 1984). If that improvement effectively reduces central variability, then the difference between initial and final estimates of V_0 should provide a rough estimate of the degree to which central variance was reduced. For AK that estimate equals about 14 $msec^2$. The final estimate should provide the minimum level of variability attributable to the central processor. That estimate equals the remarkably low value of 18 $msec^2$ for AK. This value of 18 $msec^2$ means that q, one half of the base of the triangular distribution of I (Kristofferson's model), equals 10.4 msec.

Kristofferson (1980) reported that values of q range from 12 to 200 in a doubling series for MFDD. The present quantity of q is theoretically significant because it is very close to the lowest member of that series. But no other steps that indicate the presence of other members of the doubling series are found on the PTDD function. The absence of the doubling series suggests that if there is a quantal process operating in PTDD it is either very different in its operation than the one in MFDD or it is masked by one or more additional processes for base durations greater than L. Of course there is the alternative explanation in which the process in PTDD is non-quantal in nature and that deterministic timing over the lower base durations is independent of a quantal mechanism.

We have seen that V_0 decreased with practice for AK and from Tables 2.11 and 2.12 it can be seen that the same occurred for LL and GF. V_0 decreased by about 15 $msec^2$ for LL, and by about 10 $msec^2$ for GF. According to the interpretation given above, these values should represent reductions in the variability of processing in the central stage. If afferent variance equals zero then the final estimates of V_O should provide an estimate of the minimum level of variance associated with the cental processing stage. Averaged over the three subjects, that level of variance equals 20 $msec^2$.

The quantity L appears to change as a function of practice. Changes in L, according to an interpretation which is consistent with Kristofferson's (1976) model, indicate that the deterministic interval that is inserted into the chain of events changes in duration. For AK there is a shortening of L by 100 msec (from 400 to 300 msec). For LL it increases by about 50 msec from an initial value of 310 msec to a final value 361 msec. The increase is more dramatic for GF. For him the initial value equals 120 msec and it increases to 510 msec following practice, a change of nearly 400 msec. Thus, for two subjects L increases as a result of practice and for one it decreases.

For the two Ss for whom L increased, it was noted earlier that they had negative practice effects for the two highest values of T. Although these negative practice effects were statistically non-significant, there is the possibility that they would contribute to spuriously high estimates of L. This could happen by forcing the linear portion of the model to be steeper than it should be thereby moving the intersection of the deterministic segment and the linear segment to the right. This would have the effect of artificially lengthening L. However, this effect must be minimal because the negative practice effect did not even approach significance.

Alternatively, changes in L may indicate the existence of a flexible or adaptable process. If L represents the duration of the deterministic interval then that interval is adjustible. Perhaps S adjusts the deterministic interval in "search" of an optimum duration in which together timing precision and accuracy are maximized. The outcome of such a search might depend to some extent on the value(s) of the other parameter(s) (e.g., K, V_O) or experimental considerations (e.g., the extent of practice, or range of base durations). Were that to be the case there should be a detectable relationship between changes in L and changes in some of these other variables. Indeed there is a positive relationship between L and K; an increase in L is always accompanied by an increase in K.

K, the Weber constant in Kristofferson's model for increments in excess of L, decreases from 0.056 to 0.031 for AK but it increases from 0.028 to 0.031 and from 0.030 to 0.049 for LL and GF respectively. Normally a decrease in K reflects an improvement in timing at each base duration. However, when K refers to the increments in timing above a limit L, the relative positioning of L and V_0 become important when interpreting changes in K. Certainly if L and V_0 remain constant then a reduction in K indicates an improvement in timing at each T. However if L increases, as was the case for LL and GF, then even an increase in K could mean better absolute timing at some, if not all T contained in the range of base durations described by Weber's Law. Taking these considerations into account, practice improves timing over the Weber's Law range for all three subjects.

The observed relationship between L and K means that the mechanisms giving rise to L and K might not be independent. I say might not be independent because there is the obvious factor of practice that may affect processes responsible for both L and K. If a third variable such as practice has similar affects on the mechanisms underlying L and K, the observed relationship between L and K could result. On the other hand, if the deterministic interval is generated in the afferent system, as put forth by Kristofferson (1976), and if K represents activity of the central processor, it is not unreasonable to suggest that the afferent and central stages might not be independent. Perhaps the optimum duration of the deterministic delay changes as a result of a change in K. Conversely it is possible that fine adjustments in L result in changes to K. Whatever the case may be, both K and L increase as a result of practice.

SUMMARY

One of the principle reasons for examining the PTDD procedure was to learn more about the timing mechanisms underlying explicit standard DD. In this regard the present experiment has provided some answers.

Most importantly, PTDD was investigated in an effort to determine the shape of the variability versus mean function following extensive and specific practice. The results show that the proposition that variance increases linearly with mean is clearly rejected in favour of a proportional standard deviation (i.e., Weber's law) model.

In the PTDD experiment both pre- and post-practice Weber functions were well characterized by a flat segment over short base durations followed by a rising segment that obeys Weber's law over longer base durations. The flat segment over short base durations is consistent with Kristofferson's (1976) proposal that a deterministic delay exists within the timing chain of events. The present data also indicate that the duration of the delay changes with increased experience indicating the possibility of a continuously adjustable deterministic delay.

For temporal increments in excess of L, a Weber's Law timekeeper comes into operation. Performance at base durations governed by this principle improves with practice but in contrast to MFDD, a quantal step function does not emerge. This indicates that the type of standard employed (implicit vs. explicit) is of paramount importance in terms of the timing mechanisms that are accessible to S. In summary, it appears that explicit standard duration discrimination is governed by the deterministic and stochastic principles but not by the quantal principle.

A second principle reason for conducting the PTDD experiment was to determine if there is a relationship between the principles and/or mechanisms underlying duration discrimination and those underlying motor timing. Issues concerning this topic will be addressed by comparing the PTDD results to data generated by the finger tapping experiment that is described in Chapter three.

TAPPING EXPERIMENT

INTRODUCTION

The main issue being addressed by the tapping experiment concerns the nature of the relationship between σ_C^2 and μ_I. The primary question regarding that relationship is: Does σ_C^2 or its square root increase at a constant rate when μ_I increases at a constant rate? Based on the investigations of Wing (1973) and Wing and Kristofferson (1973) it is not certain which of these is the case, primarily because the range of durations studied was not wide enough and too few values of T were investigated. However, if the motor timekeeper that is used in tapping has similar operating characteristics as the perceptual timekeeper that is used in DD or R-SS, one would expect the standard deviation, rather than the variance, to be a constant proportion of the mean (Getty, 1975; Kristofferson, 1980). Several subsidiary questions related to this issue are: 1) Which of the five models presented in the Introduction best describes the tapping Weber functions? 2) What does the shape of the function tell us about the characteristics of the underlying timing mechanism(s)? For instance, does a region or do several regions in which variability is independent of the mean, emerge as a result of practice? 3) Are the functions consistent with quantal and/or deterministic and/or stochastic timing principles? 4) What are estimates of the parameters of the timing models that best describe the data? 5) Finally, will a comparison of these parameters to those obtained from other temporal tasks provide evidence to support the idea that a common timing mechanism, or that multiple mechanisms with common operating characteristics underlie human timing abilities? For example, will there be a range of durations over which response variability remains constant? And if there is such a range, will it be equal to 400 msec as was found to be the case for R-SS (Kristofferson, 1976). Will a quantal step function emerge as a result of extensive and specific practice and if one does emerge does it correspond to the doubles set found by Kristofferson (1980) in the context of MFDD?

A second goal of the present experiment is to establish the temporal range within which the TPM is valid. To accomplish that goal the TPM and four of its generalizations will be evaluated over a wider range of temporal intervals than have been evaluated in the past. In the present investigation the range will span from a lower limit of 175 msec to an upper limit of 1468 msec. The TPM has not been systematically evaluated over a range of T greater than about 500 msec. An analysis of the autocovariance functions will provide the necessary information to answer the following questions concerning this issue: 1) Which of the TPM and its generalizations will best predict the obtained autocovariance functions and what are the optimal parameter estimates? 2) Are estimates of central (s_C^2) and efferent delay variance (s_D^2) valid for each duration studied? 3) If not, at what point are valid estimates no longer forthcoming? 4) If there appears to be a violation of an assumption, such as the assumption of independence between C_j and D_j, can any of the generalizations of the TPM better account for the obtained results?

A third, but less important, goal is to investigate practice effects on IRI timing. An attempt to determine whether practice significantly improves performance will be made. Does practice improve performance at the same rate and to the same extent for each T? If the results are similar to those obtained during DD (Kristofferson, 1980), we would expect practice to affect performance differentially at different intervals. Specifically, if the timekeeper is the same for DD as it is for tapping, we expect that practice should decrease s_C^2 more for those durations that are at the higher end of the treads of the quantal step function (Kristofferson, 1980). Furthermore, if both efferent and central components are subject to the effects of practice one would expect that the improvement in performance should be slightly greater for tapping than DD.

METHOD

SUBJECTS

Four adult Ss participated in this experiment but only three completed it - the same three that completed the PTDD experiment. The results of the one S for whom data are incomplete will not be considered. Of the three whose data will be presented, all are right handed and LL is the only female. AK has had the most experience as a subject in previous psychophysics experiments but LL has had extensive experience as well.

APPARATUS

All stimulus and response timing for AK and LL was performed by an Apple IIe microcomputer in conjunction with a DI09 interface card and an Assembler program. During every msec the computer is programmed to control stimulus events (e.g., turn the pulses on or off when appropriate), scan for a response, store the IRI time if a response is detected, and perform various other computations. When all of these activities have been completed the computer waits until the onset of the next msec to start the process over again. The accuracy of all response timing therefore is to within 1 msec - that is, the duration of an IRI will not vary more than 1 msec from its recorded time.

The accuracy of stimulus timing is even higher than response timing and for the purposes of the present experiment may be considered to be non-variable. Stimulus timing for pulses presented to GF was performed by an external apparatus which had an accuracy of ± 1 msec. IRI times for GF were measured by a slightly modified version of the Assembler program that was used for the other Ss, one that did not use the DI09 card. Timing accuracy using that routine was also accurate to within ± 1 msec. The reason for switching to a totally internal timing method was to be able to determine the relative timing of stimulus and response events. Because the old method of timing was used for GF it is impossible to determine the relative positioning of stimulus and response events for his SP response sequences.

The response key is housed in a wooden box and placed on a table in front of S who is seated in a well ventilated sound attenuating booth. Neither the wooden box nor S's arm are restrained in any way.

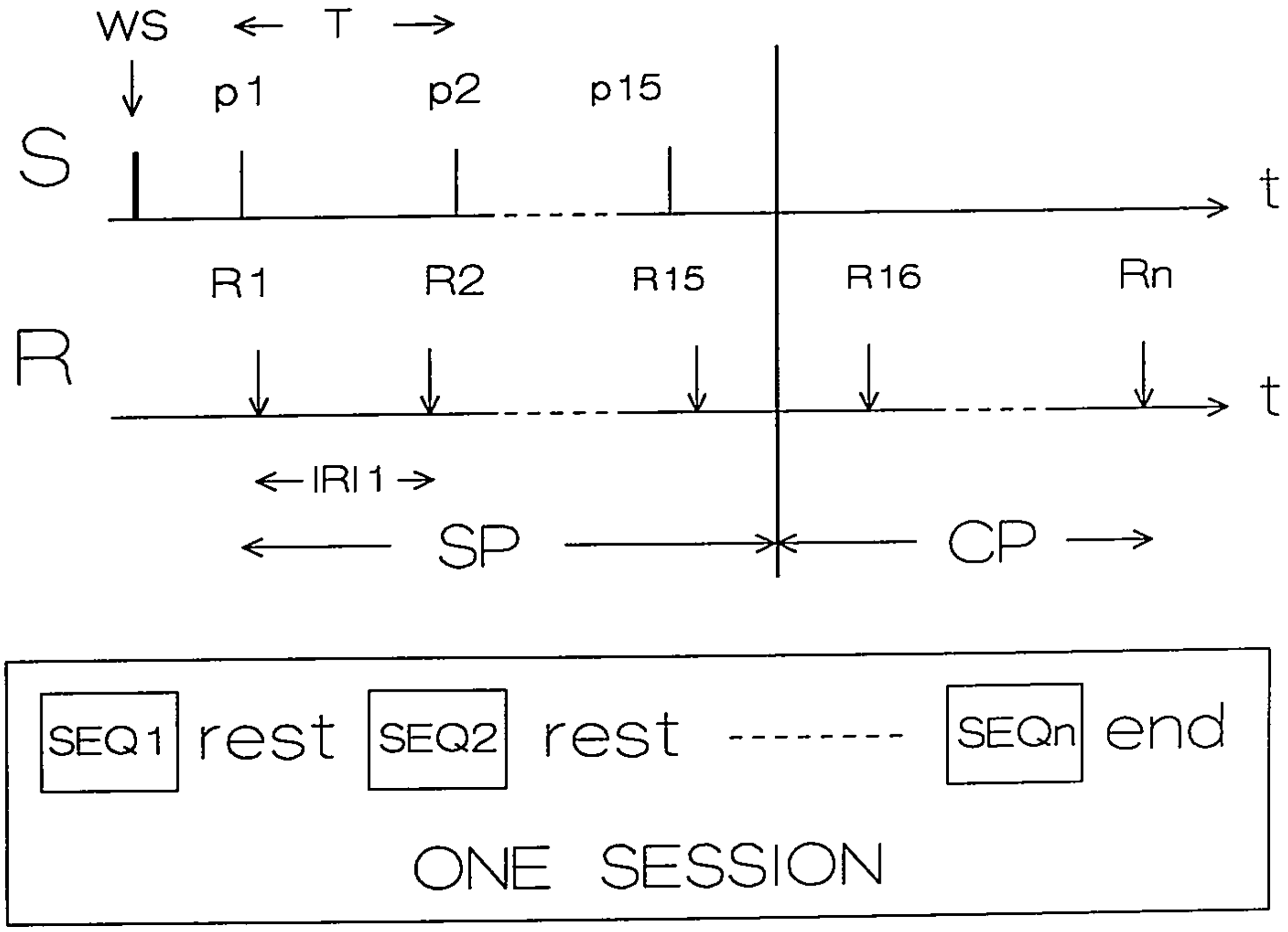
PROCEDURE

Each session of this experiment is composed of a predetermined number of sequences. Except for the first two sequences of each session, all sequences that contain no unacceptable responses will be used for parameter estimation purposes (for a description of the details of how a response is defined as acceptable or not, and for how the problem of key-bounces was handled see Appendix 1). The first two sequences are excluded as they are used to provide Ss with a period of time to become adjusted to the experimental situation. Every sequence is made up of a SP and a CP (see Fig. 3.1).

During the SP S is instructed to synchronize Morse telegraph key presses to the onsets of 15 (for AK and LL) or 25 (for GF) clearly audible clicks which are presented over headphones. Each click is 10 msec in duration and the interval between the onsets of two successive clicks, T, is constant for all sequences in a session. The CP begins immediately after the SP. It involves the same response as in the SP but in the absence of external stimuli. S is instructed to continue tapping at the rate which was established during the SP. The sequence is terminated by a computer generated beep after the completion of 10 CP IRIs (for AK and LL) or 30 (for GF). There is an interval of approximately 15 seconds between the end of one sequence and the beginning of the next. A session typically includes 52 "good" sequences. However, for extremely long T (e.g. 932 and 1468 msec) this number was reduced, in some cases, in order to avoid excessive fatigue.

FIGURE 3.1

Stimulus and response events during each sequence in the tapping experiment. The upper panel shows the events in a sequence. S and R are stimulus and response time lines respectively. pj marks the stimulus pulses and Rj the corresponding response. SP is the synchronization phase and CP the continuation phase. The enclosed box shows the organization of sequences within a session.


WS
T
p1
p2
p15
S
t
R1
R2
R15
R16
Rn
R
t
IRI1
SP
CP
SEQ1
rest
SEQ2
rest
SEQn
end
ONE SESSION

S is asked to tap on the response key with his/her index finger of the preferred hand and is instructed to keep the mode of responding as constant as possible within and between sessions. He/she is asked not to count in any way to assist in improving timing accuracy. Ss are encouraged to run one session per day and only one S may enter the experimental chamber at any given time.

Seven values of T were used: 175, 233, 367, 466, 734, 932, and 1468 msec. These values were chosen because they correspond to the lower and higher base duration values which fall near the extreme ends of the treads on the steps in the quantal step function (Kristofferson, 1980). In addition, the three higher values are included because the TPM has not been evaluated in that range. S proceeds from one value to the next only after it is clear that he has attained a stable low s_I^2 in the CP. Thus, the number of sessions run at each T may vary between Ss and between different values of T.

CONTINUATION PHASE: RESULTS AND DISCUSSION

Due to individual differences Ss required differing numbers of sessions at each T to achieve a stable level of responding. The order in which the Ss encountered the different values of T and the number of sessions each subject ran at each T are presented in Table 3.1. Data for AK could not be collected at T = 175 msec because that rate of tapping proved to be too fast.

The TPM (Wing, 1973) was developed to account for the timing of CP, not SP, IRIs. For this reason the following presentation will focus heavily on an analysis of CP IRI sequences. A brief analysis of SP IRIs will follow in a later section.

INTERRESPONSE INTERVAL TREND ANALYSIS

Figure 3.2 shows m_I as a function of position in the response sequence for all sequences in the last five sessions for each T. In many of these figures it can be seen that there is a clear point of transition between the end of the SP and the beginning

TABLE 3.1

Details of the tapping experiment.

LEGEND:

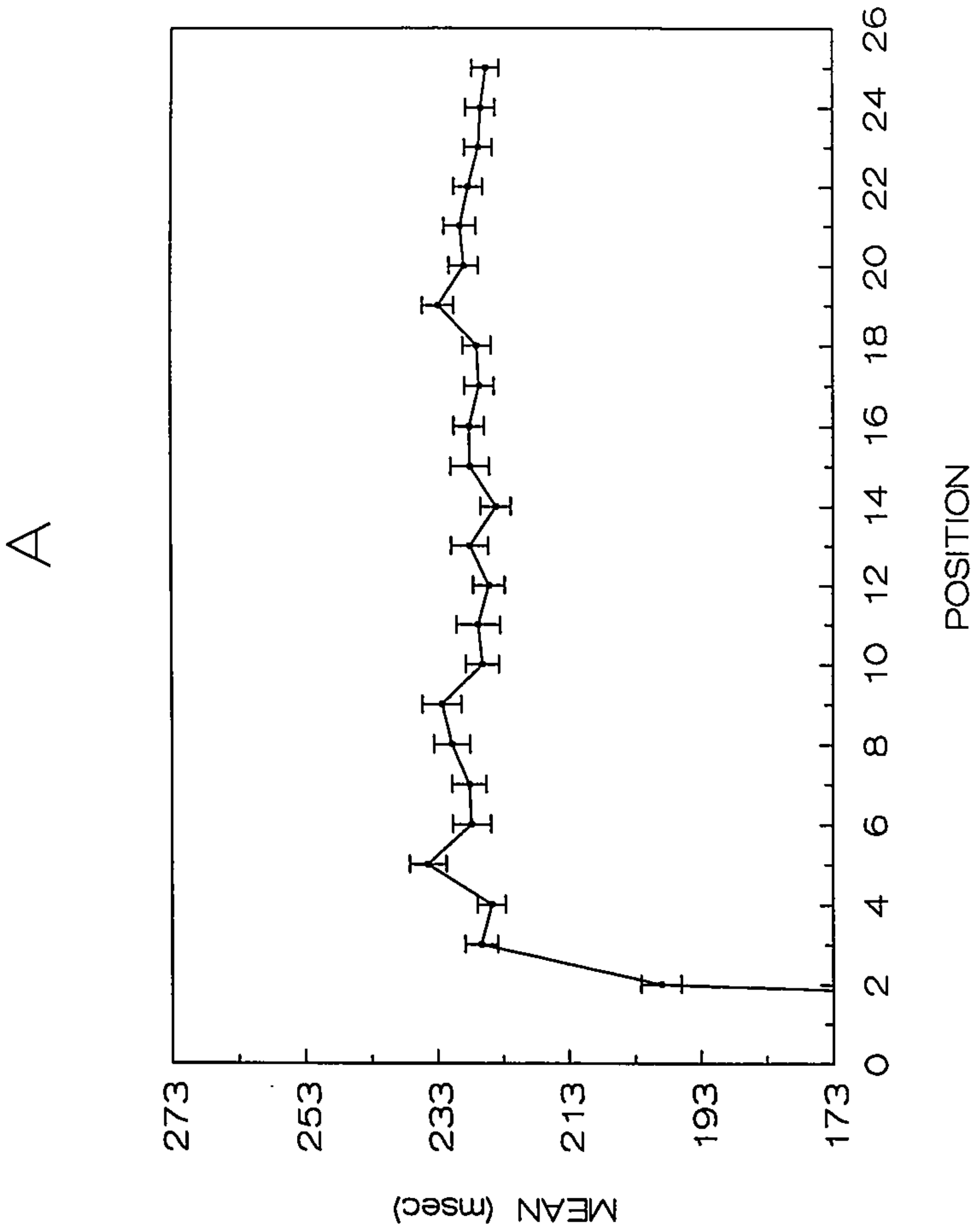
SYMBOL	DESCRIPTION
O	sequential order of T
#S	number of sessions

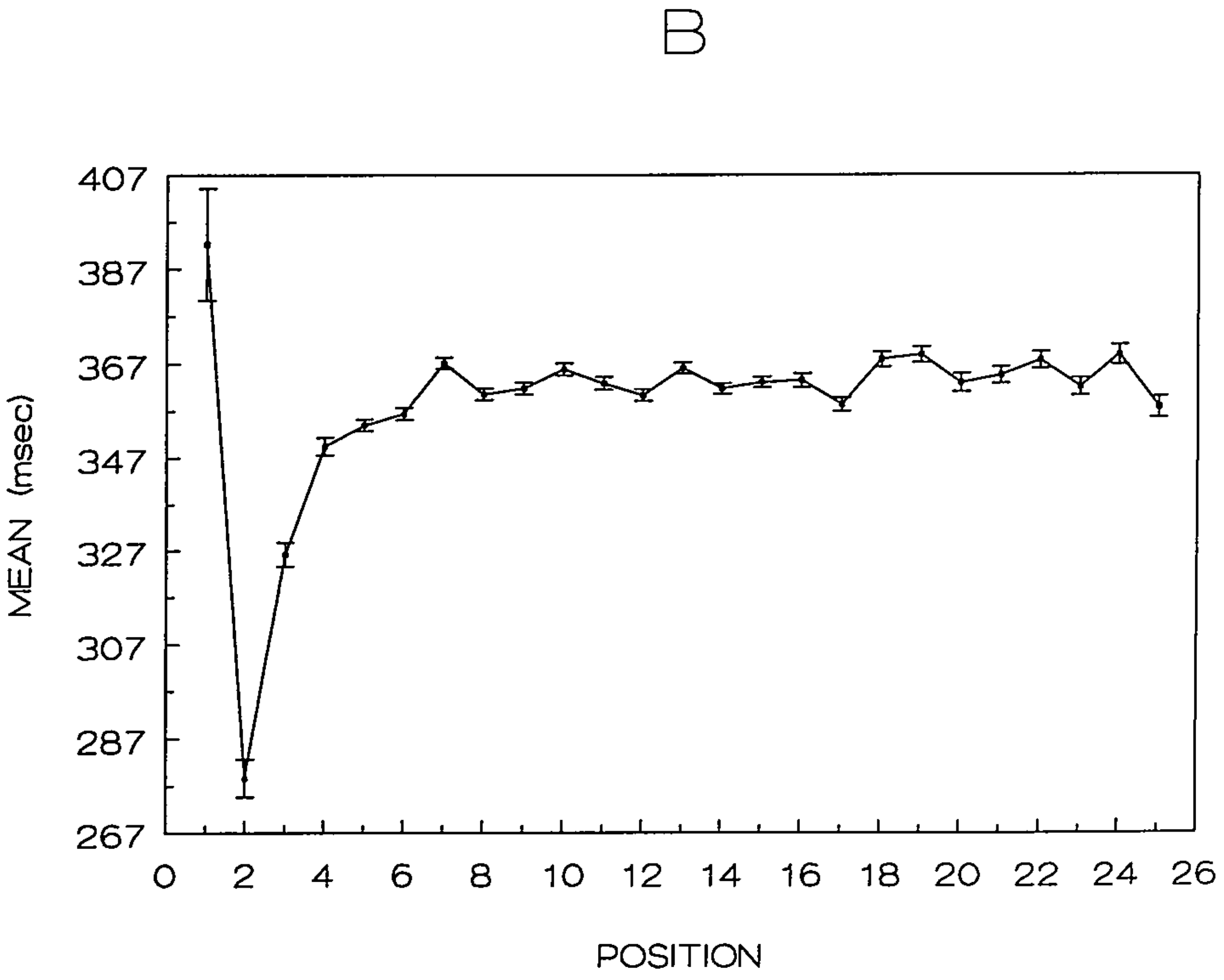
T (msec)	AK		LL		GF	
	O	#S	O	#S	O	#S
175			6	15	6	30
233	4	34	4	20	2	53
367	2	47	7	31	1	49
466	6	42	5	31	3	23
734	1	57	2	67	4	20
932	5	60	1	40	7	20
1468	3	61	3	38	5	22

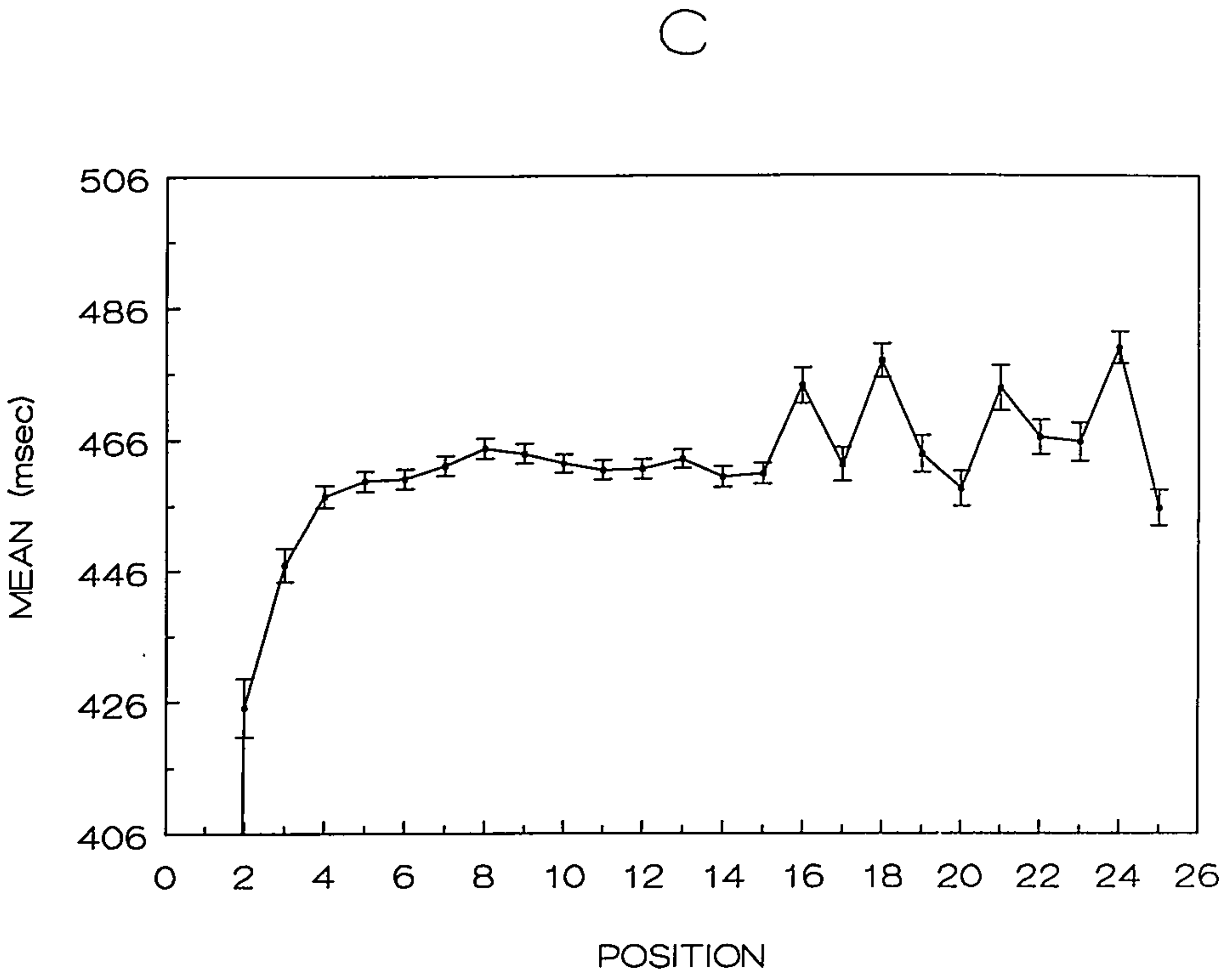
FIGURE 3.2

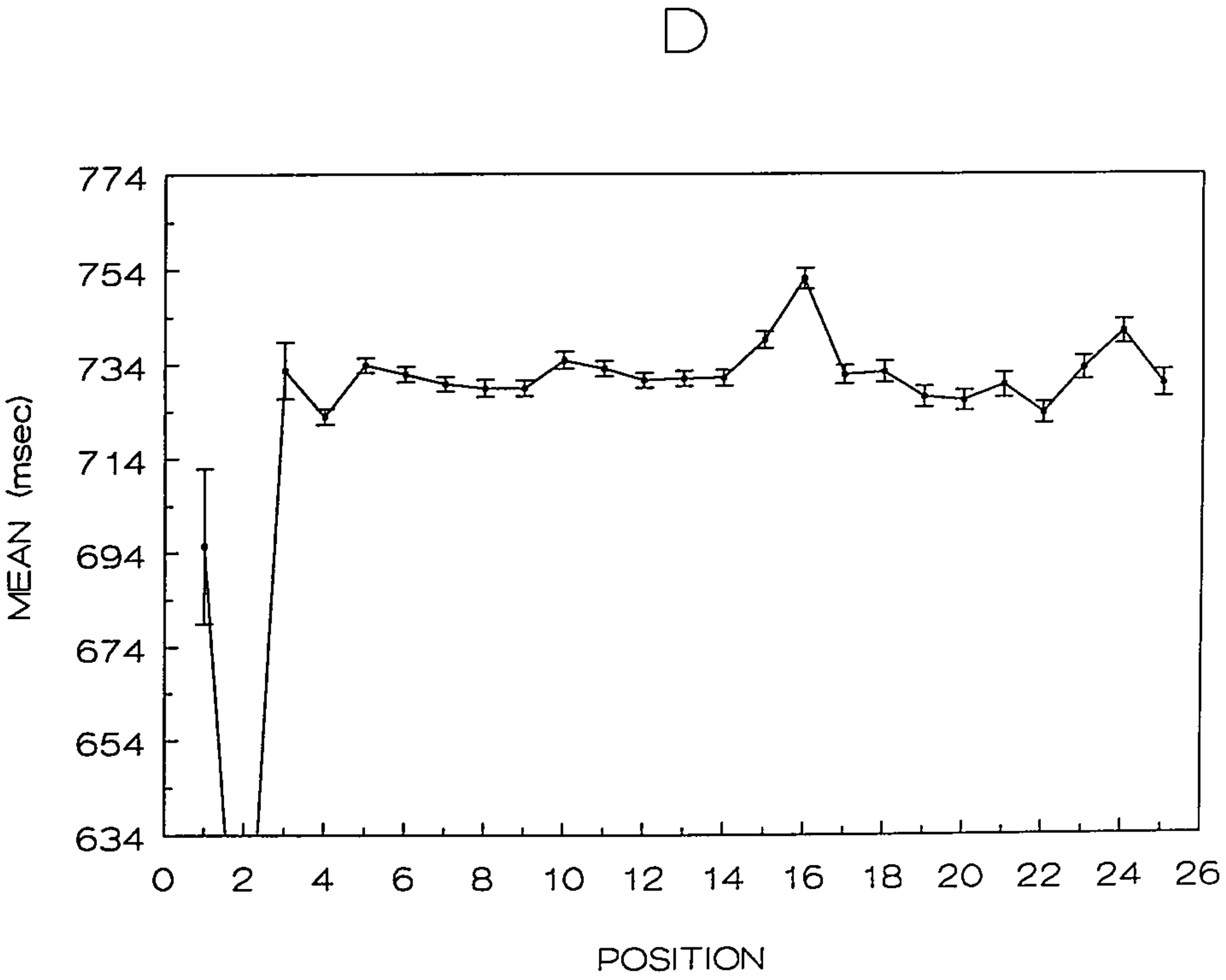
Mean IRI computed across all sequences in the last five sessions plotted as a function of sequence position. Error bars are two standard errors about the mean.

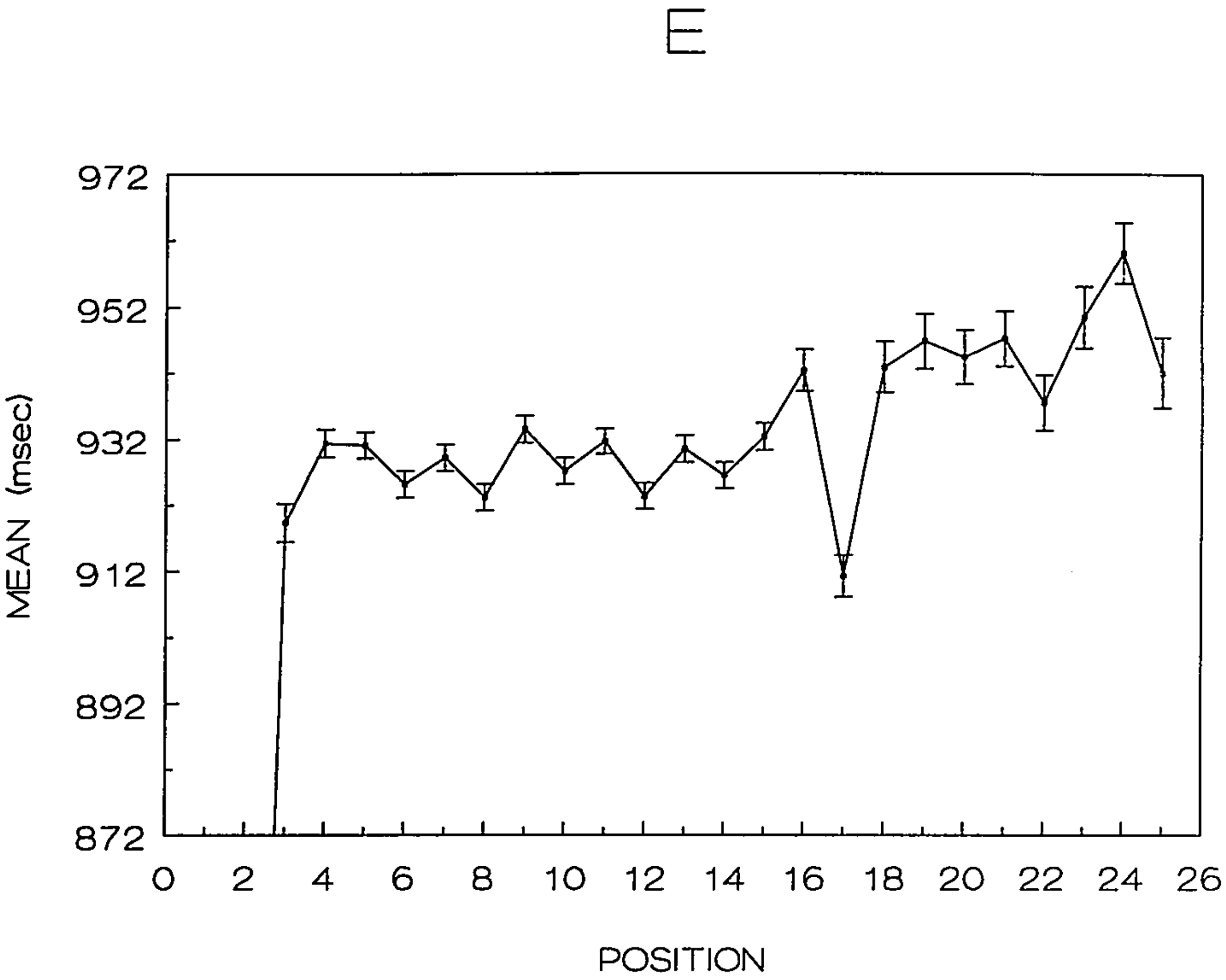
PANEL	SUBJECT	T (msec)
A	AK	233
B	AK	367
C	AK	466
D	AK	734
E	AK	932
F	AK	1468
G	LL	175
H	LL	233
I	LL	367
J	LL	466
K	LL	734
L	LL	932
M	LL	1468
N	GF	175
O	GF	233
P	GF	367
Q	GF	466
R	GF	734
S	GF	932
T	GF	1468

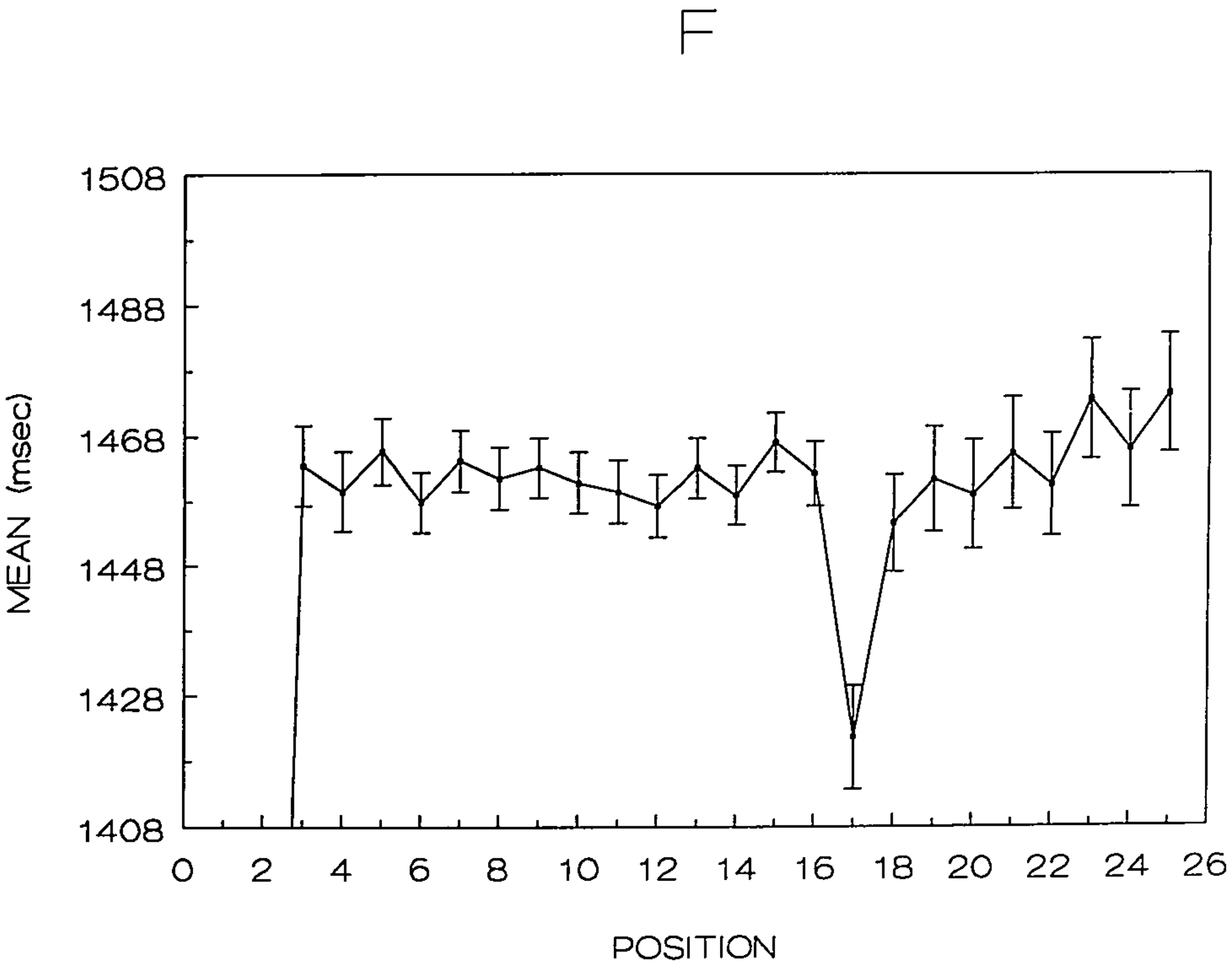

A
MEAN (msec)
273
253
233
213
193
173
0
2
4
6
8
10
12
14
16
18
20
22
24
26
POSITION

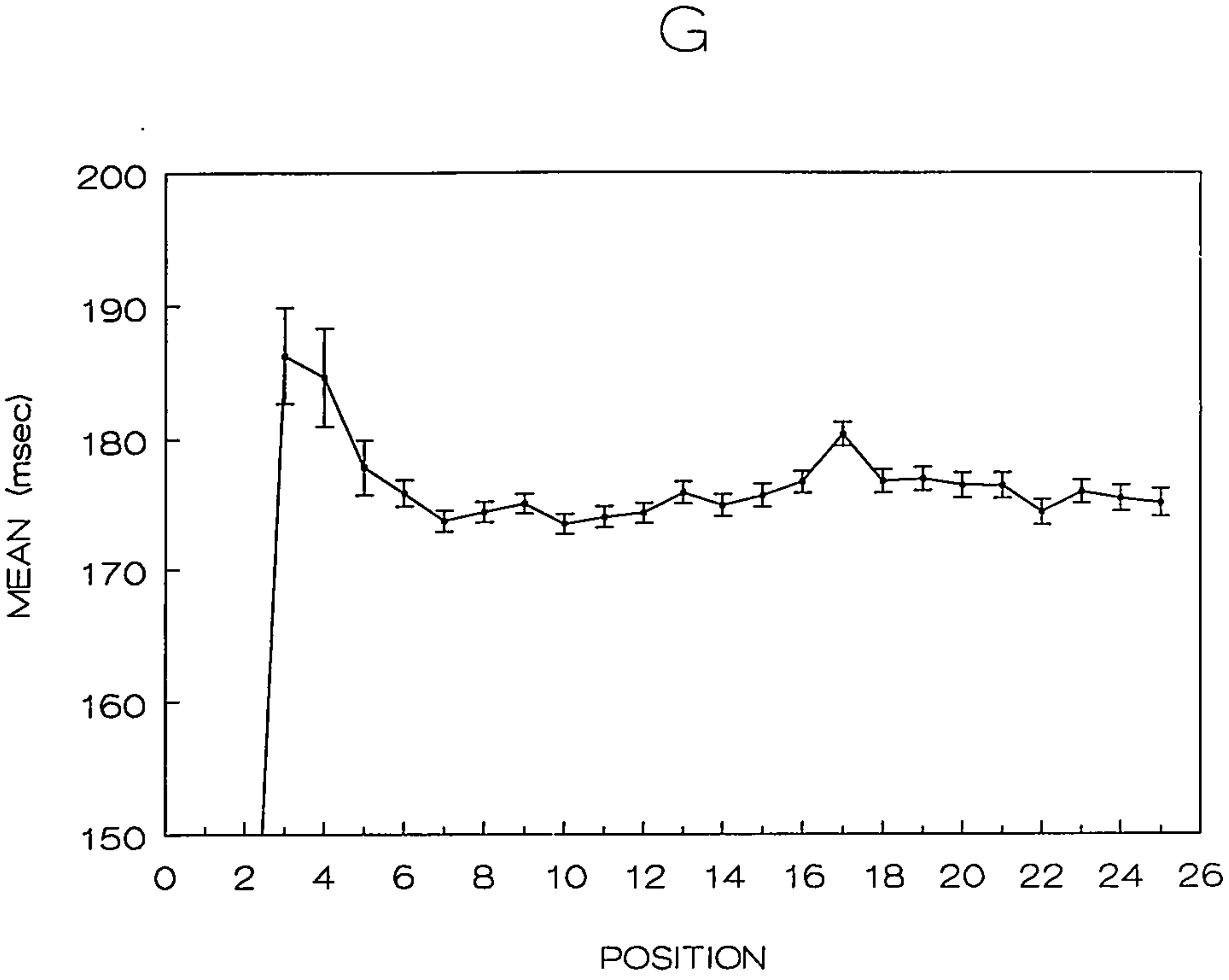

B
MEAN (msec)
407
387
367
347
327
307
287
267
0
2
4
6
8
10
12
14
16
18
20
22
24
26
POSITION

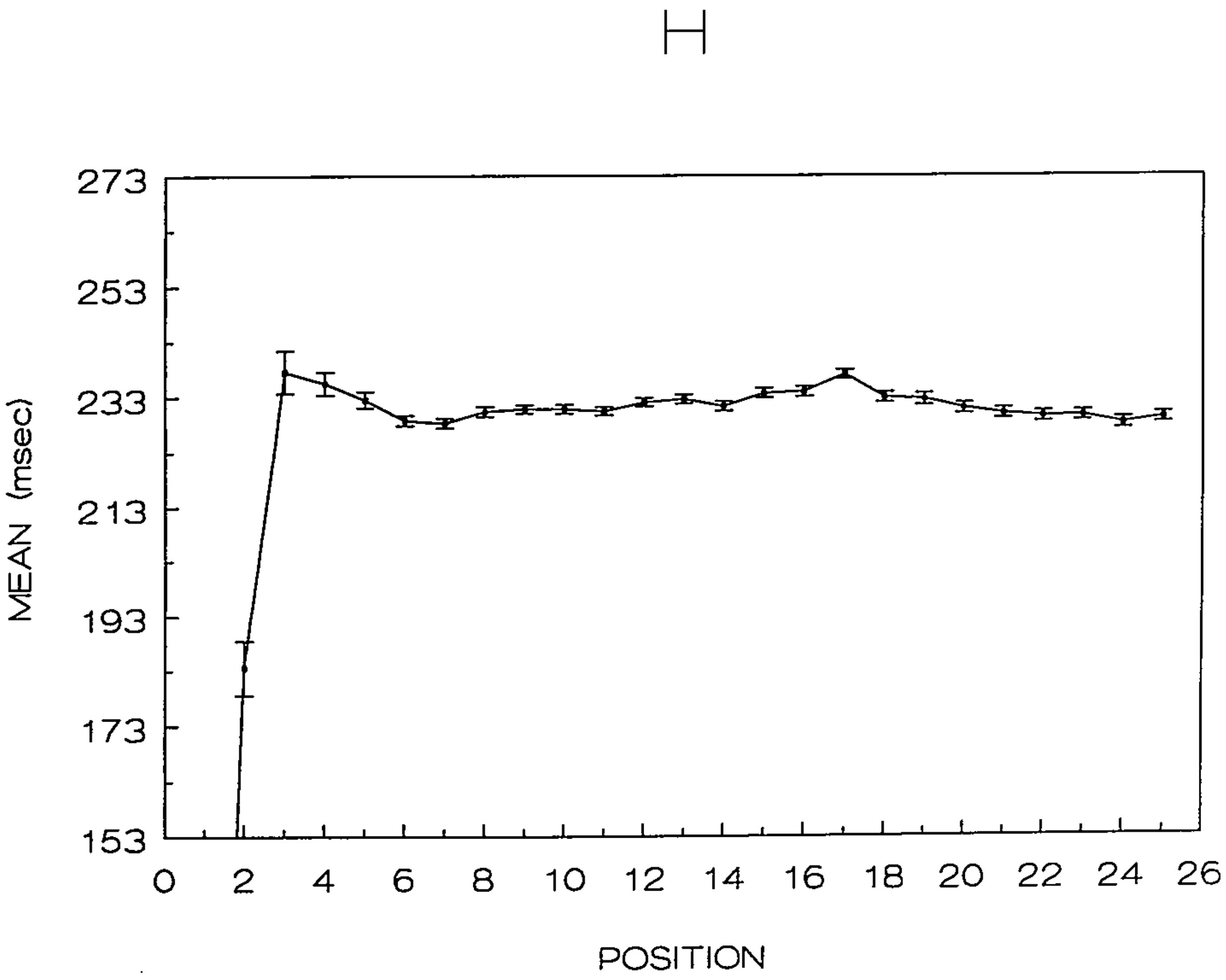

C
MEAN (msec)
506
486
466
446
426
406
0
2
4
6
8
10
12
14
16
18
20
22
24
26
POSITION


D
MEAN (msec)
774
754
734
714
694
674
654
634
0
2
4
6
8
10
12
14
16
18
20
22
24
26
POSITION

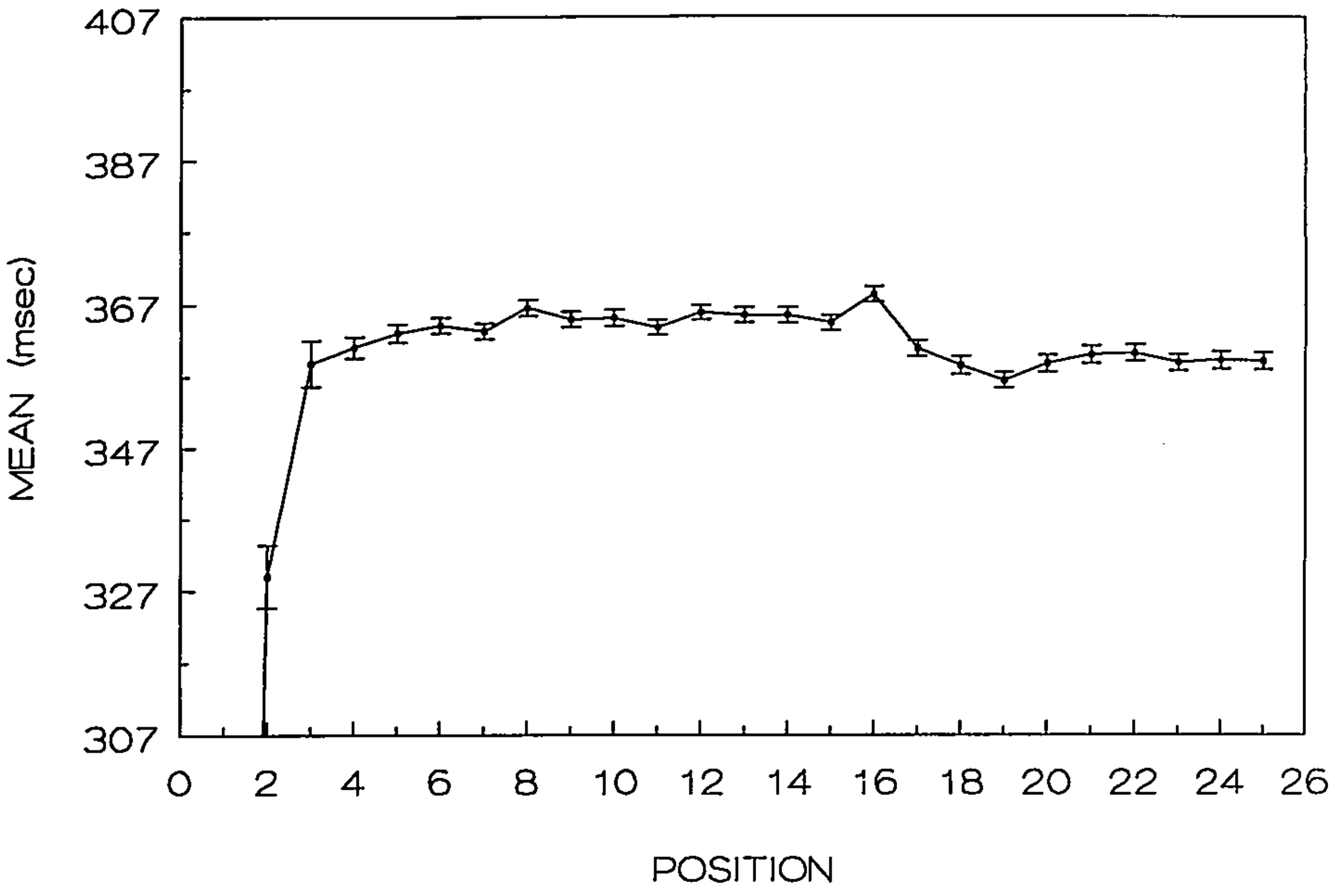

E
MEAN (msec)
972
952
932
912
892
872
0
2
4
6
8
10
12
14
16
18
20
22
24
26
POSITION

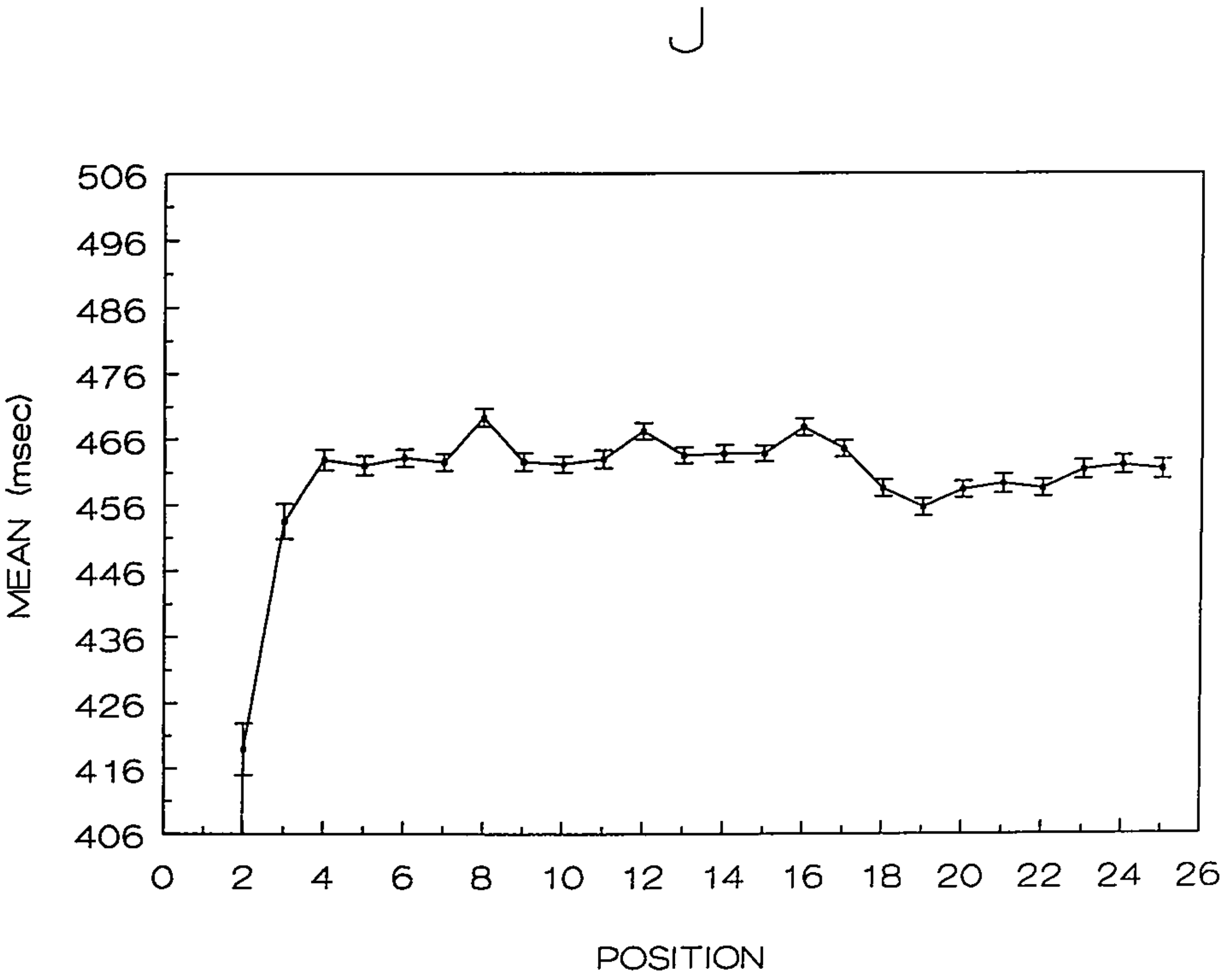

F
MEAN (msec)
1508
1488
1468
1448
1428
1408
0
2
4
6
8
10
12
14
16
18
20
22
24
26
POSITION


G
200
190
180
170
160
150
MEAN (msec)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
POSITION

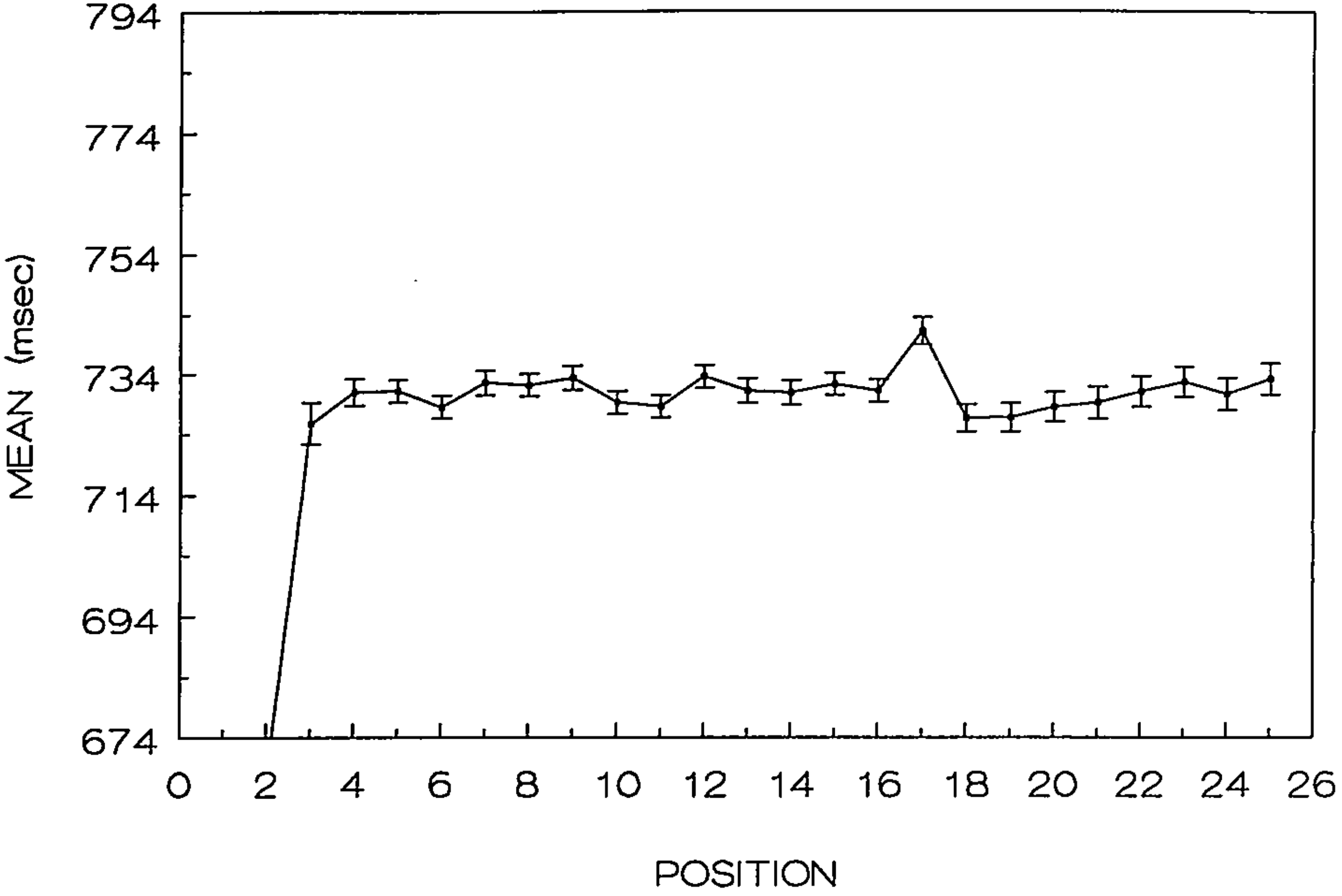


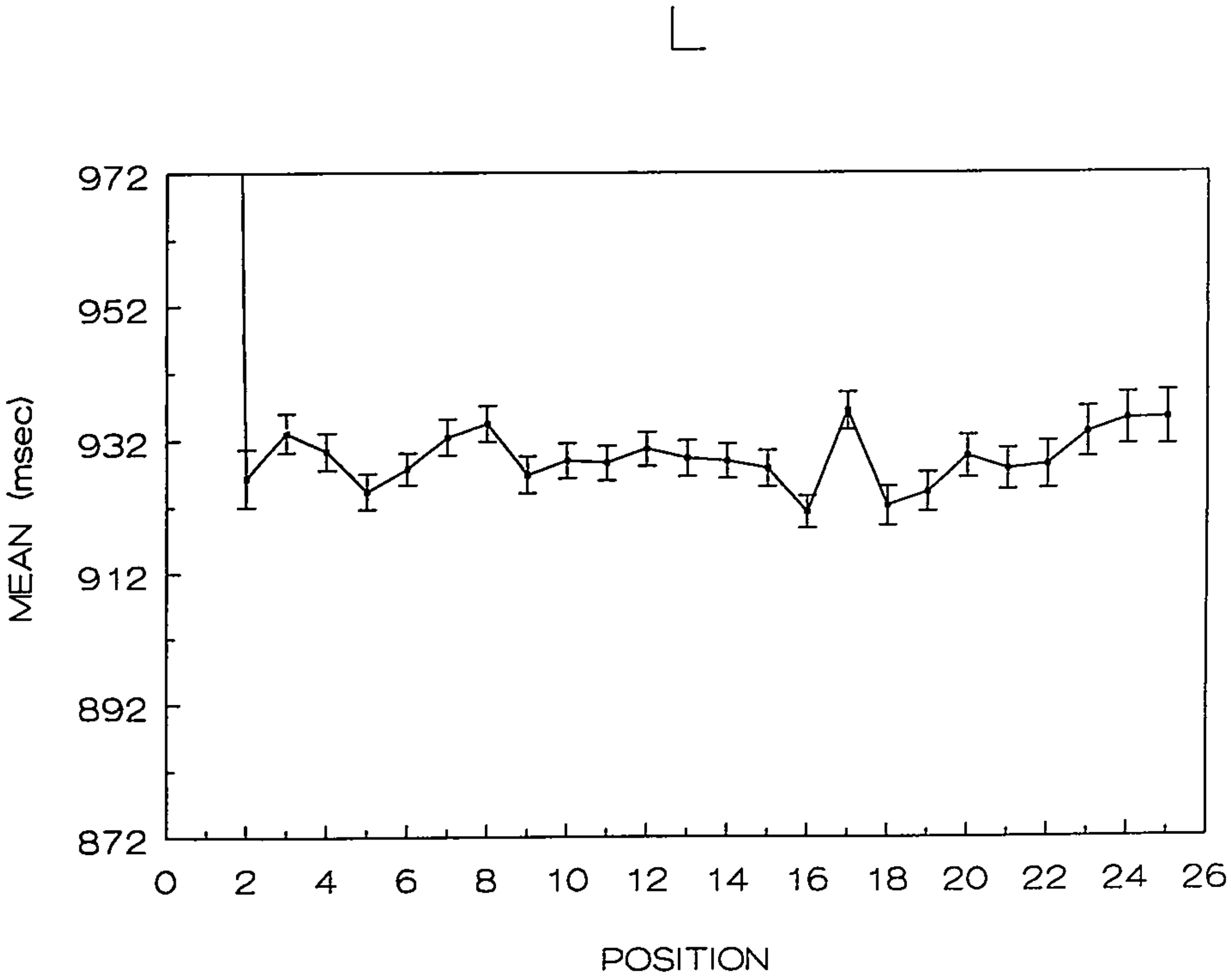
H
MEAN (msec)
273
253
233
213
193
173
153
0
2
4
6
8
10
12
14
16
18
20
22
24
26
POSITION

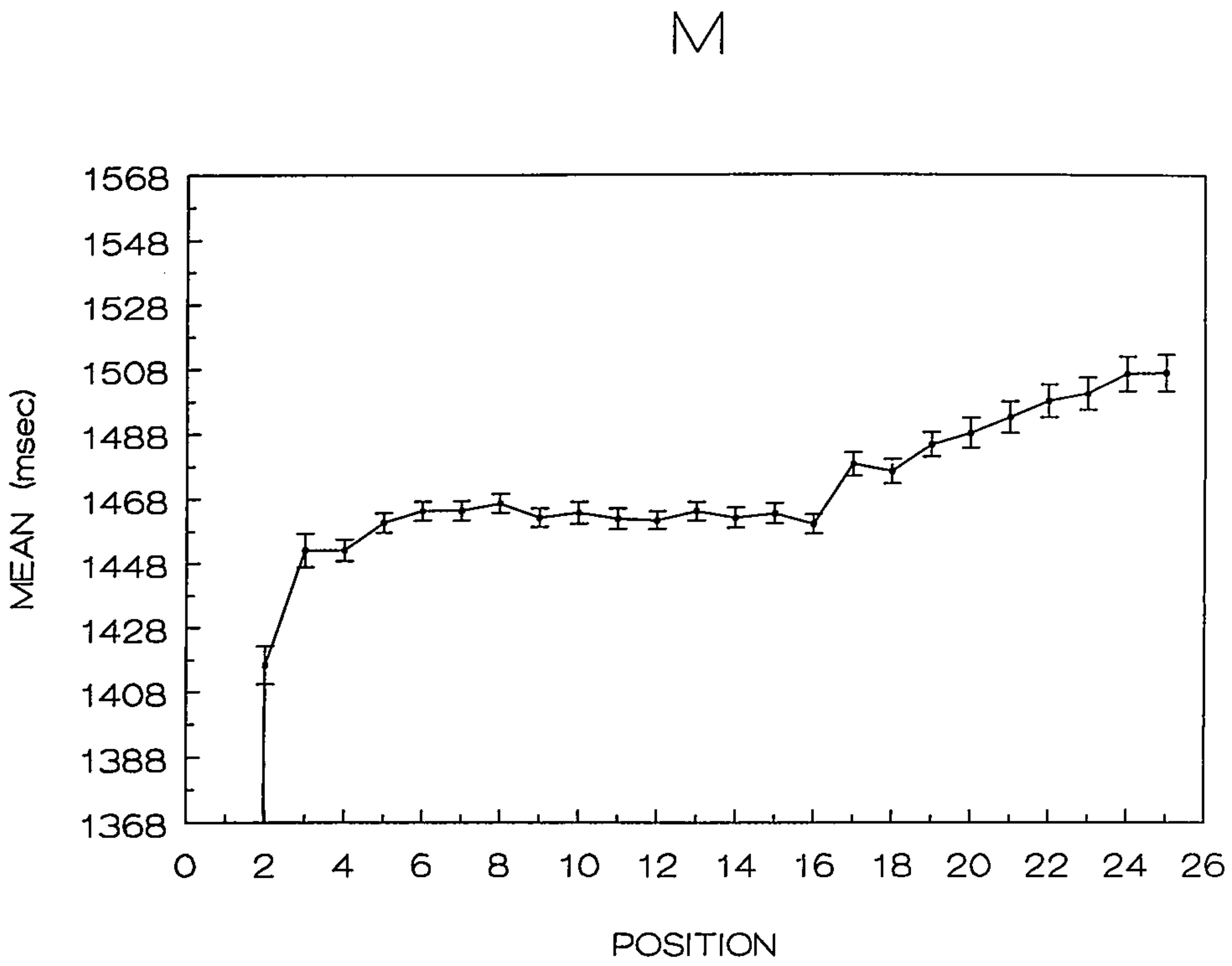

407
387
367
347
327
307
MEAN (msec)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
POSITION


J
MEAN (msec)
506
496
486
476
466
456
446
436
426
416
406
0
2
4
6
8
10
12
14
16
18
20
22
24
26
POSITION

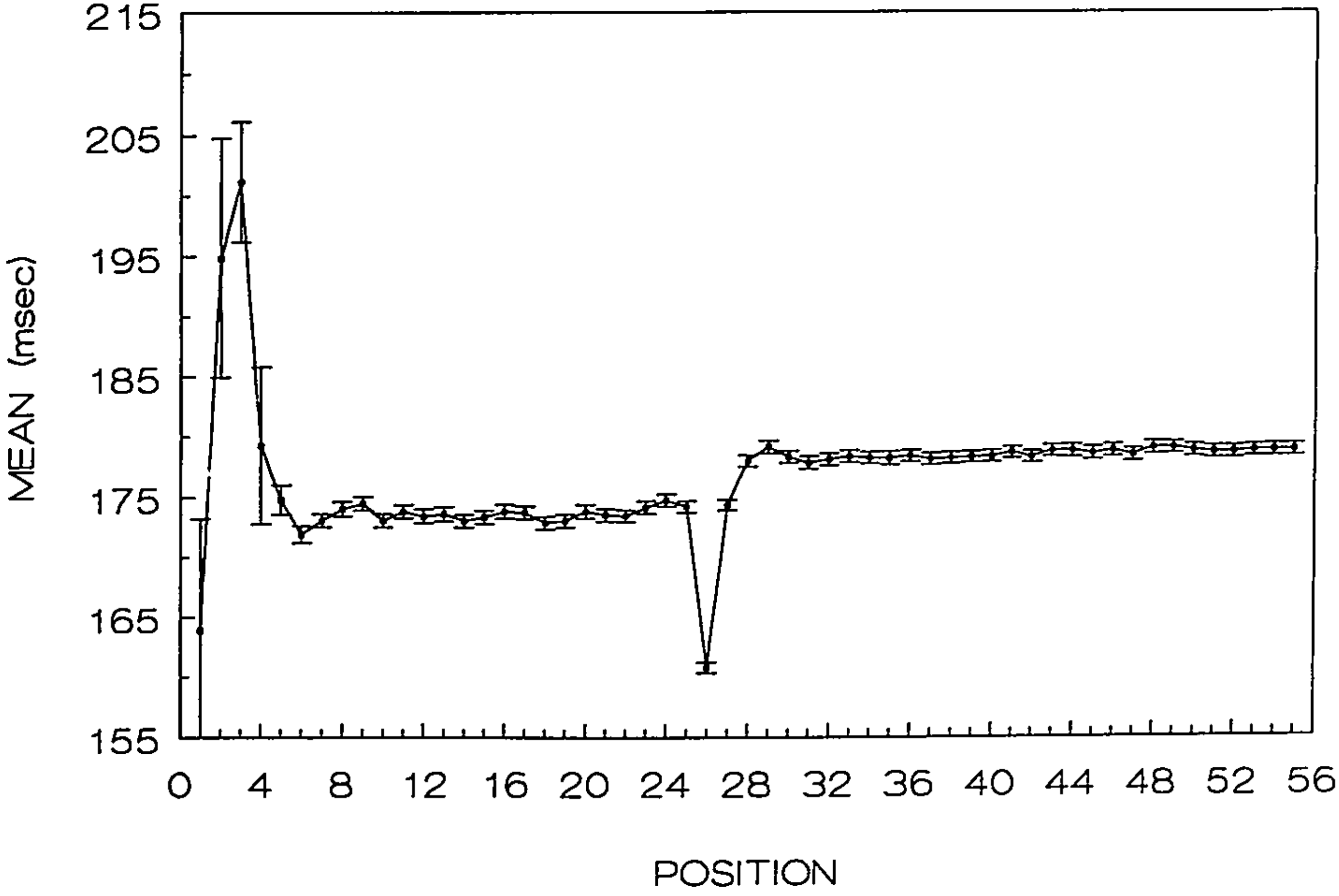
K


794
774
754
734
714
694
674
MEAN (msec)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
POSITION

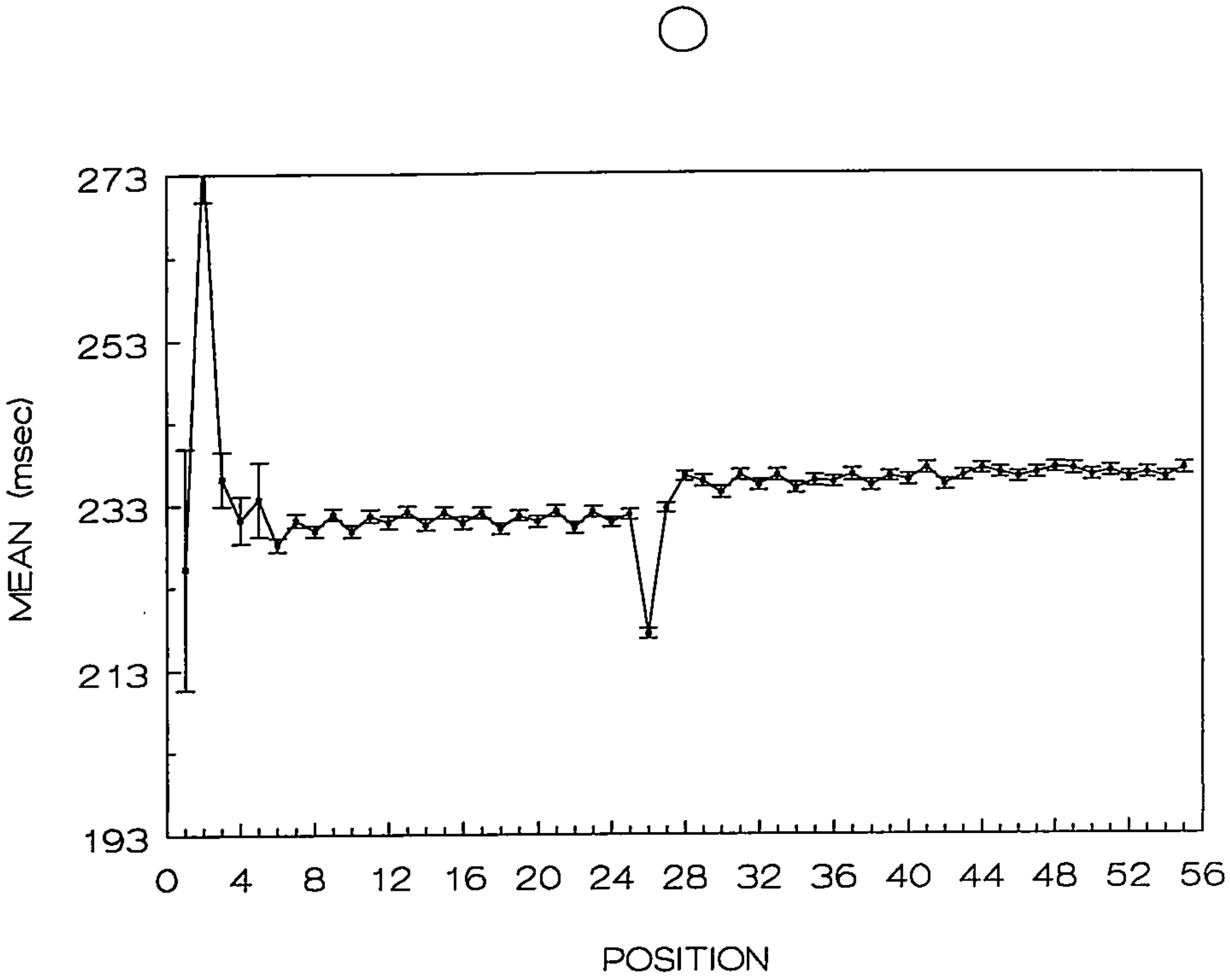

L
MEAN (msec)
972
952
932
912
892
872
0
2
4
6
8
10
12
14
16
18
20
22
24
26
POSITION

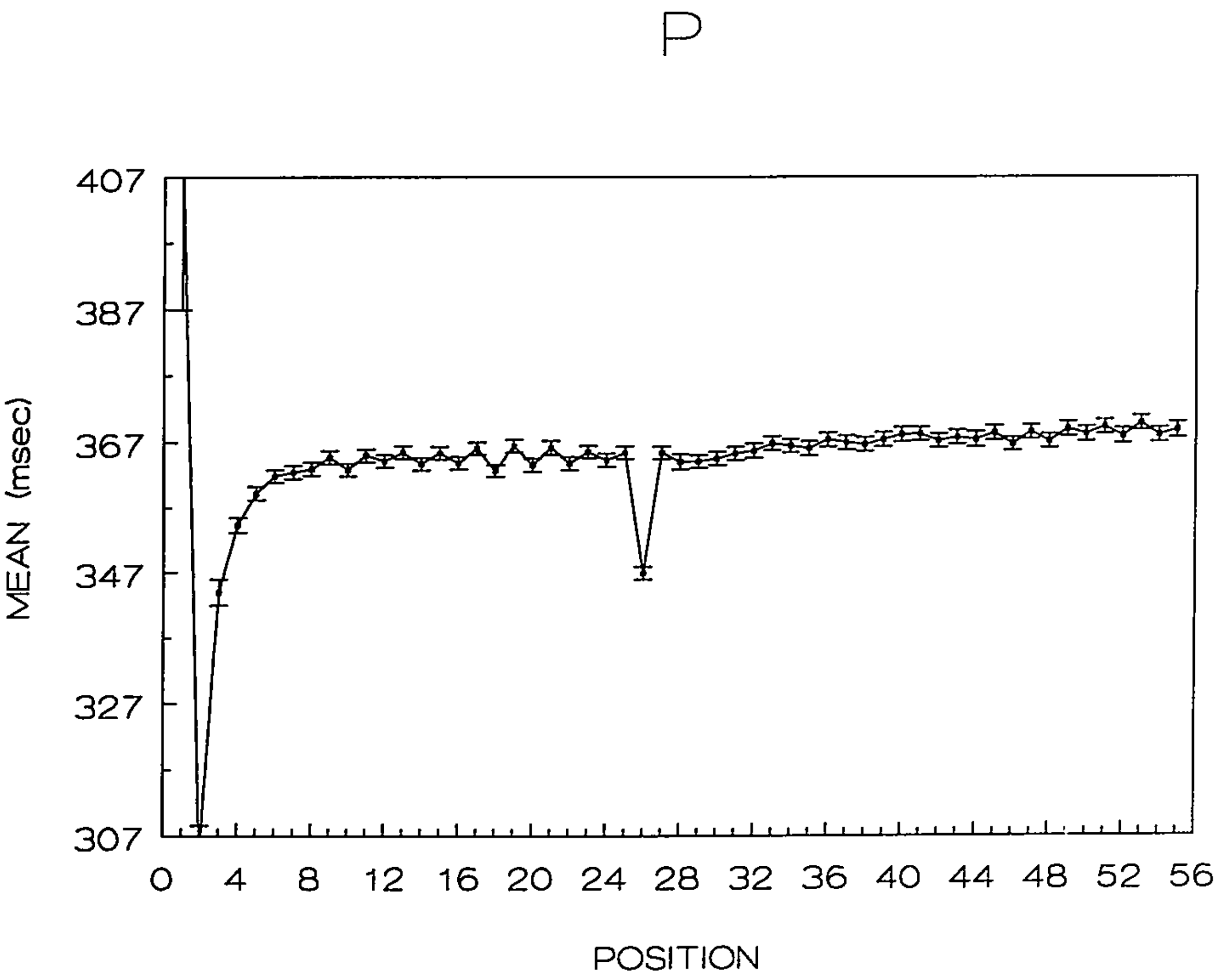

M
MEAN (msec)
1568
1548
1528
1508
1488
1468
1448
1428
1408
1388
1368
0
2
4
6
8
10
12
14
16
18
20
22
24
26
POSITION

N



MEAN (msec)
215
205
195
185
175
165
155
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
POSITION


O
MEAN (msec)
273
253
233
213
193
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
POSITION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407
387
367
347
327
307
MEAN (msec)
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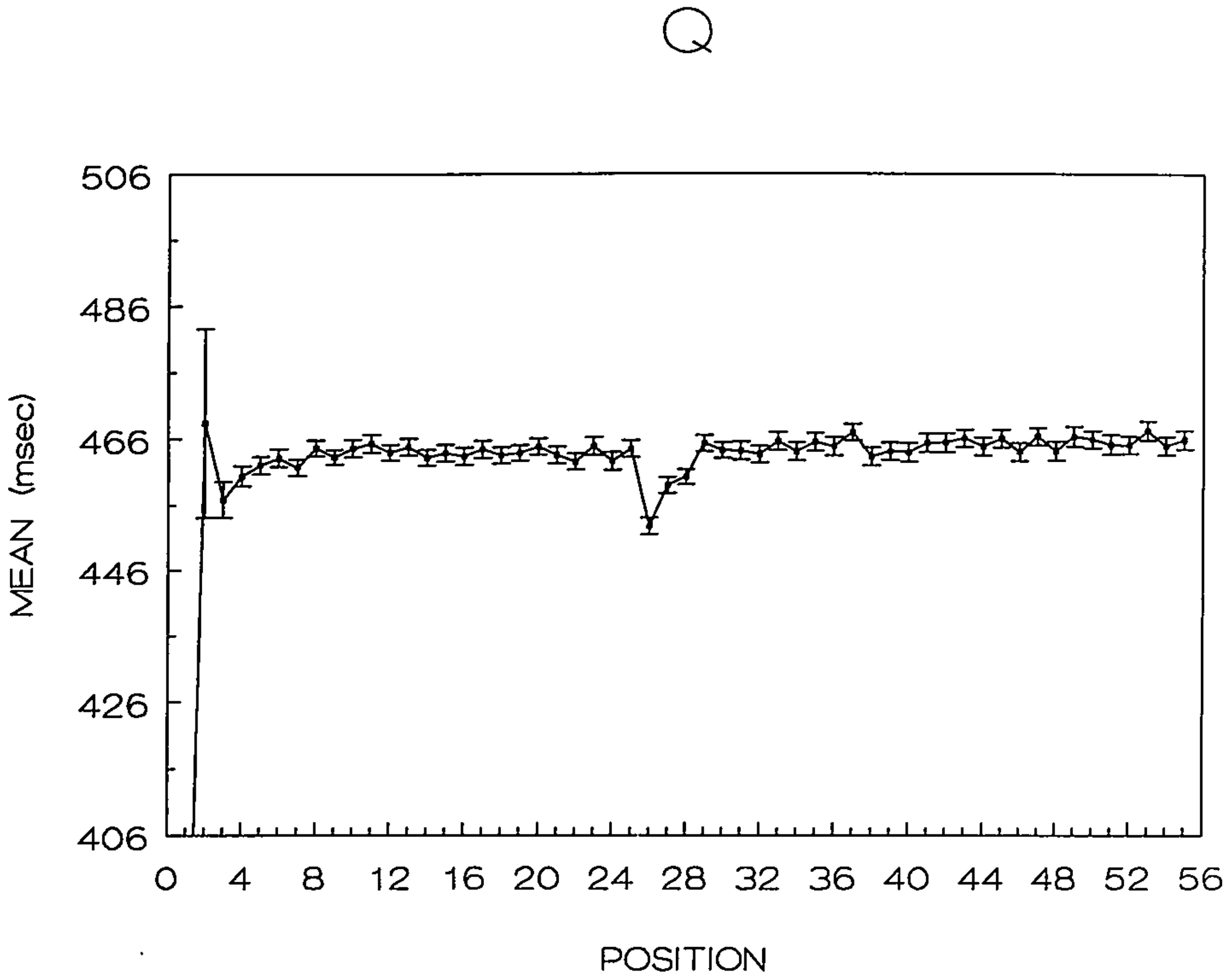
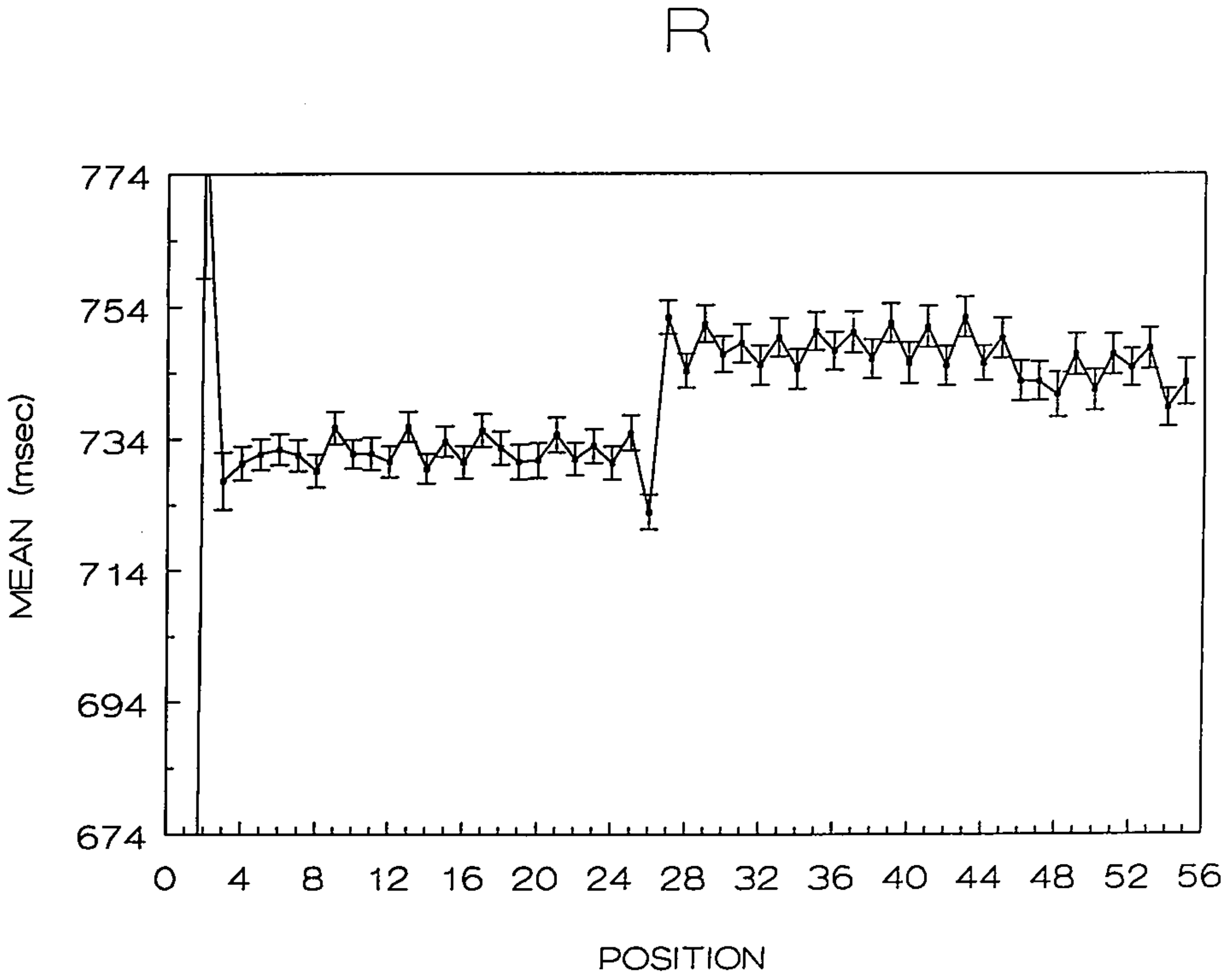
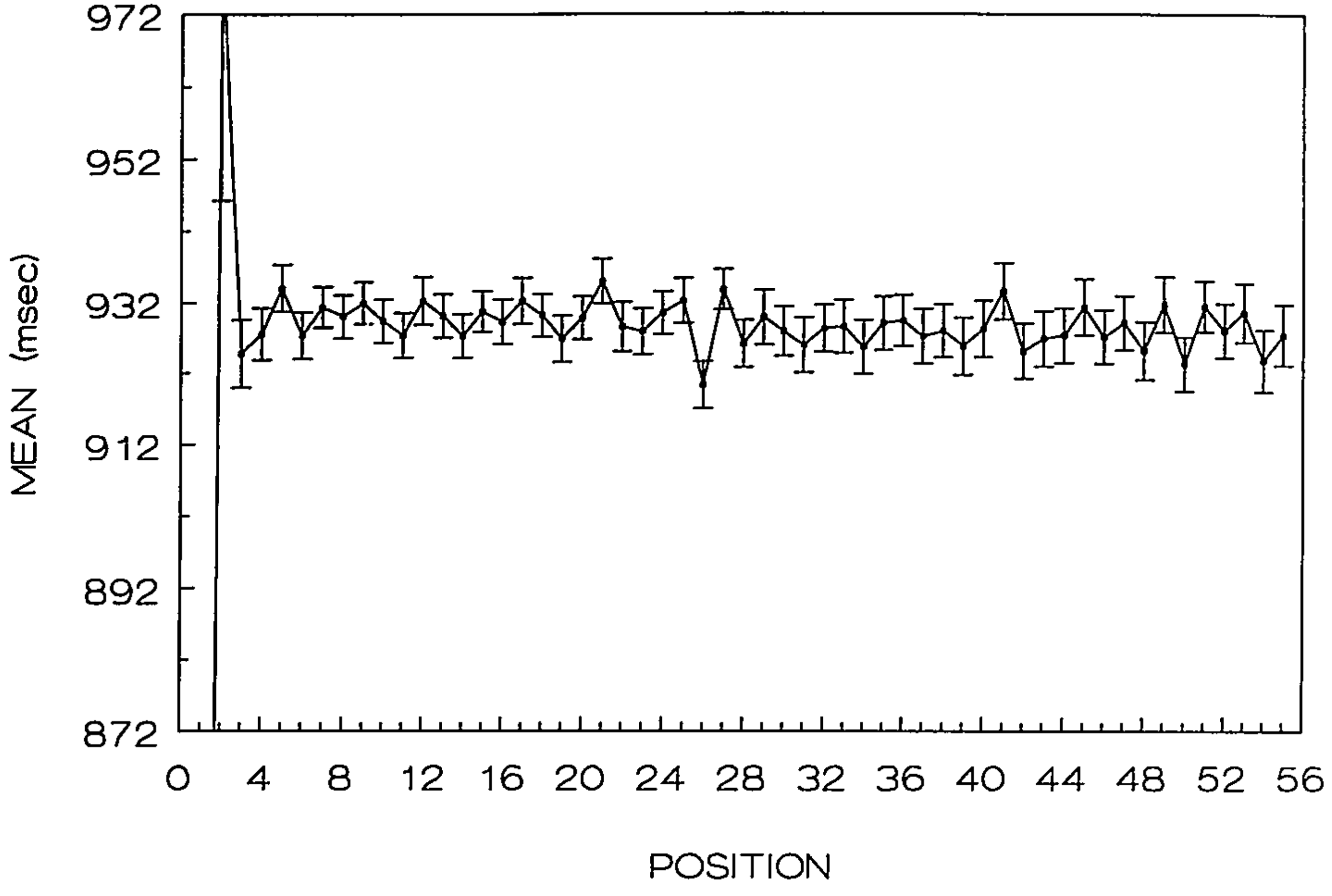
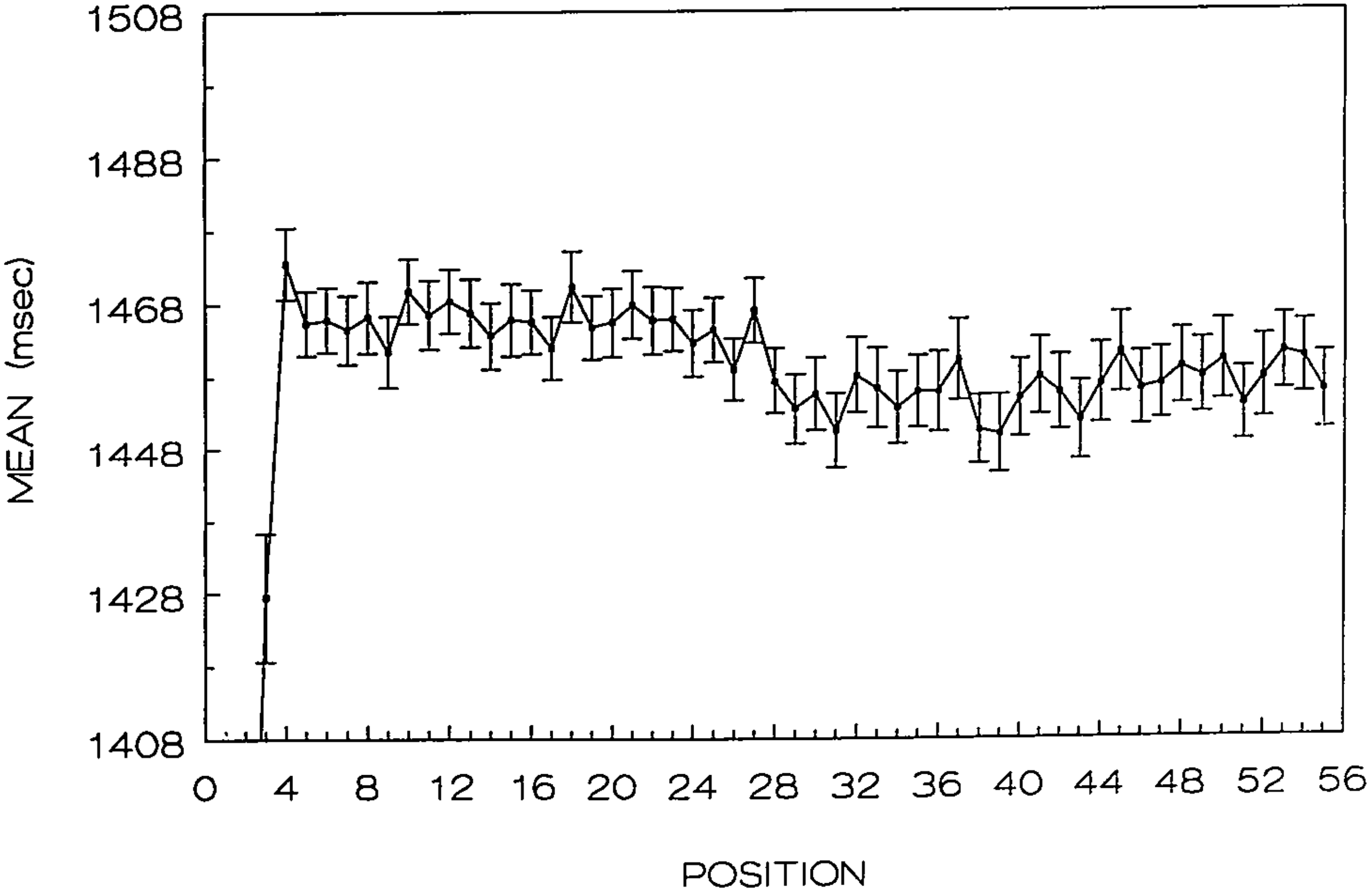
4
8
12
16
20
24
28
32
36
40
44
48
52
56
POSITION


Q
MEAN (msec)
506
486
466
446
426
406
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
POSITION


R
MEAN (msec)
774
754
734
714
694
674
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
POSITION

S


MEAN (msec)
972
952
932
912
892
872
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
POSITION


T

1508
1488
1468
1448
1428
1408
MEAN (msec)
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
POSITION

of the CP. The first few IRIs following the last pulse in the SP often deviate abruptly from all other SP and CP IRIs.

The transitional IRI differs quantitatively as well as qualitatively from all other CP and SP IRIs. Its uniqueness is a result of its onset being made in an attempt to synchronize to an external pulse (i.e., the last pulse of the pulse train) and its offset being made in the absence of an external pulse. No other CP response involves an attempt to synchronize to an external pulse and no other SP response is made in the absence of an external pulse. At the very least then, the uniqueness of this transitional IRI disqualifies it from membership as either an SP or CP IRI.

One might expect a deviation to occur in the transitional IRI if S knows for certain which pulse corresponds to the end of the pulse train. Knowing when the pulse train will end could lead to cognitive influences (e.g., expectations) that have effects on the timekeeping process and that manifest themselves by the observed deviations. This cognitive hypothesis is plausible because the number of pulses in a pulse train is small and constant for each S. Thus, counting the pulses during a sequence is possible.

A more appealing alternative to the cognitive hypothesis is one in which the process underlying the timing of SP IRIs is different from that in the CP. According to this hypothesis a switch from the SP process to the CP process occurs during the transitional IRI. That switch causes the transitional IRI to differ from the others presumably because the switching process consumes some time.

The response that defines the end of the transitional IRI also defines the beginning of the first genuine CP IRI - that is, an IRI whose defining responses are made without reference to and in the absence of any external pulses. This first CP IRI also deviates quantitatively from subsequent CP IRIs in the sequence. Thus it appears that whatever it is that takes place between the SP and the CP it takes at least until the end of the first genuine CP IRI to complete. Because these two IRIs may not accurately reflect the functioning of the motor processor they will not be considered in attempts to model the motor process. All analyses and modeling of CP IRI will be based on the last eight IRIs in the CP of each sequence for AK and LL. For similar reasons the last 25 IRIs will be considered in analyses of GF's CP data.

Eliminating those two IRIs from consideration reduces the number of sequences that contain significant monotone trends. However eliminating them might not remove all potential sources of non-stationarity. It is conceivable that a gradual monotonic trend might be an inherent characteristic of CP IRIs independent of the transition process. The analysis that follows is intended to test for this more gradual and, in the present context, more important form of non-stationarity.

To test for increasing or decreasing monotone trends in CP IRI sequences (i.e., non-stationarities), the Mann statistic (Gibbons, 1985; this statistic was described in Chapter 2) is computed for each sequence of the last five sessions at each T. The proportion of sequences that reach statistical significance is compared to the proportion that is expected to reach statistical significance ($p = .05$) under the null hypothesis that a monotonic trend does not exist (i.e., the sequences are stationary). The results, which are presented in Table 3.2, show that, on average, only 3% of the sequences tested contain significant trends. This is a reassuring figure because it is in line with what might be expected to occur by chance and as such it supports the use of the TPM as an analytical tool.

In a previous assessment of non-stationarity, Wing (1973) compared the mean of the first half of the IRIs to the mean of the second half and found that the differences between the means were statistically significant in approximately 50% of the cases examined. From these results he concluded that there were significant trends in the CP IRI sequences. But because the change in the mean rate of responding was only about

1% of T, Wing (1973) decided that the sequences were adequately stationary for his purposes.

The results of the present study parallel those reported by Wing (1973). The differences between the means of the first and second halves of the CP, which are shown in Table 3.3, are statistically significant more often than reported by Wing (1973) (two standard errors about the mean difference does not include zero in 80% of the cases). But because the magnitude of the differences are a very small proportion of m_I (they are of the order of 1% of m_I or less) the response sequences are considered to be stationary.

Taken together, the two analyses presented above indicate that CP IRI sequences are adequately stationary for present purposes (especially when the average difference over subjects is considered - that difference is only -2.17 msec). The proportion of sequences for which non-stationarities exist is at, or slightly below, the level expected to occur by chance and the difference between the mean of the first half and the mean of the second half of the CP IRIs is always a very small proportion of m_I. These analyses indicate that while minute trends characterize the data, detrending is not necessary because the magnitude of the trends are so small.

INTERRESPONSE INTERVAL DISTRIBUTIONS

The distribution of CP IRIs made within the last five sessions at each T can be described as being unimodal and symmetric with midpoints located very close to T. Relative frequency IRI distributions for each S are shown in Fig. 3.3 in the form of relative frequency polygons. These distributions are similar to those reported by Michon (1967) for T in the same range. However Michon's (1967) distributions for T equal to 1667 and 3333 msec, and on some occassions 1000 msec, showed "pronounced multiple peaks" (p. 37). Michon interpreted the multimodal shape of his frequency histograms to suggest the operation of a psychological moment similar in nature to the one suggested by Stroud (1955). Adjacent peaks in his distributions were separated by about 100 msec,

TABLE 3.2

Proportion of Continuation Phase sequences with significant ($p \leq .05$) monotonic trends in interresponse intervals. Significance based on Mann's test for trend.

T (msec)	AK	LL	GF
175		.012	.029
233	.000	.048	.022
367	.032	.028	.018
466	.004	.020	.022
734	.040	.040	.031
932	.056	.032	.023
1468	.068	.040	.040
Mean	.033	.031	.026

TABLE 3.3

The average differences between the means of the first and second halves of the continuation phase sequences over the last five sessions.

T (msec)	AK	LL	GF
175		*1.40	*-0.47
233	*2.83	*2.49	*-0.83
367	*1.97	*-0.93	*-1.21
466	1.64	*-2.91	-0.56
734	*-3.10	*-4.07	*3.95
932	-2.23	*-7.11	-0.02
1468	*-8.57	*-17.30	*-3.11
Mean overall change	-1.24	-4.97	-0.29

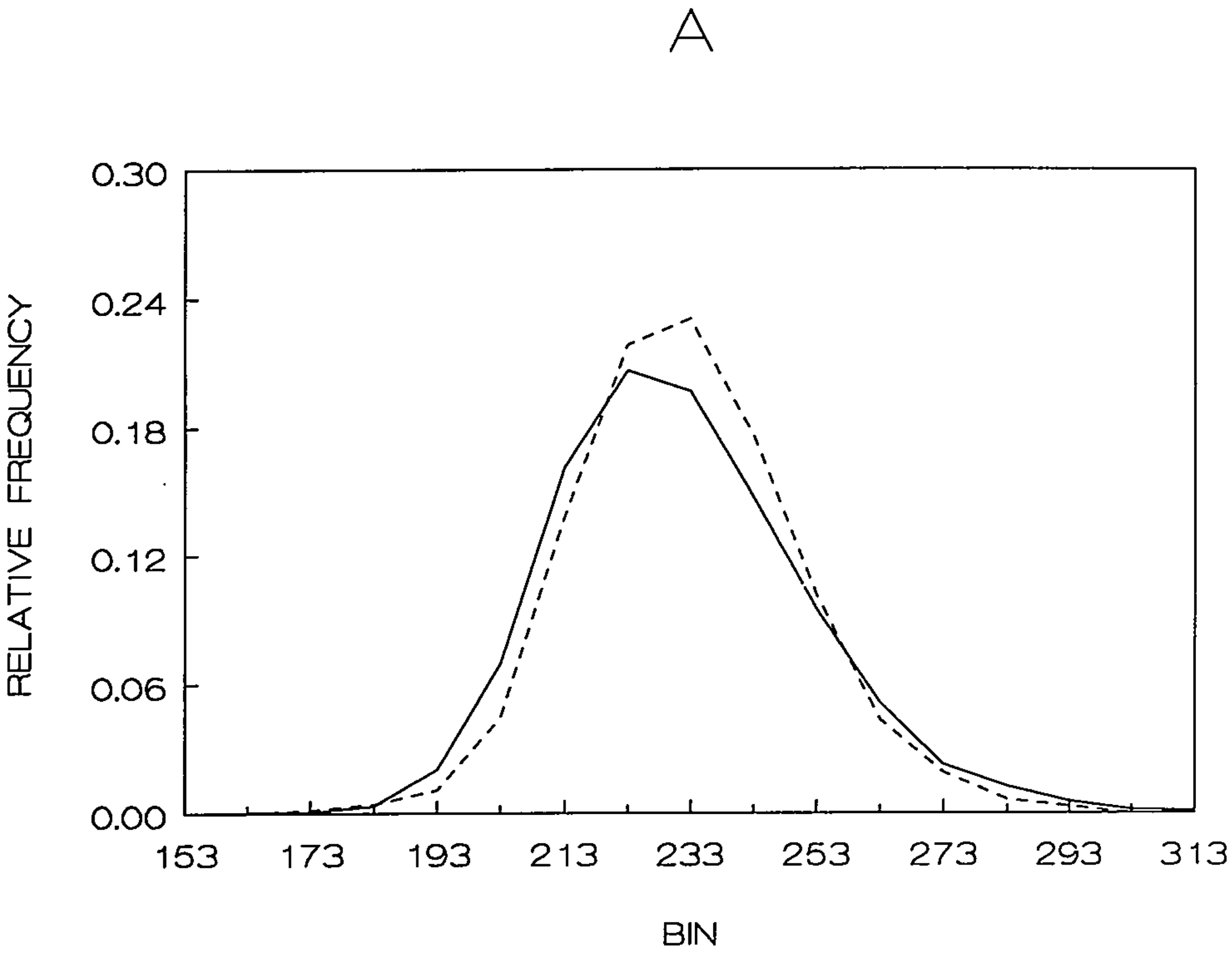
---

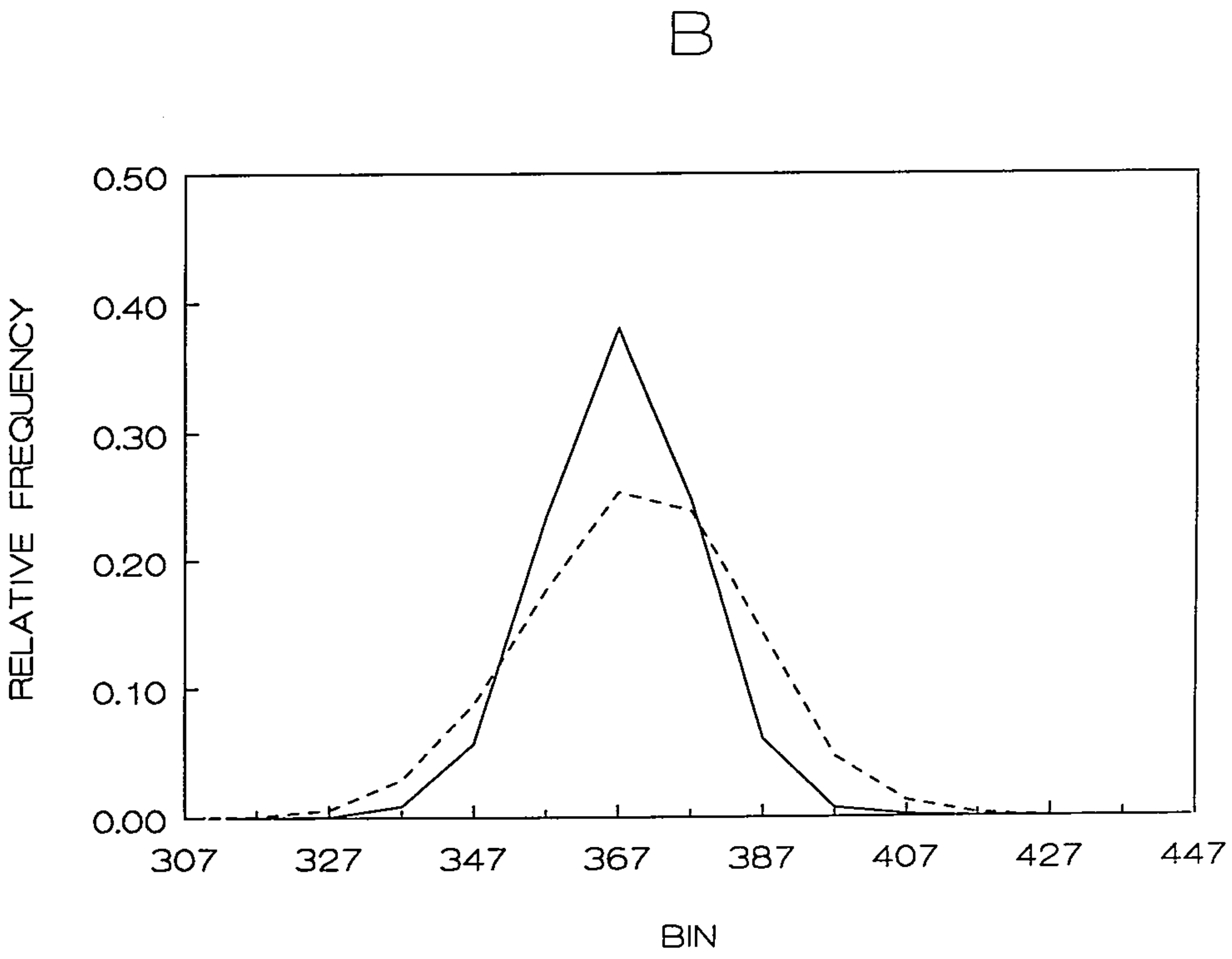
* 2 s.e. about the mean difference does not contain zero

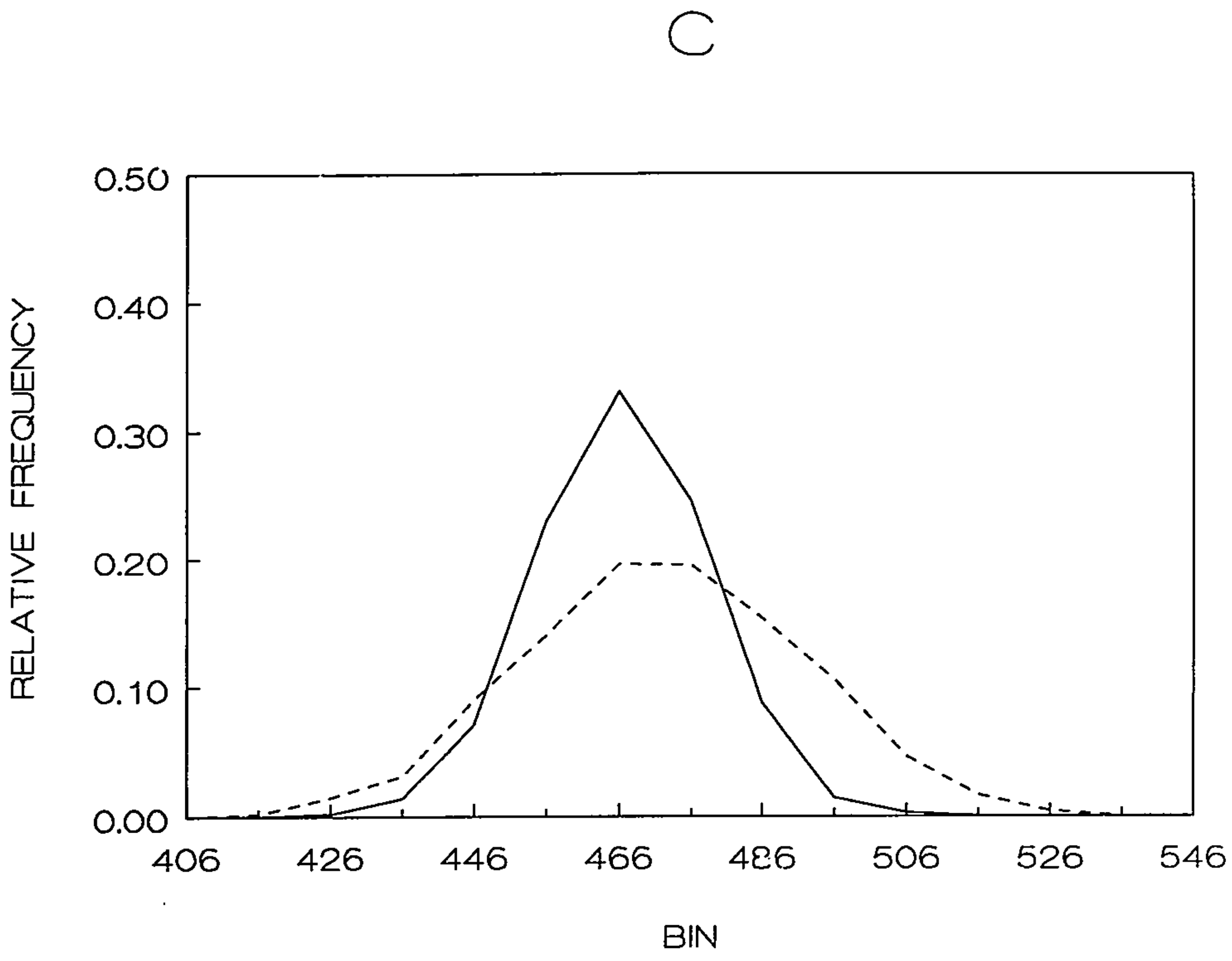
FIGURE 3.3

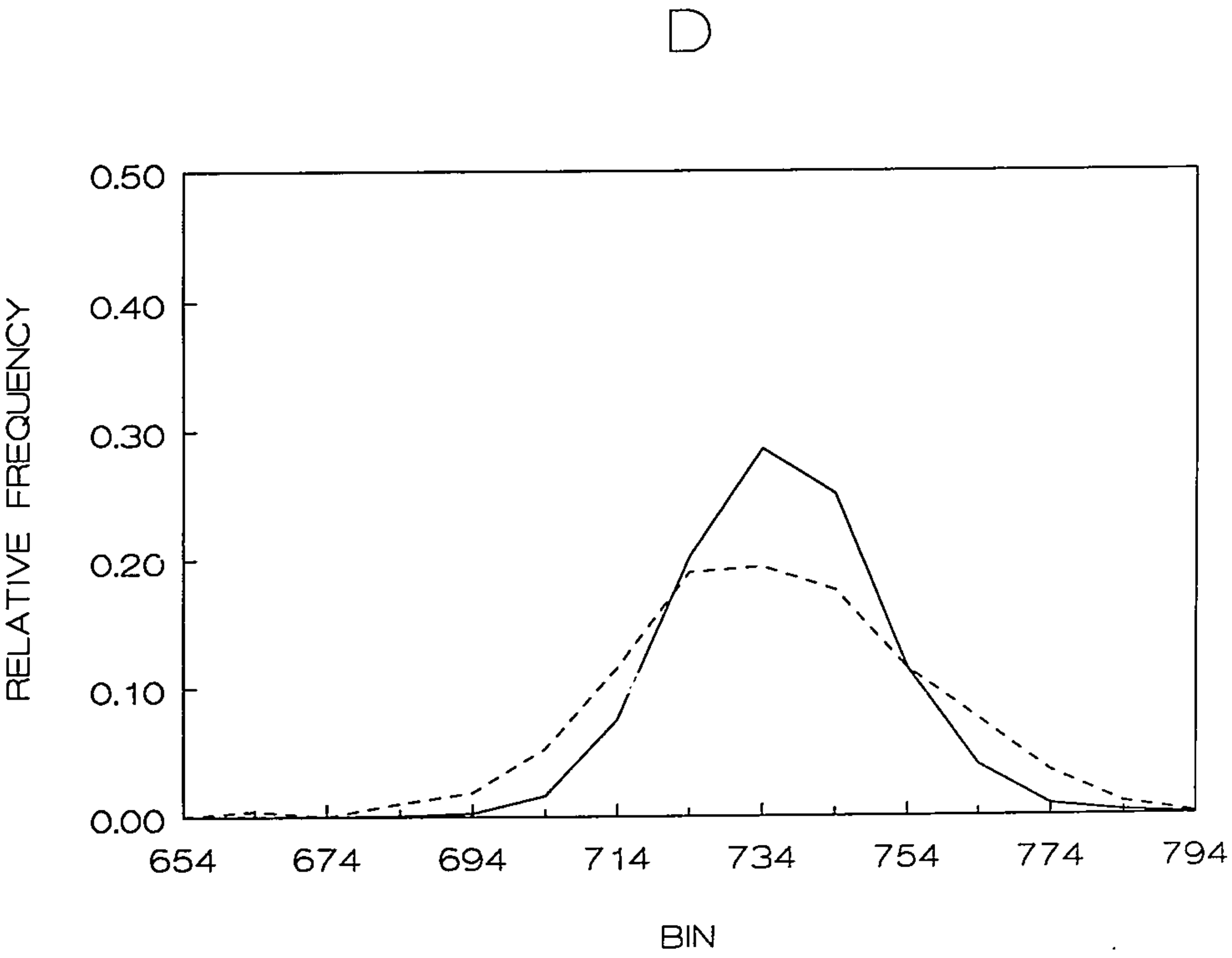
SP (solid line) and CP (dashed line) IRI relative frequency polygons for all IRIs in the last five sessions.

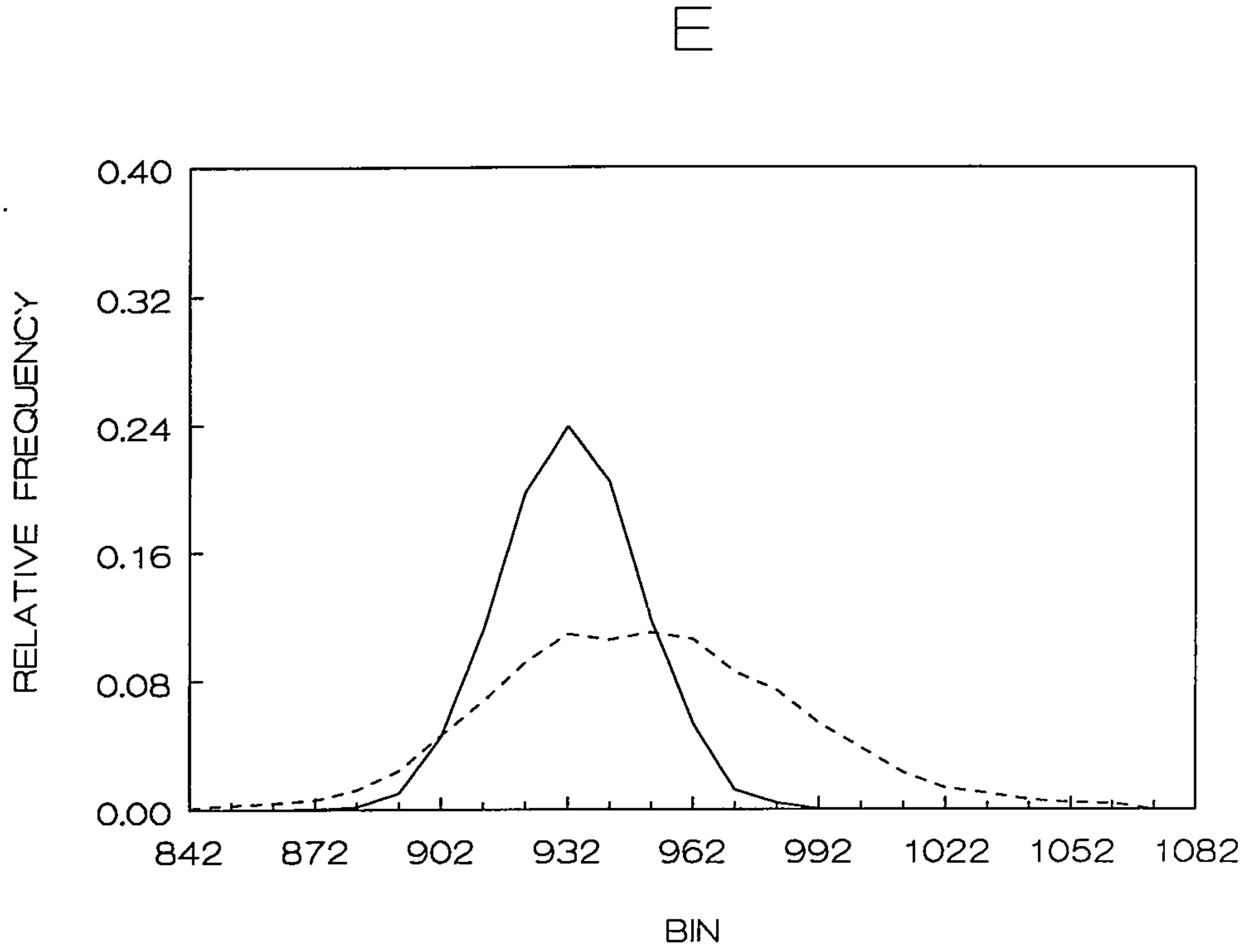
PANEL	SUBJECT	T (msec)
A	AK	233
B	AK	367
C	AK	466
D	AK	734
E	AK	932
F	AK	1468
G	LL	175
H	LL	233
I	LL	367
J	LL	466
K	LL	734
L	LL	932
M	LL	1468
N	GF	175
O	GF	233
P	GF	367
Q	GF	466
R	GF	734
S	GF	932
T	GF	1468

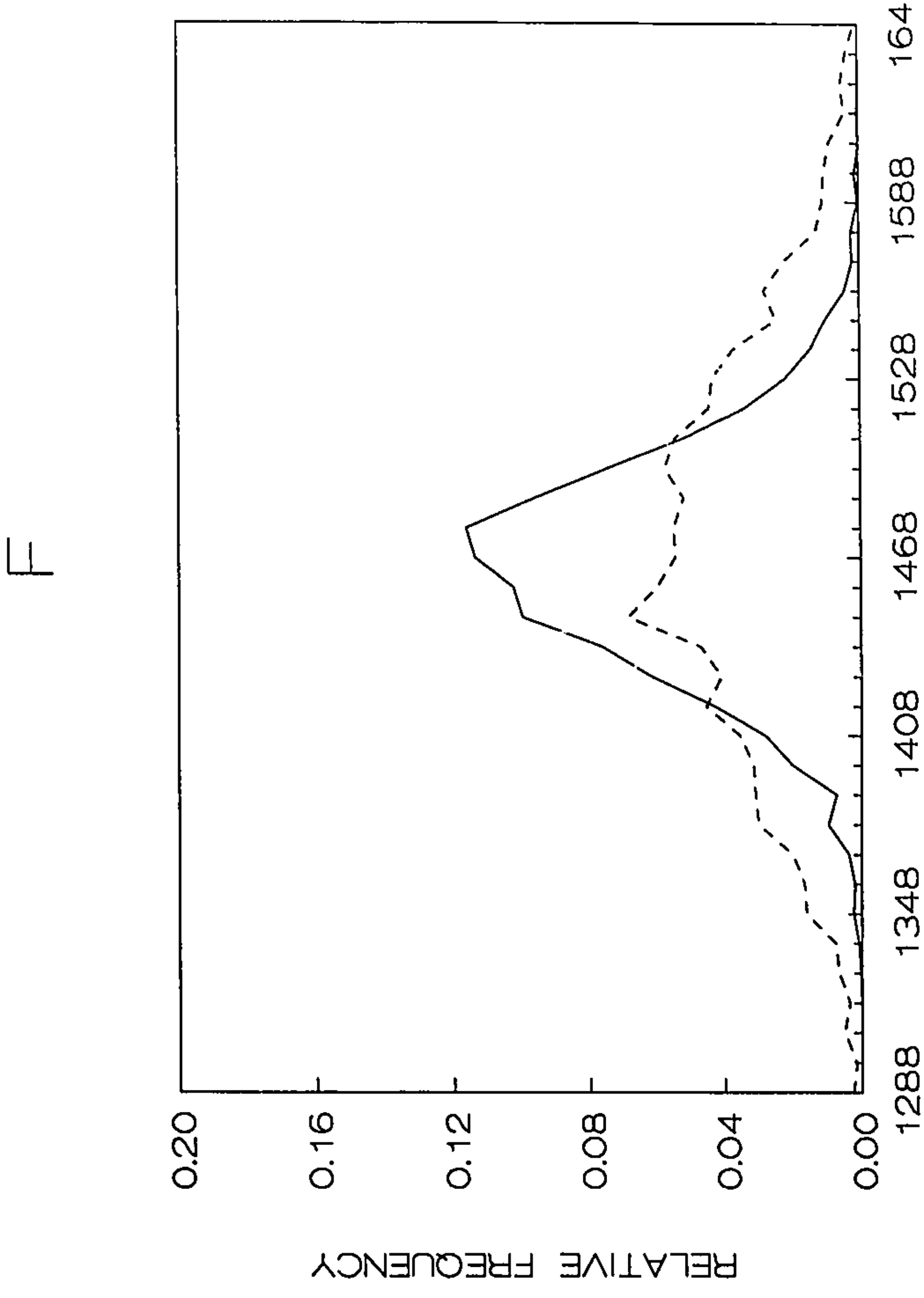

A
0.30
0.24
0.18
0.12
0.06
0.00
RELATIVE FREQUENCY
153
173
193
213
233
253
273
293
313
BIN

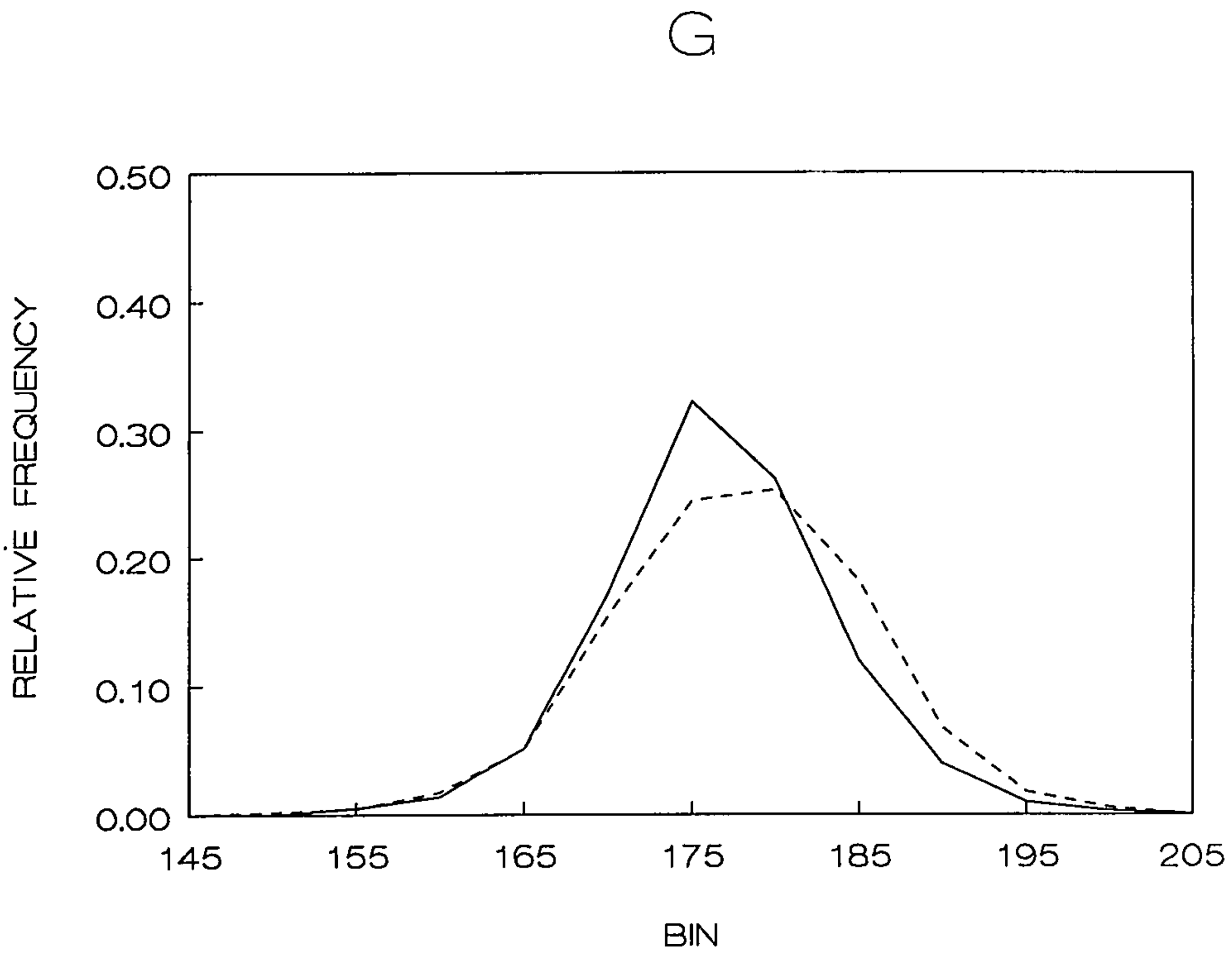

B
0.50
0.40
0.30
0.20
0.10
0.00
RELATIVE FREQUENCY
307
327
347
367
387
407
427
447
BIN

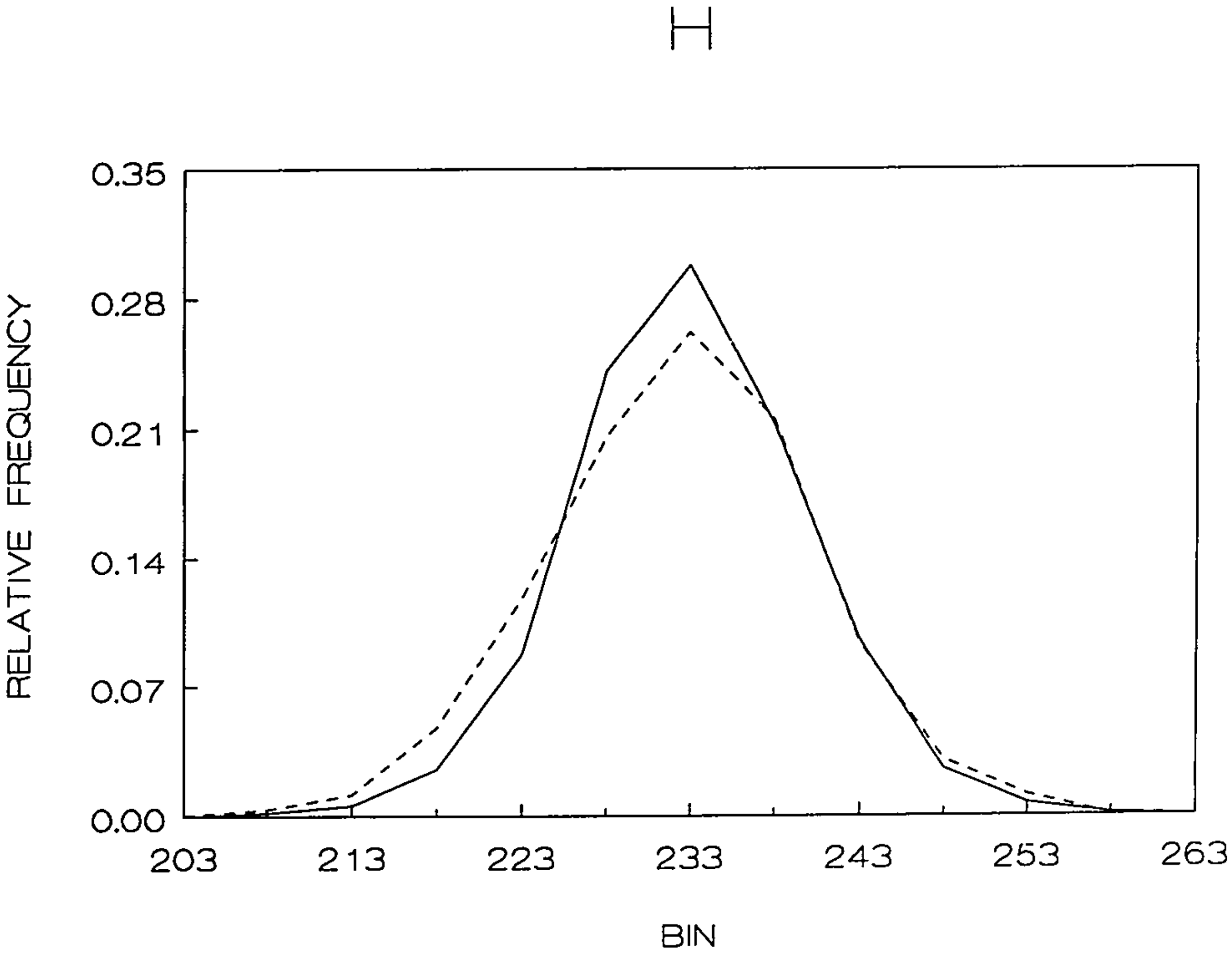

C
RELATIVE FREQUENCY
0.50
0.40
0.30
0.20
0.10
0.00
406
426
446
466
486
506
526
546
BIN

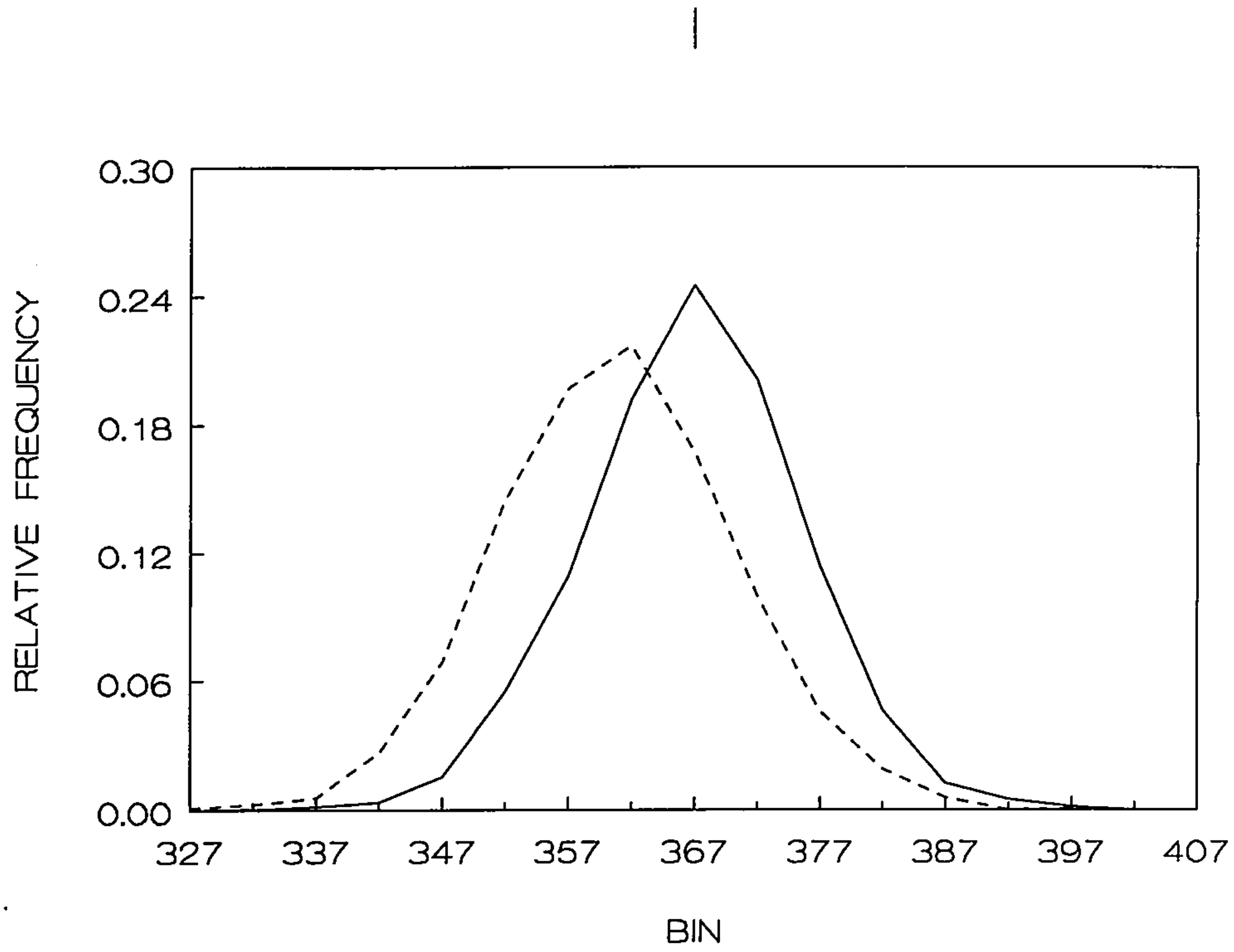

D
RELATIVE FREQUENCY
0.50
0.40
0.30
0.20
0.10
0.00
654
674
694
714
734
754
774
794
BIN

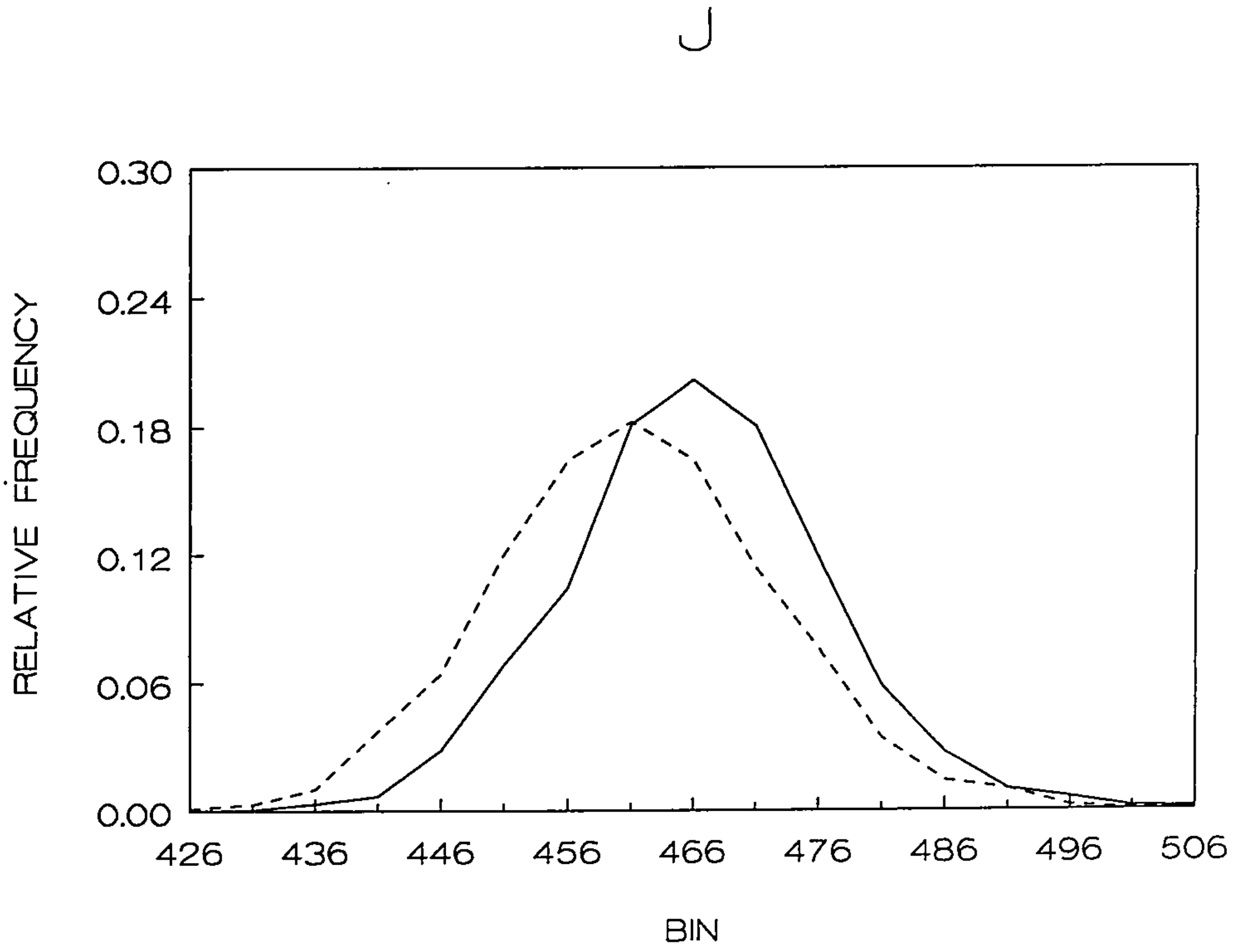

E
RELATIVE FREQUENCY
0.40
0.32
0.24
0.16
0.08
0.00
842
872
902
932
962
992
1022
1052
1082
BIN

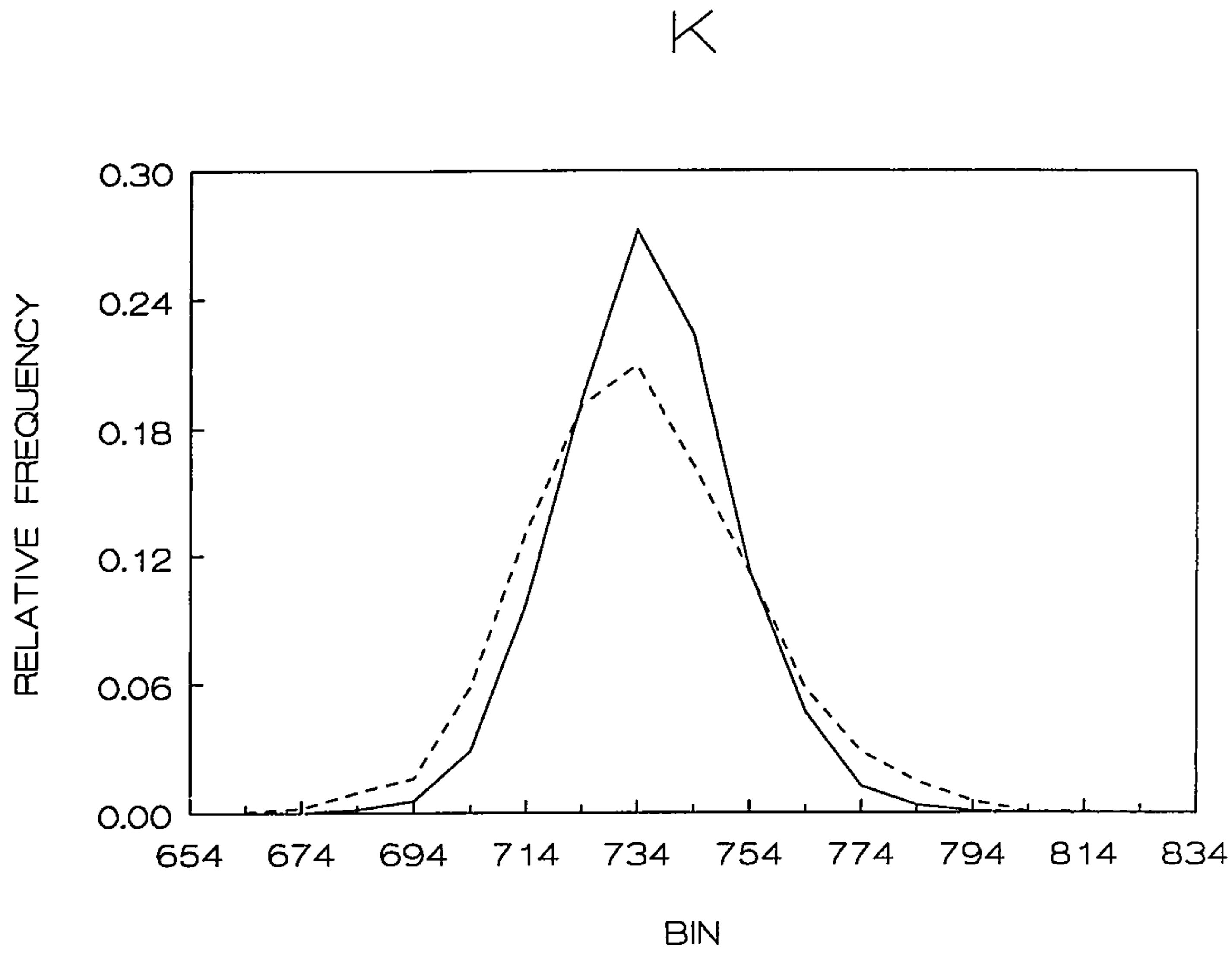

F
RELATIVE FREQUENCY
0.00
0.04
0.08
0.12
0.16
0.20
BIN
1288
1348
1408
1468
1528
1588
1648

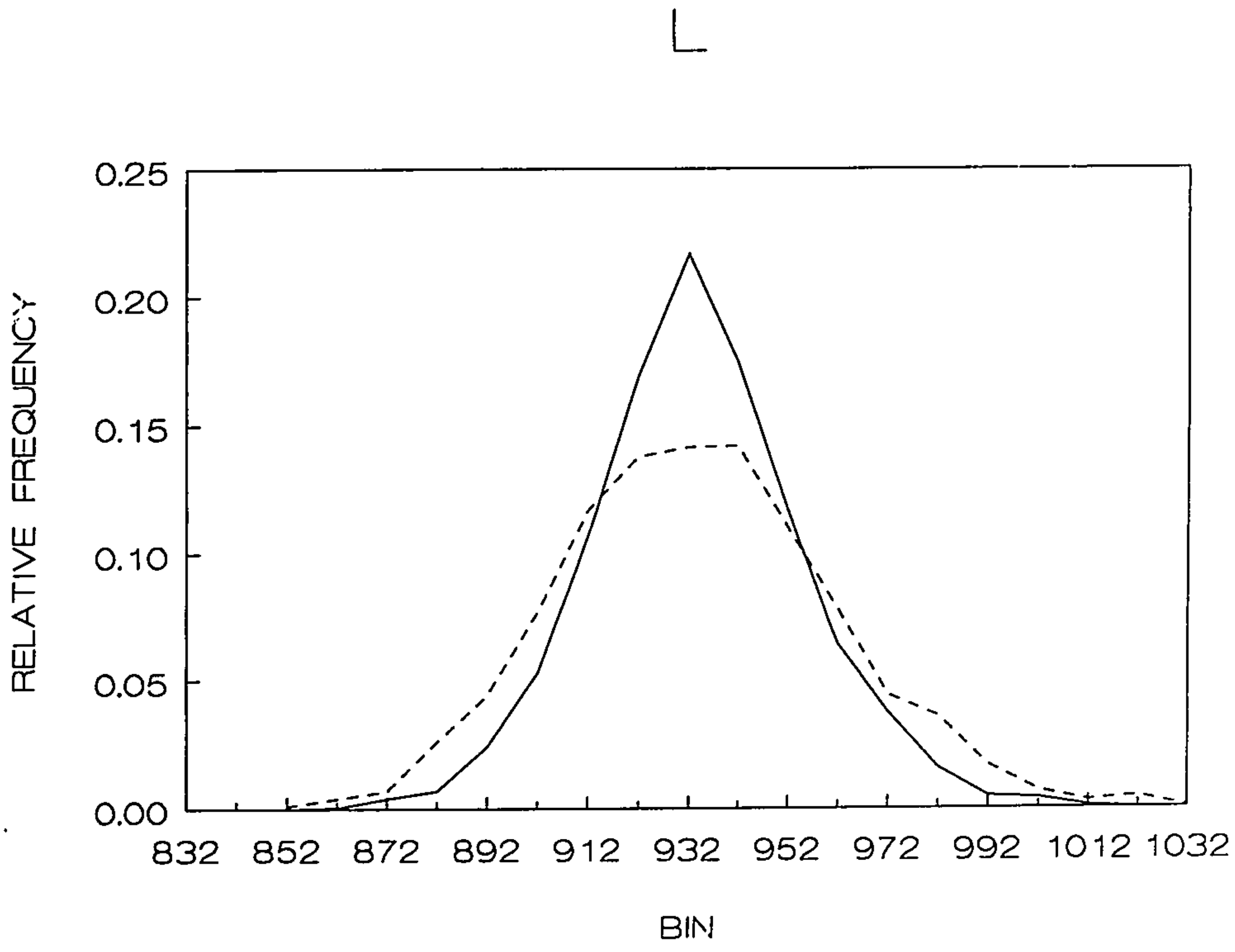

G
RELATIVE FREQUENCY
0.50
0.40
0.30
0.20
0.10
0.00
145
155
165
175
185
195
205
BIN

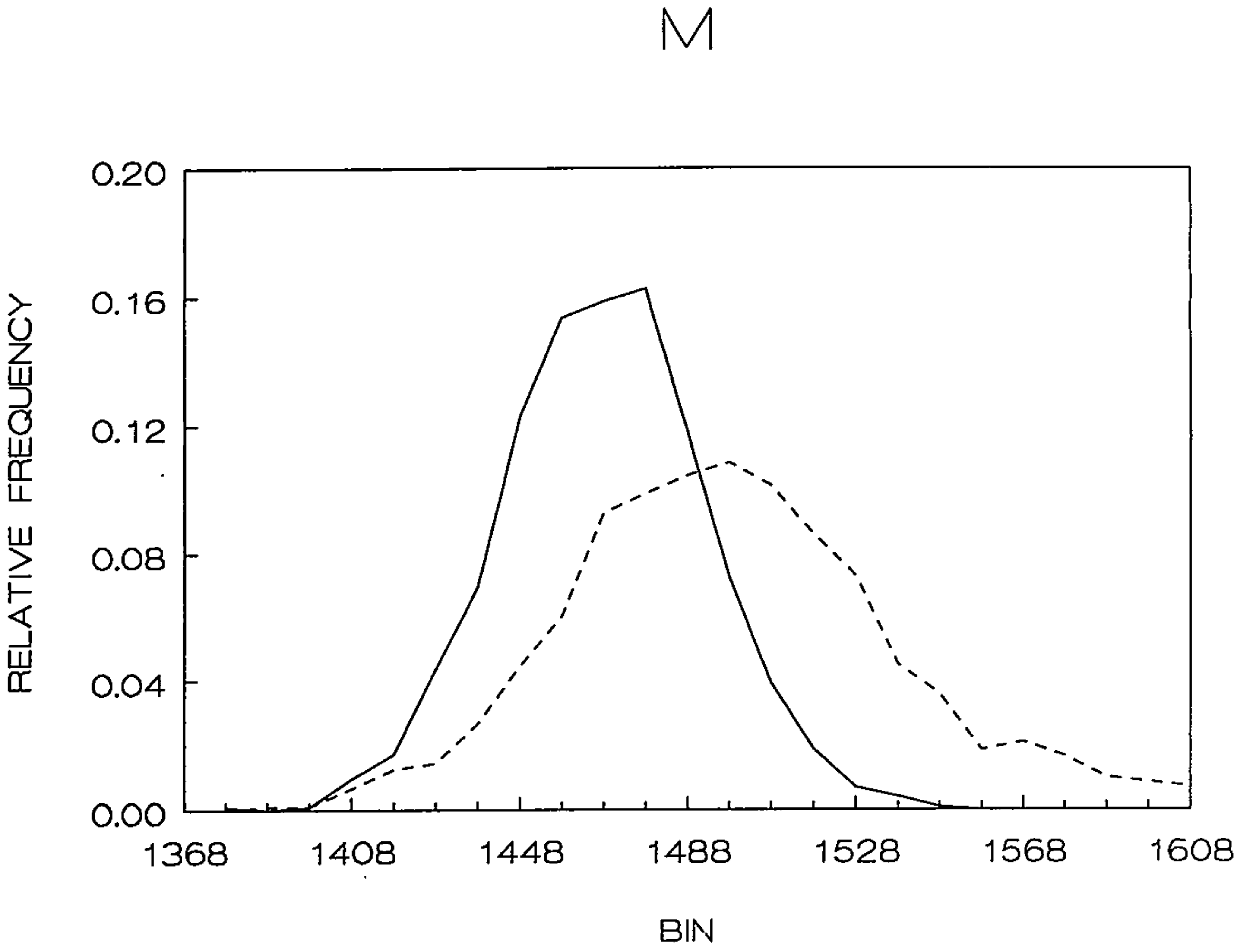

H
RELATIVE FREQUENCY
0.35
0.28
0.21
0.14
0.07
0.00
203
213
223
233
243
253
263
BIN

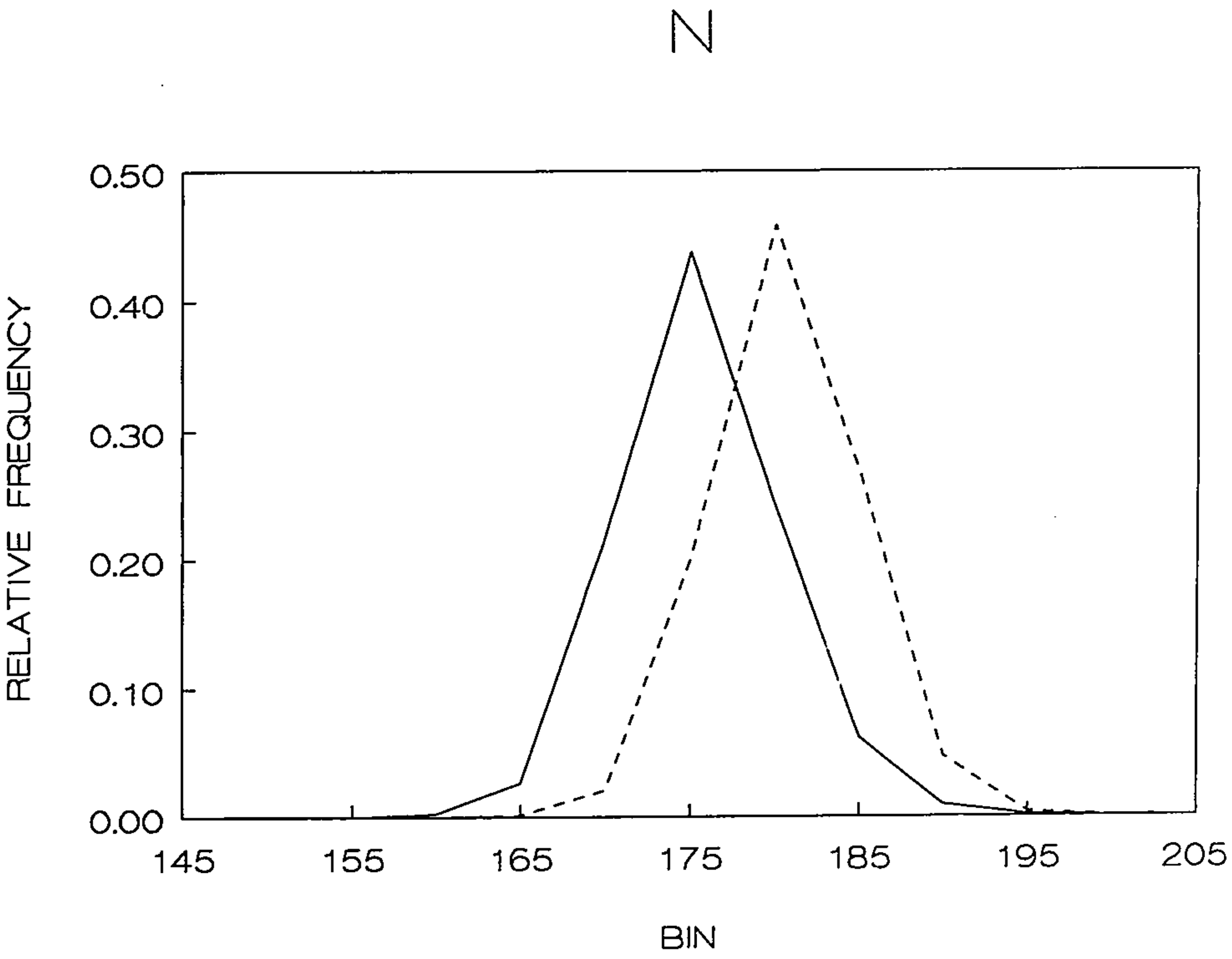

0.30
0.24
0.18
0.12
0.06
0.00
RELATIVE FREQUENCY
327
337
347
357
367
377
387
397
407
BIN

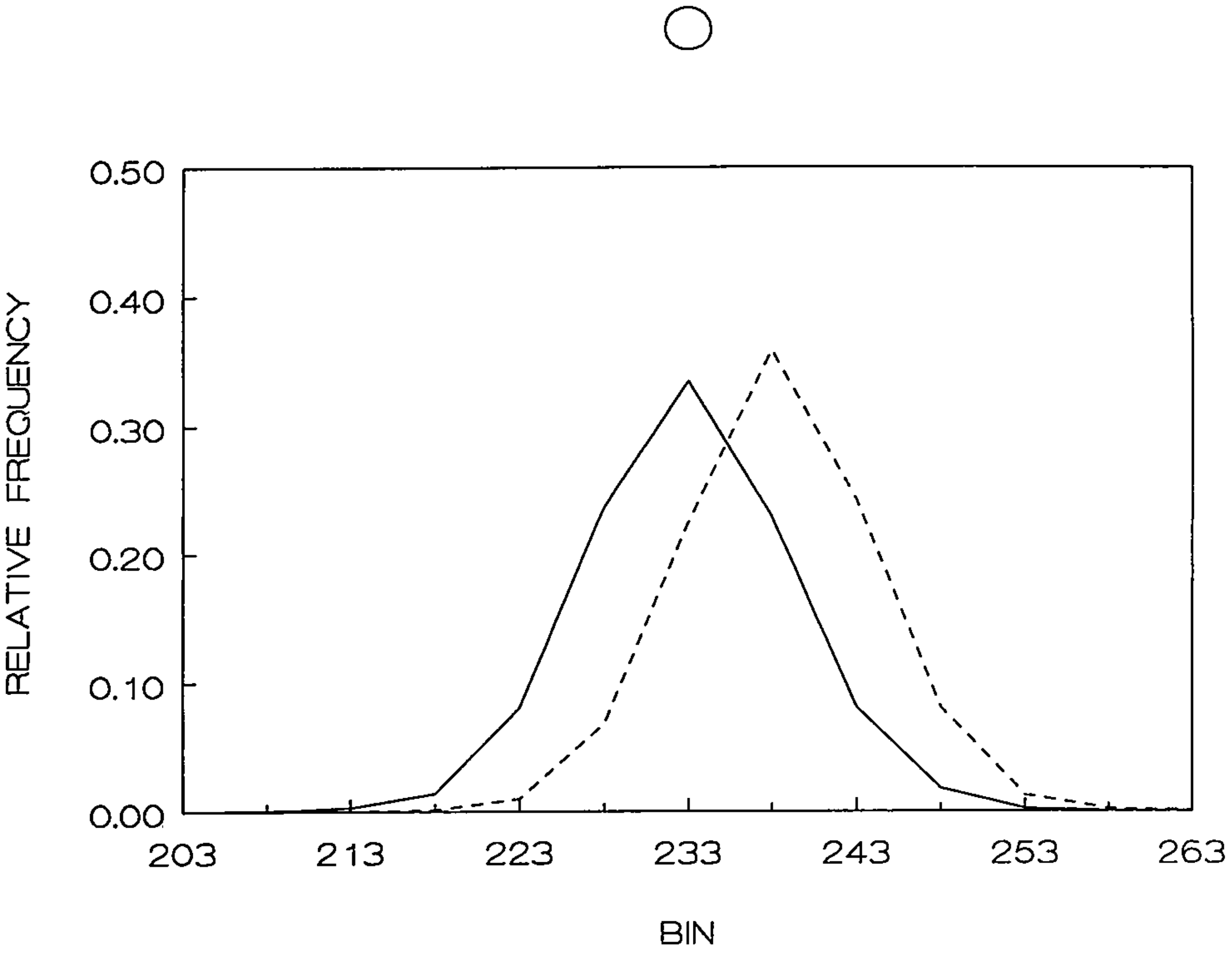

J
RELATIVE FREQUENCY
0.30
0.24
0.18
0.12
0.06
0.00
426
436
446
456
466
476
486
496
506
BIN

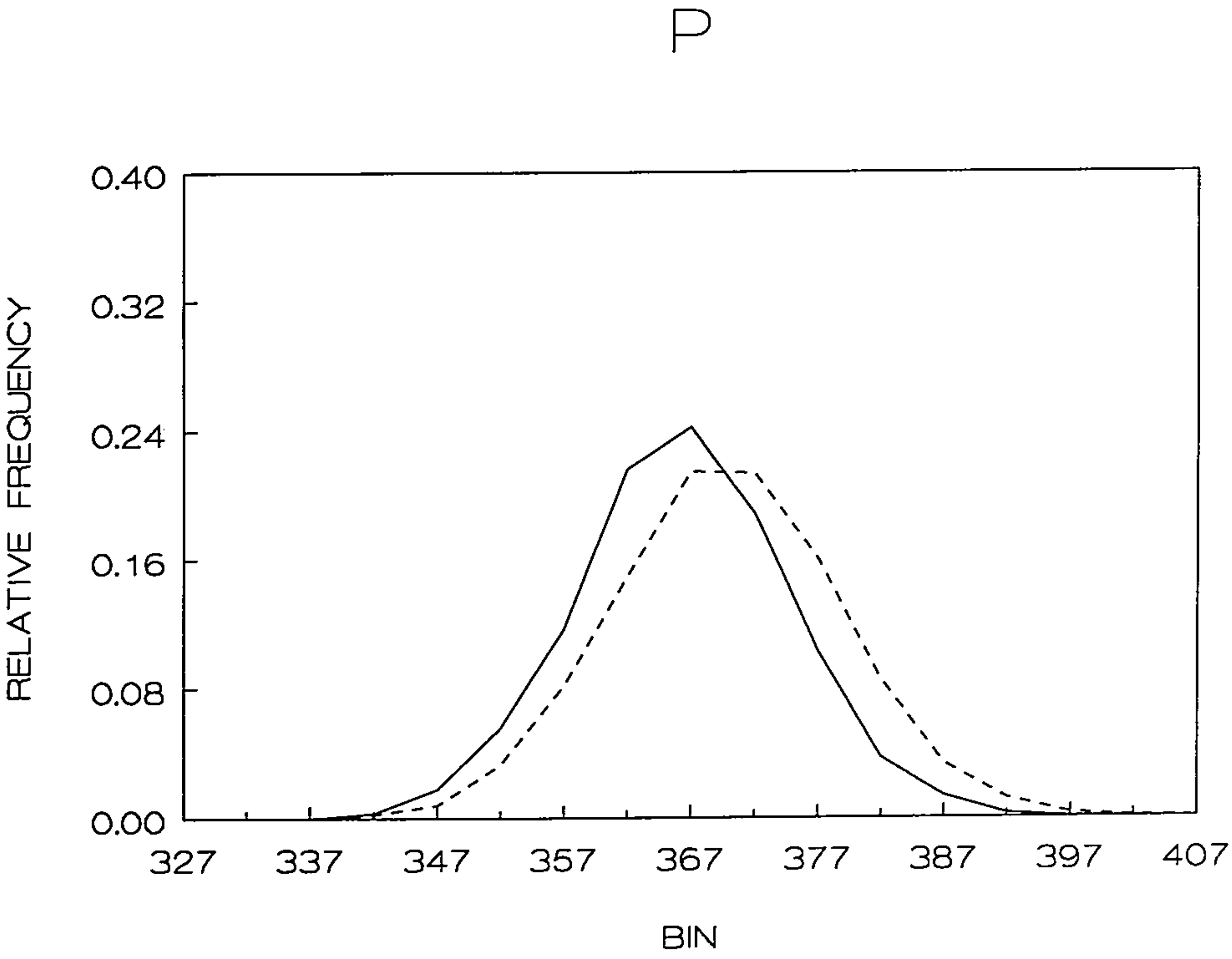

K
RELATIVE FREQUENCY
0.30
0.24
0.18
0.12
0.06
0.00
654
674
694
714
734
754
774
794
814
834
BIN

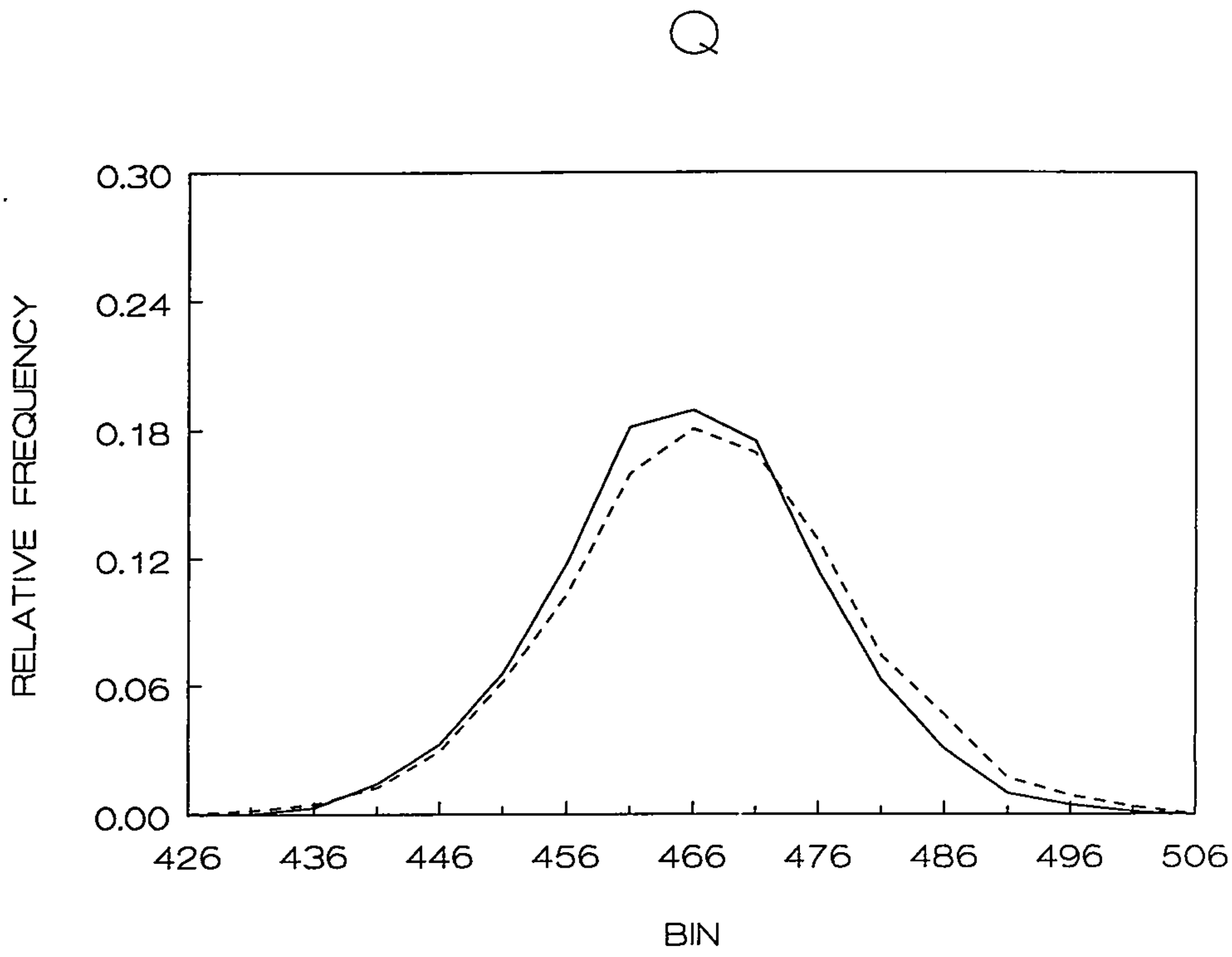

L
RELATIVE FREQUENCY
0.25
0.20
0.15
0.10
0.05
0.00
832
852
872
892
912
932
952
972
992
1012
1032
BIN

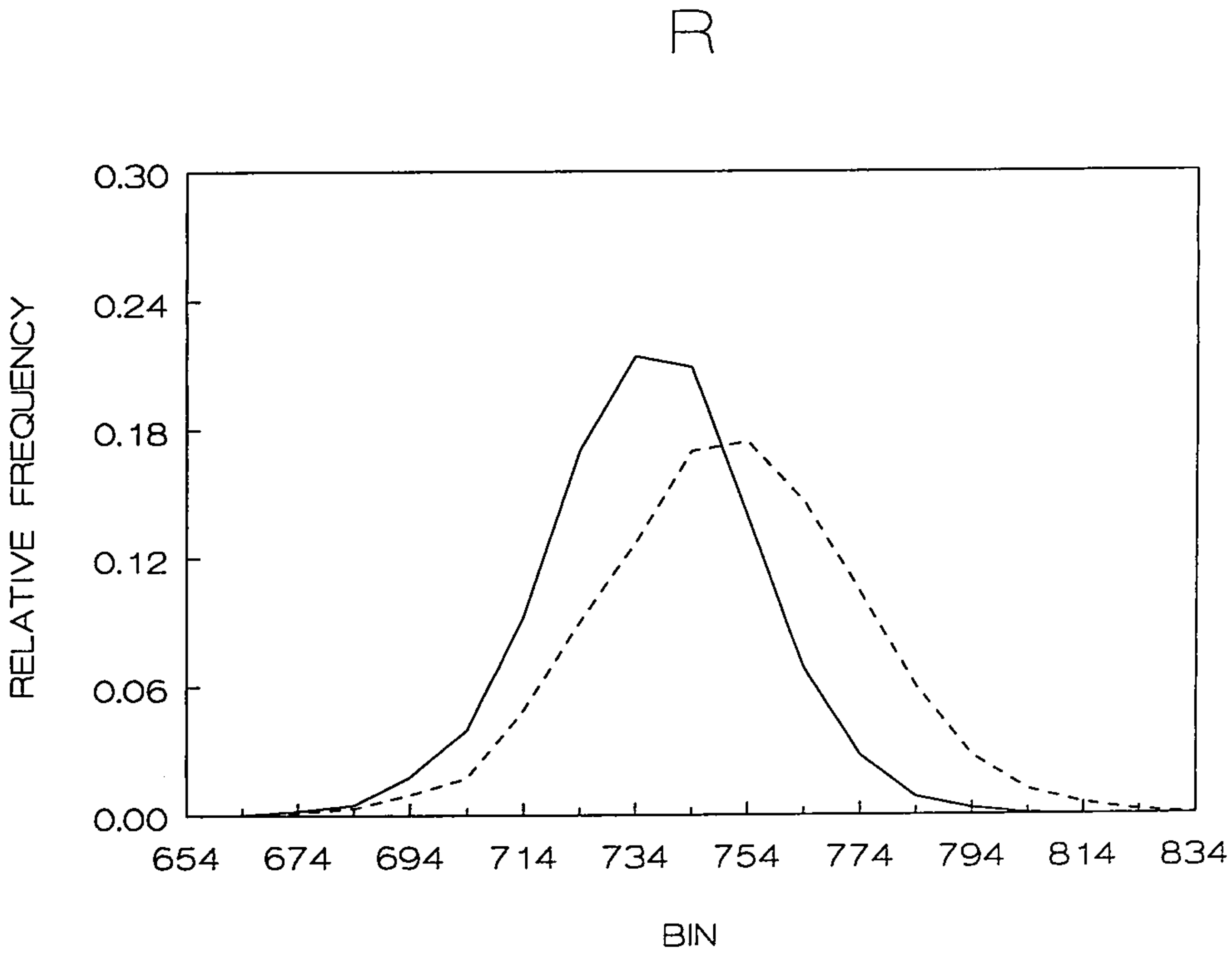

M
RELATIVE FREQUENCY
0.20
0.16
0.12
0.08
0.04
0.00
1368
1408
1448
1488
1528
1568
1608
BIN

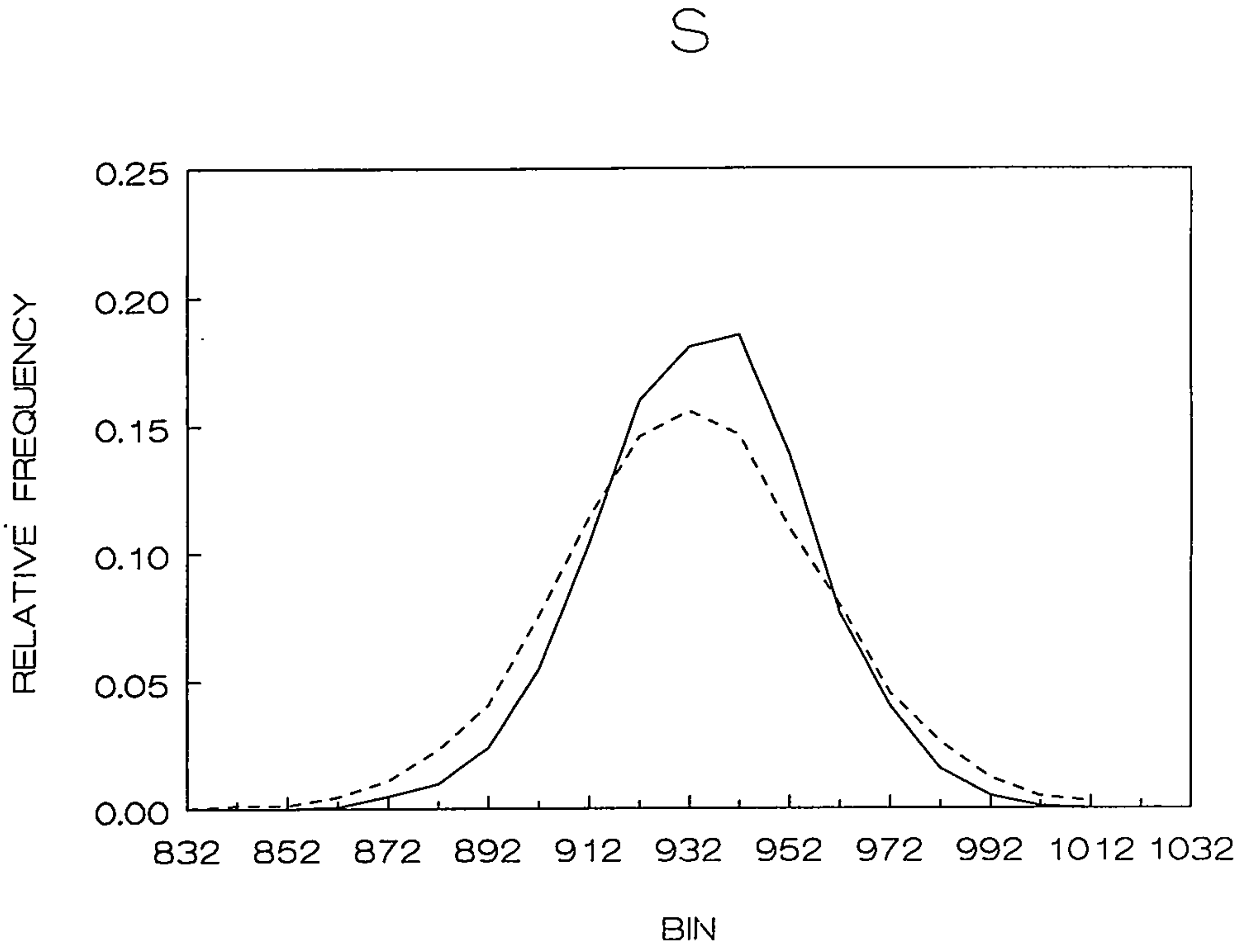

N
RELATIVE FREQUENCY
0.50
0.40
0.30
0.20
0.10
0.00
145
155
165
175
185
195
205
BIN

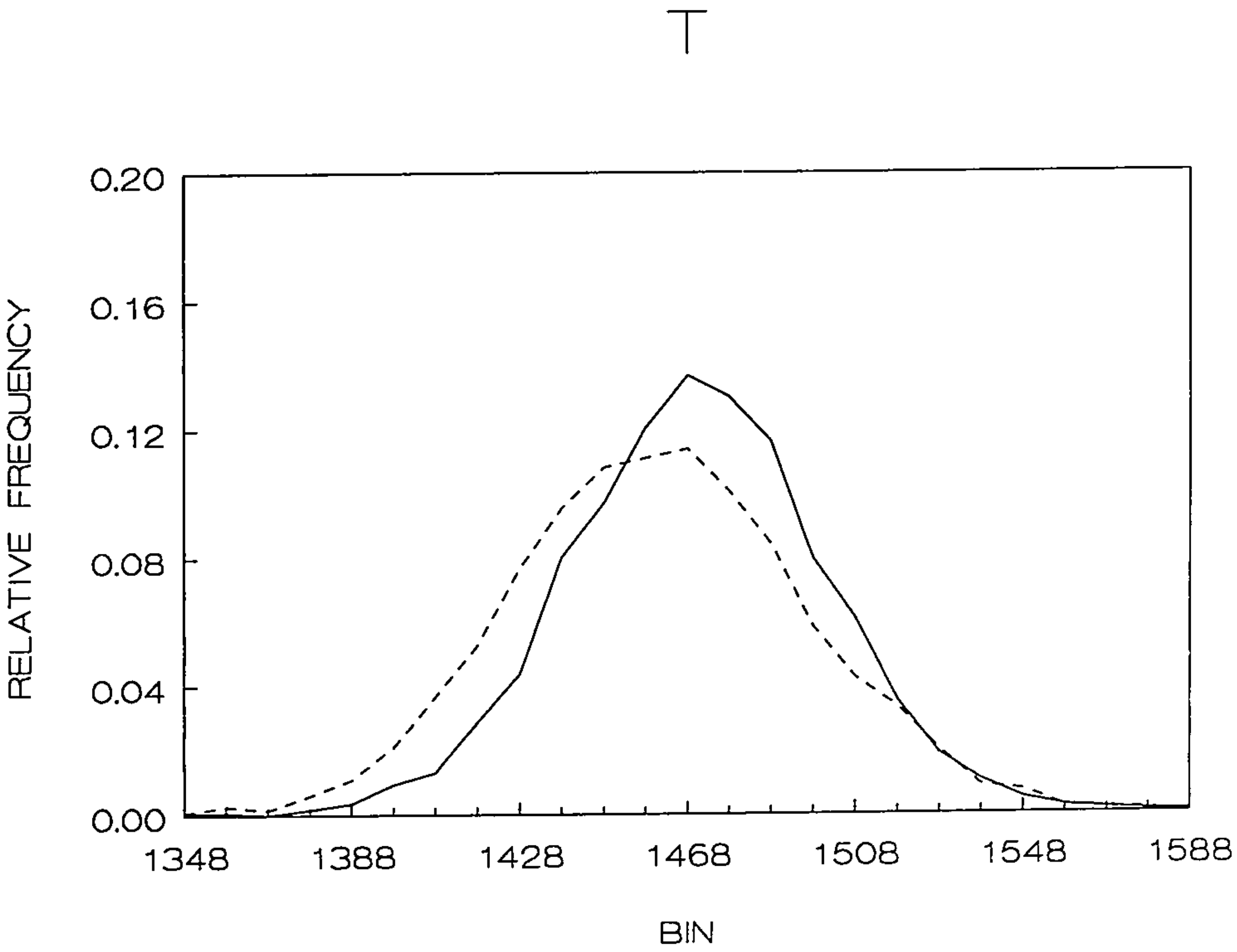

0.50
0.40
0.30
0.20
0.10
0.00
RELATIVE FREQUENCY
203
213
223
233
243
253
263
BIN


P
RELATIVE FREQUENCY
0.40
0.32
0.24
0.16
0.08
0.00
327
337
347
357
367
377
387
397
407
BIN


Q
RELATIVE FREQUENCY
0.30
0.24
0.18
0.12
0.06
0.00
426
436
446
456
466
476
486
496
506
BIN


R
RELATIVE FREQUENCY
0.30
0.24
0.18
0.12
0.06
0.00
654
674
694
714
734
754
774
794
814
834
BIN


S
RELATIVE FREQUENCY
0.25
0.20
0.15
0.10
0.05
0.00
832
852
872
892
912
932
952
972
992
1012
1032
BIN



T

RELATIVE FREQUENCY
0.20
0.16
0.12
0.08
0.04
0.00
1348
1388
1428
1468
1508
1548
1588
BIN

a duration which was taken to be equal to that of the psychological moment. If one peak represents the distribution of a count of n moments then the one to its right must represent a similar distribution of n+1 moments. Michon (1967) suggests that the presence of only one peak in the distributions of responses for T less than 1000 msec reflects the fact that all responses fall within the duration of one moment.

Within the context of Kristofferson's time quantum theory, the shape of the distribution of IRIs should be highly peaked, unimodal, and symmetrical. That should be the case because it represents the convolution of two rectangular distributions which represent variability in I, the centrally timed interval, and two small normal distributions which represent the temporal distributions along the efferent pathway. Thus the overall shapes of the IRI distributions are consistent with Kristofferson's quantal timing hypothesis.

INTERRESPONSE INTERVAL VARIANCE ESTIMATES AND PRACTICE EFFECTS

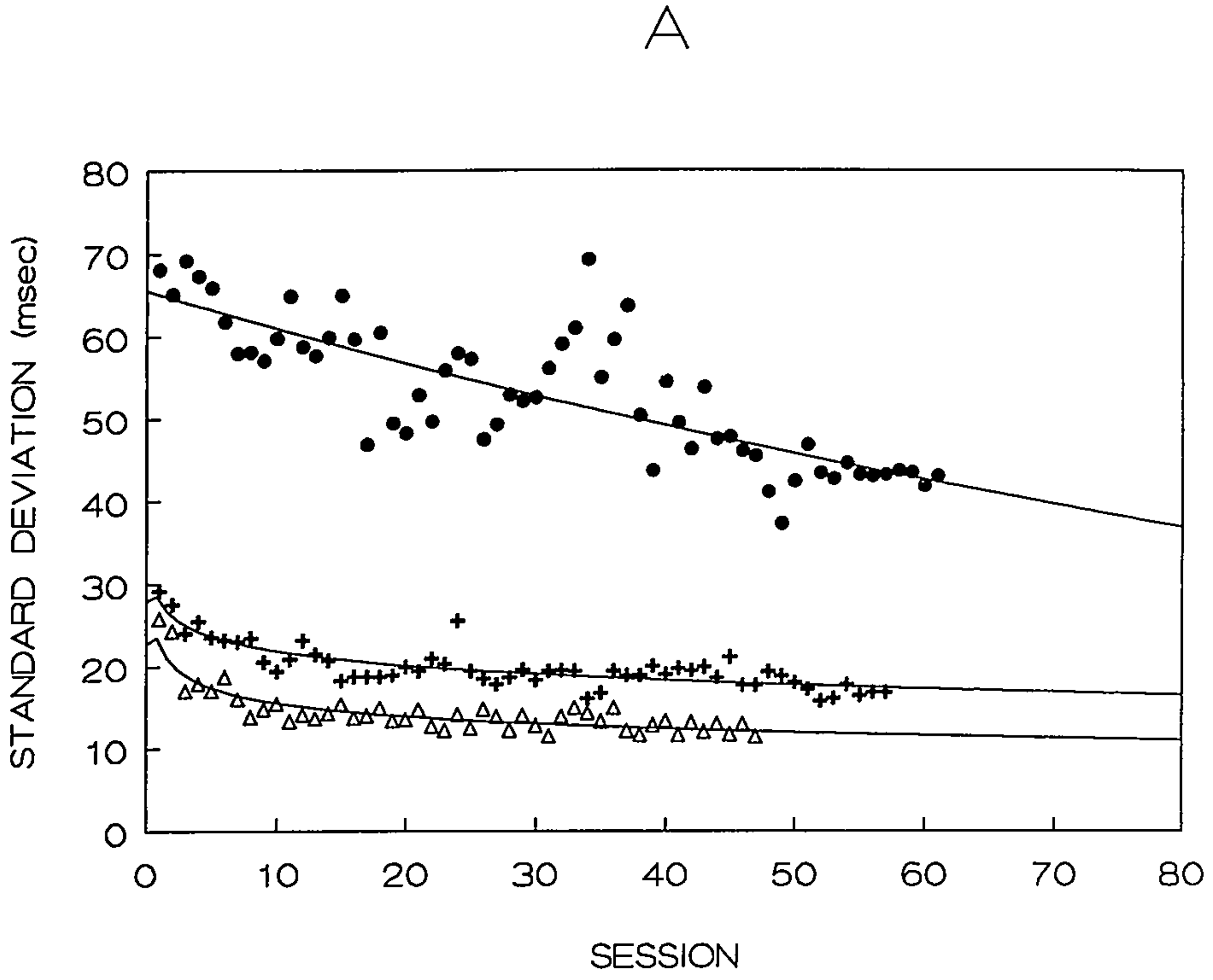
Figures 3.4 show how mean within session s_I changes as a function of session number for each value of T and for each subject. For these practice curves each point is composed of the mean within session variance estimated over all good sequences of that session.

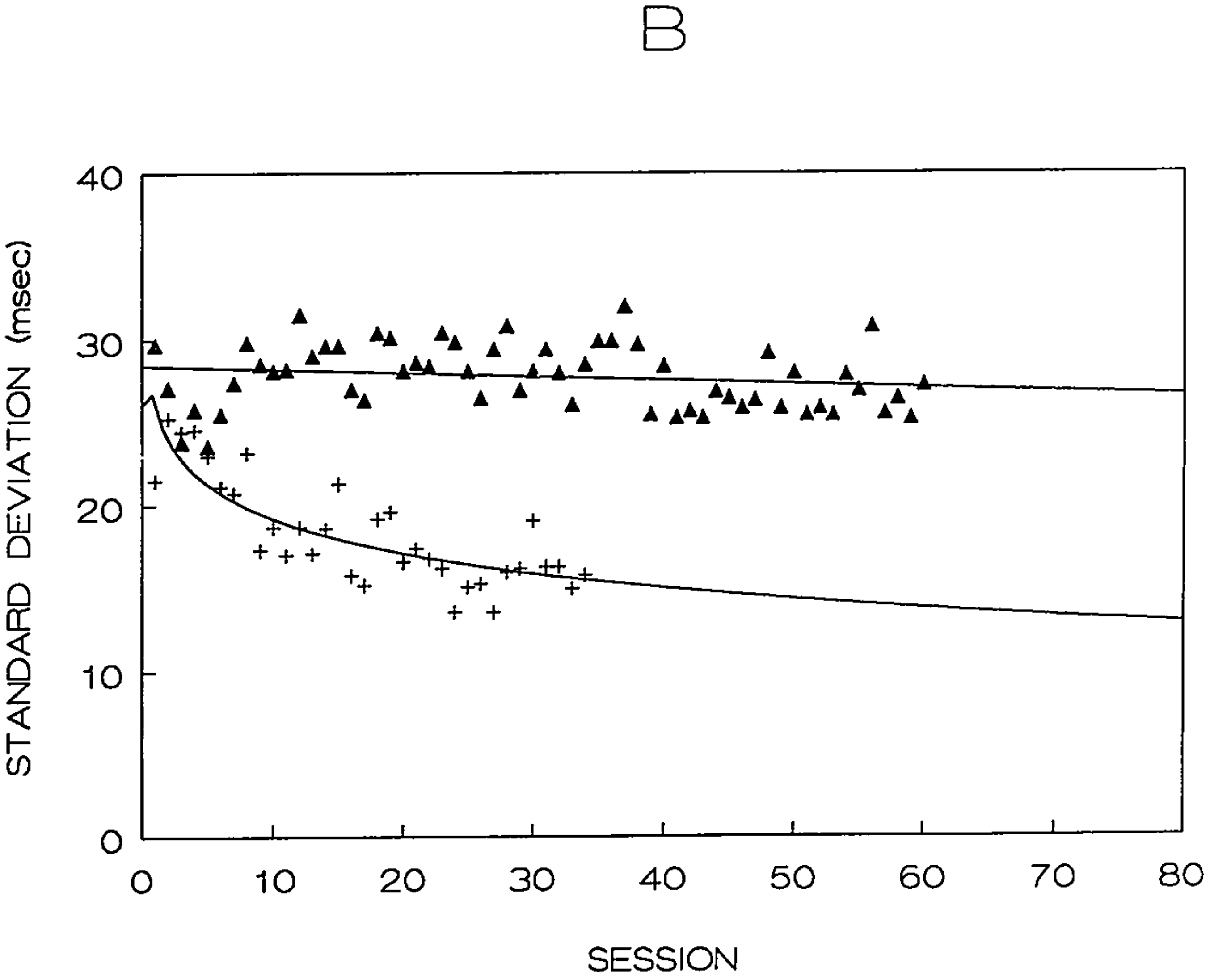
It can be seen that extended practice greatly reduces s_I. However, while the reduction in s_I is pronounced it is also very gradual; many sessions are required to achieve consistent between session levels of s_I. The practice curves appear to be negatively accelerating, monotone decreasing functions of session. A test for monotone trend using Mann's test reveals a significant negative monotone trend for a large proportion of the practice curves (see Table 3.4). With only one exception ($T \doteq 466$ for AK), all of the curves that did not reach significance showed a strong tendency toward

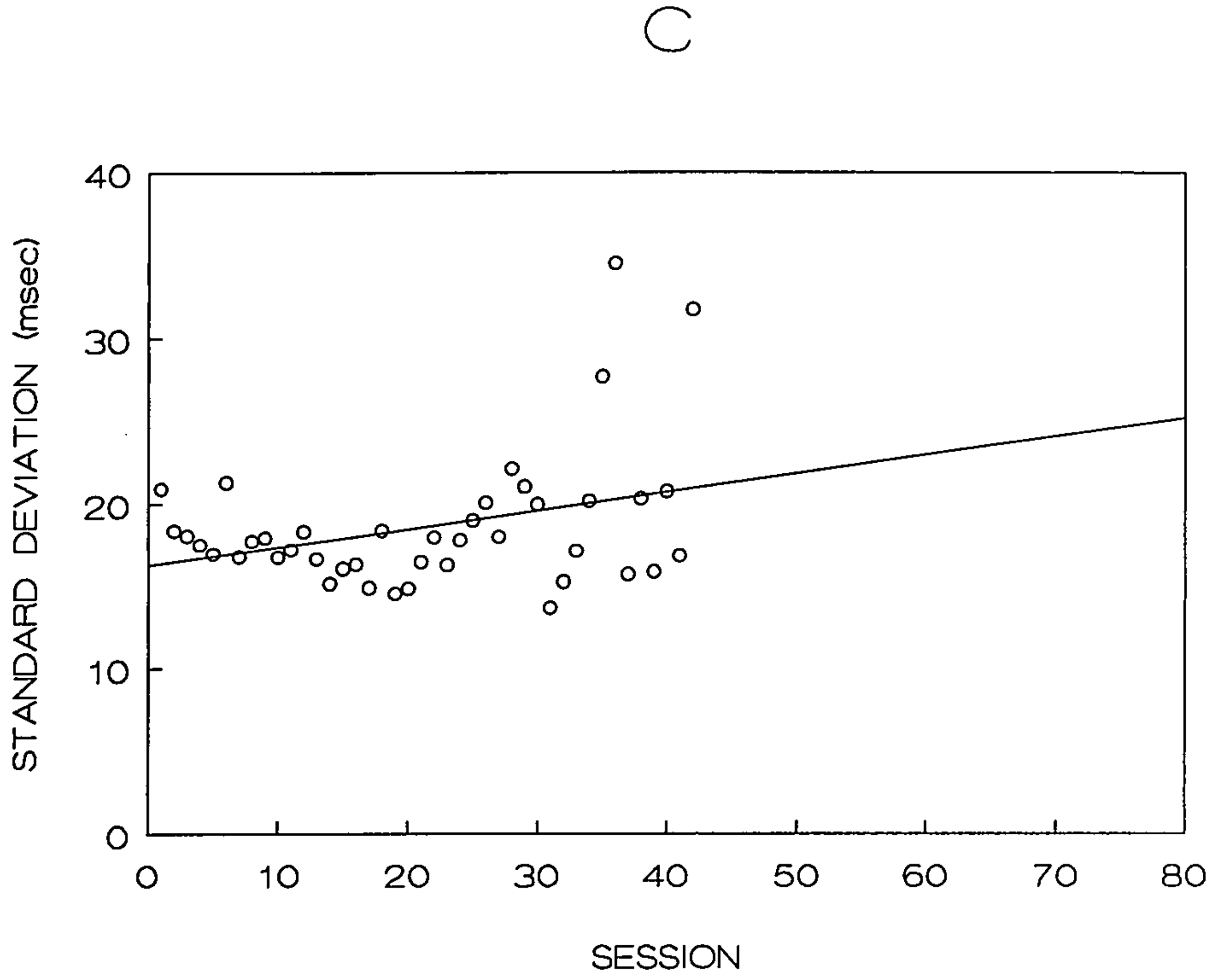
FIGURE 3.4

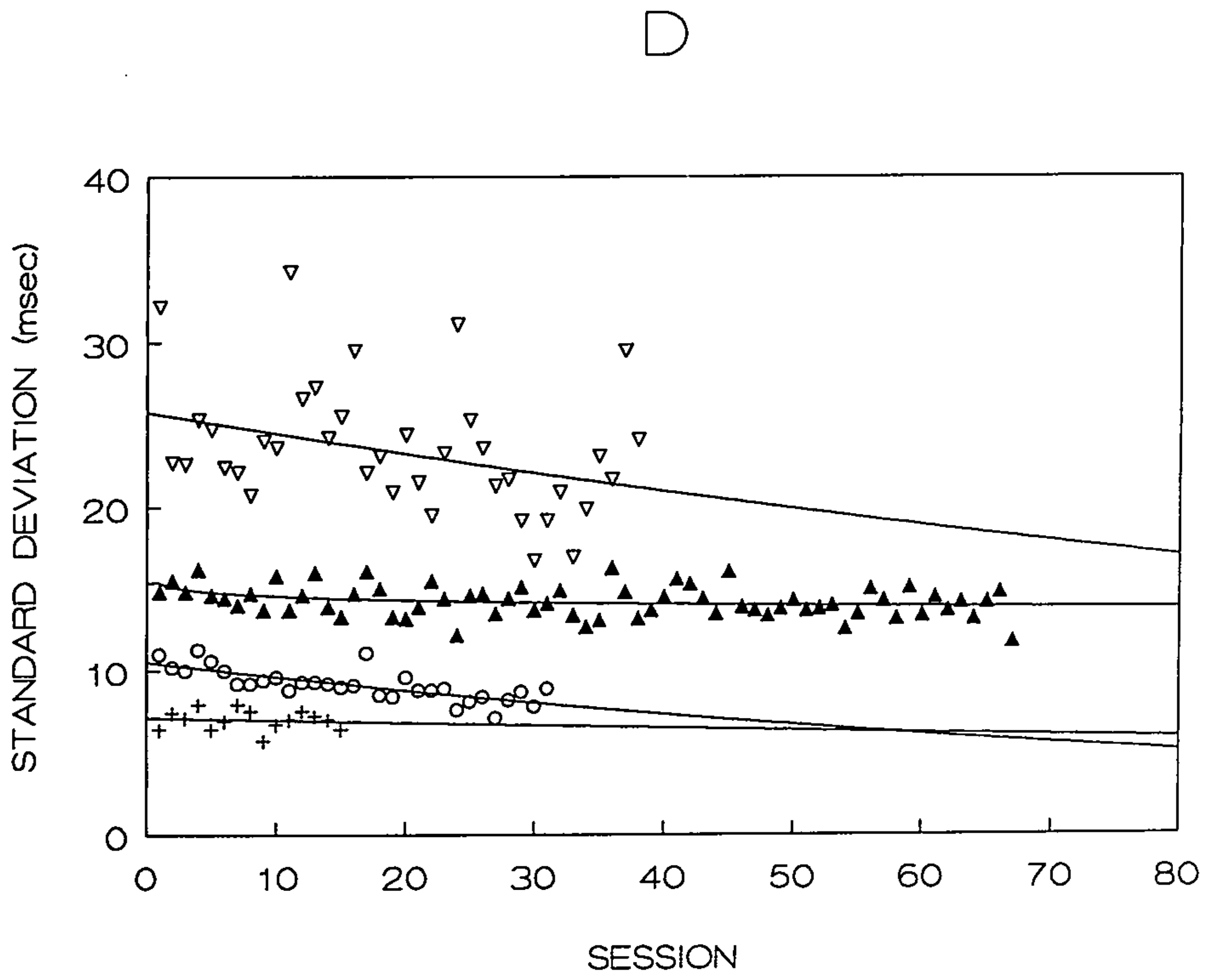
Mean within session CP IRI standard deviation plotted as a function of session number for each subject and value of T. Best fitting curve (see text for curve fitting procedure) is superimposed on data points.

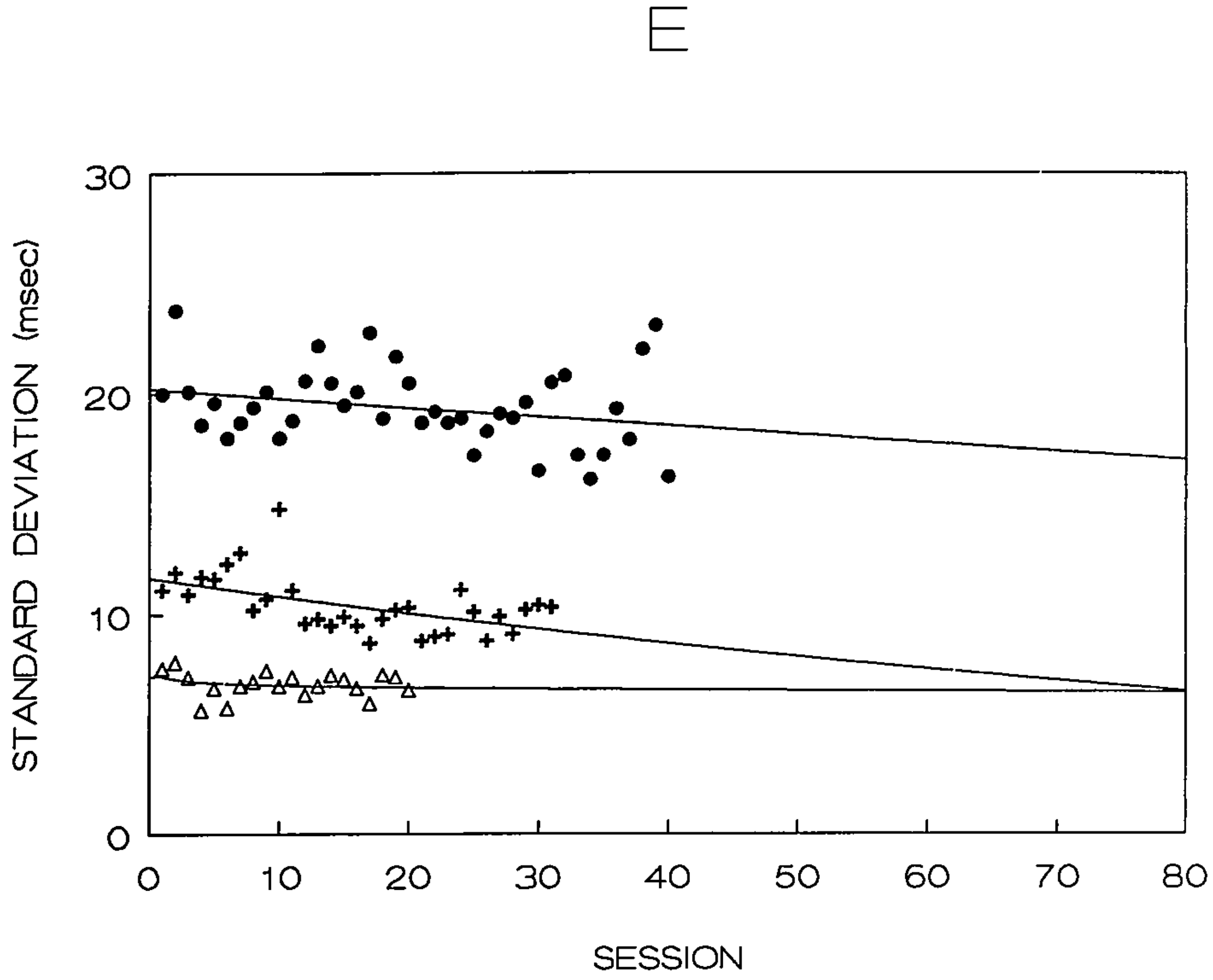
PANEL	SUBJECT	T (msec)
A	AK	367 (triangles), 734 (plusses), 932 (dots)
B	AK	233 (plusses), 932 (triangles)
C	AK	466 (circles)
D	LL	175 (plusses), 367 (circles), 734 (filled triangles), 1468 (open triangles)
E	LL	233 (triangles), 466 (plusses), 932 (dots)
F	GF	175 (plusses), 367 (circles), 734 (filled triangles), 1468 (open triangles)
G	GF	233 (triangles), 466 (plusses), 932 (dots)

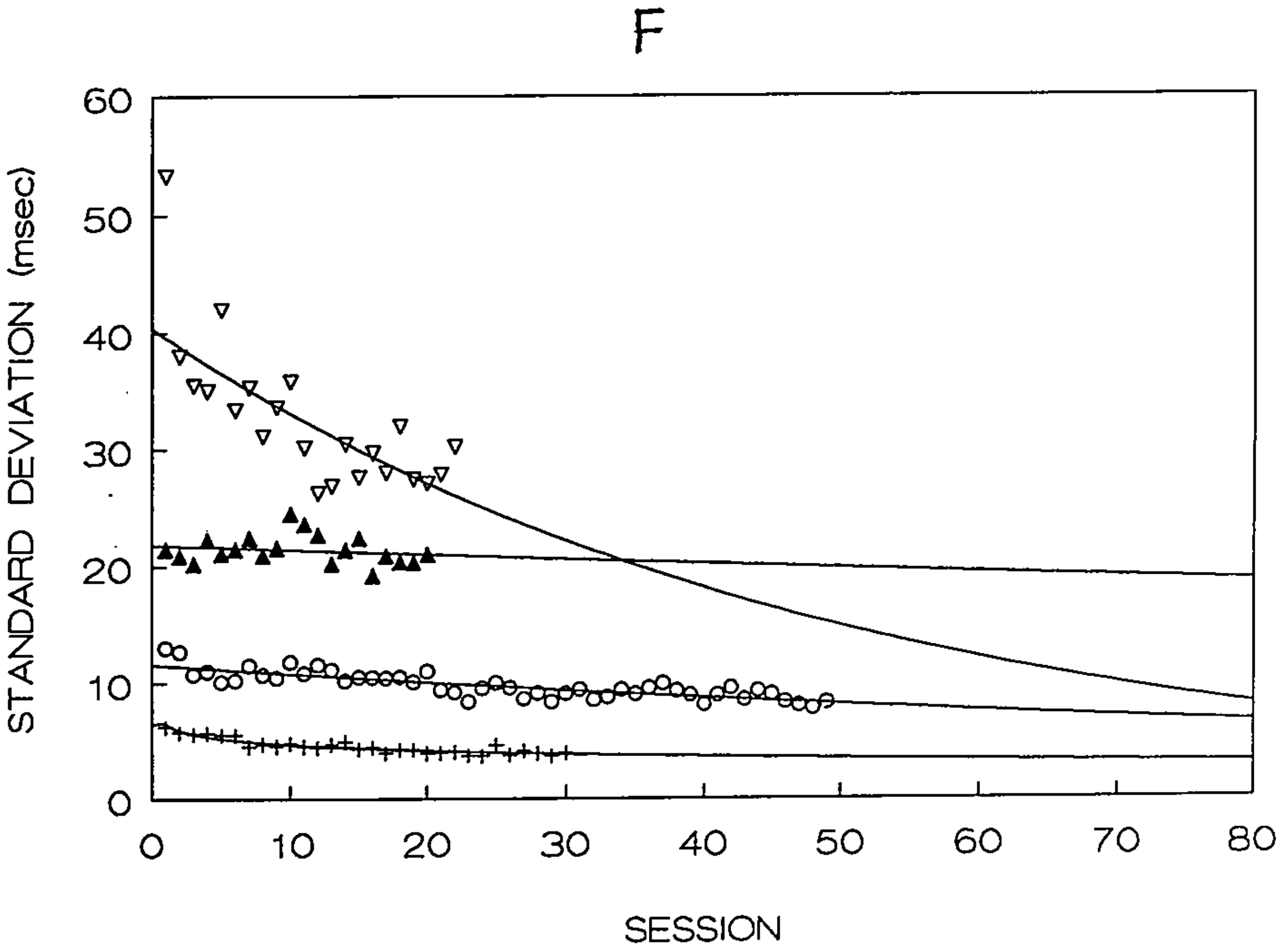

A
STANDARD DEVIATION (msec)
0
10
20
30
40
50
60
70
80
SESSION
0
10
20
30
40
50
60
70
80


B
STANDARD DEVIATION (msec)
40
30
20
10
0
0
10
20
30
40
50
60
70
80
SESSION


C
STANDARD DEVIATION (msec)
40
30
20
10
0
0
10
20
30
40
50
60
70
80
SESSION


D
STANDARD DEVIATION (msec)
0
10
20
30
40
0
10
20
30
40
50
60
70
80
SESSION


E
STANDARD DEVIATION (msec)
30
20
10
0
0
10
20
30
40
50
60
70
80
SESSION


F
STANDARD DEVIATION (msec)
0
10
20
30
40
50
60
0
10
20
30
40
50
60
70
80
SESSION

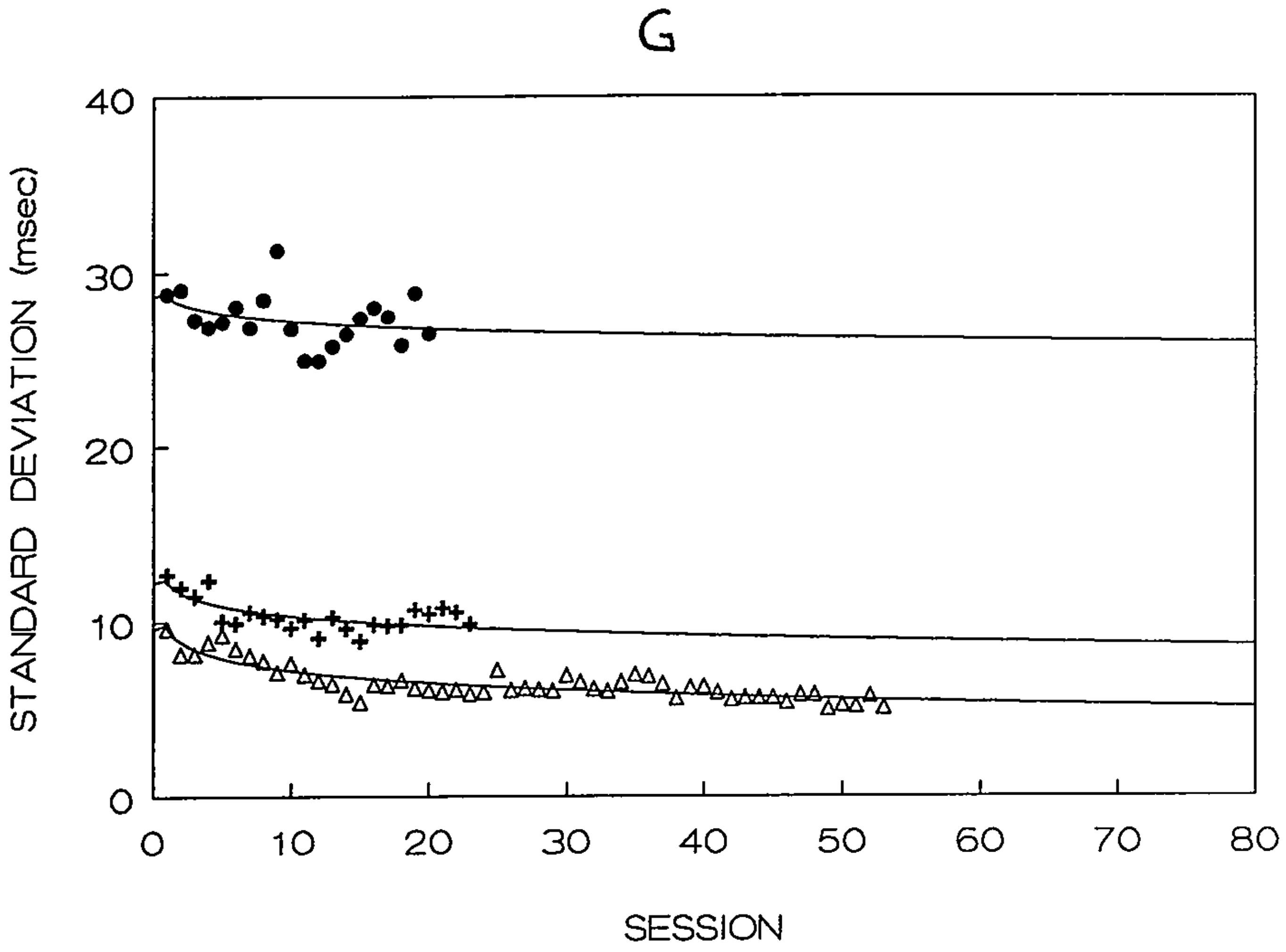

G
STANDARD DEVIATION (msec)
0
10
20
30
40
0
10
20
30
40
50
60
70
80
SESSION

TABLE 3.4

Test for monotone trends in the continuation phase s_I^2 vs session practice functions.

LEGEND:

SYMBOL	DESCRIPTION
N	number of sessions
τ	tau statistic

Subject	N	τ	
AK			
233	34	-0.5811	**
367	47	-0.5523	**
466	42	0.0964	
734	57	-0.5388	**
932	60	-0.1695	*
1468	61	-0.6158	**
LL			
175	15	-0.0667	
233	20	-0.0947	
367	31	-0.6237	**
466	31	-0.3376	**
734	67	-0.2022	**
932	40	-0.1603	
1468	38	-0.2603	*
GF			
175	30	-0.7287	**
233	53	-0.6074	**
367	49	-0.6497	**
466	23	-0.2490	*
734	20	-0.1263	
932	20	-0.2000	
1468	22	-0.5584	**

---

* $(p \leq .05)$
** $(p \leq .01)$

negative monotonicity. Based on this analysis one can conclude that CP IRI variance decreases with practice.

In order to learn more about the nature of the practice effect the CP s_I practice curves were further analyzed. The best fitted logarithmic, power, and exponential functions were determined according to the least squares criterion for each curve with the best of these three being superimposed on Fig 3.4. No single function consistently fitted the practice functions better than the others so no further attempt to model the practice effect with these functions was made. The only firm conclusion that arises out of this analysis is that practice significantly reduces CP IRI variance along a monotonic decreasing axis.

Because of the relatively steep decrease in s_I over the first few sessions estimates of the initial level were made by way of the best fitted functions. That quantity, symbolized by s_F, is equal to the predicted point at session 1 for the function that best fitted the practice curve. Session 0 could have been used for this purpose but it was not used because that would have involved extrapolating outside the empirical range. The same procedure was used to estimate the level of IRI variability for the last session of each practice curve, s_L. s_L is almost identical to the mean s_I taken over the last n sessions, where n is a small number such as 5. s_F and s_L are presented in Table 3.5a for all three Ss.

If the reduction in variability is expressed as a percentage of the initial level of variability one obtains the percent practice effect. This is a useful quantity because it enables one to compare practice effects across values of T to determine if practice changes as a function of T. Percent practice, which is expressed as $(s_L - s_F)/ s_F$, is shown in Table 3.5b along with overall percent practice effect for each S.

The mean overall percent practice effect across Ss is -20 percent but there is substantial within and between S variability. In general, and as an initial description,

TABLE 3.5a

Continuation phase s_F and s_L for each subject and level of T.

T	AK sF	LL sF	GF sF
175		7.12	6.43
233	26.11	7.14	9.58
367	22.72	10.44	13.13
466	16.19	11.57	12.23
734	27.91	15.36	21.77
932	28.43	20.20	28.65
1468	65.06	25.64	47.54

T	AK sL	LL sL	GF sL
175		6.89	3.85
233	15.52	6.63	5.53
367	12.03	7.96	8.74
466	20.93	9.26	9.64
734	17.40	13.91	21.00
932	27.13	18.54	26.77
1468	42.27	21.19	27.41

TABLE 3.5b

Continuation phase percent practice effect $[(s_L - s_F)/s_F]$ for each subject and level of T.

T	AK	LL	GF
175		-3.23	-40.12
233	-40.56	-7.14	-42.28
367	-47.05	-23.75	-33.43
466	29.28	-19.97	-21.18
734	-37.66	-9.44	-3.54
932	-4.57	-8.22	-6.56
1468	-35.03	-17.36	-42.34
Mean Overall	-22.60	-12.73	-24.89

practice improves performance most at the low and high ends of the range studied and least at the intermediate values around 734 msec.

INTERRESPONSE INTERVAL MEAN ESTIMATES AND PRACTICE EFFECTS

The arithmetic mean of all IRIs of the CP, which is symbolized by m_I, is taken as an estimate of Ss ability to accurately reproduce T. m_I changes very little with experience. In order to evaluate the extent of the practice effect the CP m_I versus session functions were tested for monotone trends. The results of the monotone trend analysis are presented in Table 3.6. Only 6 of the 23 m_I practice curves show statistically significant monotone trends. Of those, four were upward and two downward trends. Thus, unlike the s_I practice curve, the m_I practice curves do not generally contain monotone trends and when they do, they are not consistently of the same sign.

One might think that there would be a positive trend when m_I is initially less than T, or a negative trend when it is greater than T, but that is not always the case. The results indicate that while m_I becomes a better approximation to T in some cases it becomes a worse approximation in others. Table 3.7a shows m_F and m_L, estimates of μ_I for the first and last session at each T respectively. Computations of m_F and m_L are made by the identical procedure used to obtain s_F and s_L. A comparison between the values of m_F and T and m_L and T illustrates how well Ss match m_I to T.

BIAS AND OSCILLATOR SIGNATURE PATTERNS

Collyer et al. (1992) analyzed CP IRI m_I vs T functions and reported evidence supporting their discrete timekeeper hypothesis. Oscillator signature patterns of a particular form in residual bias functions formed the basis of that evidence. In order to determine if such patterns were present in the CP data the m_L vs T function was first analyzed to see if there was an identity relation between those two variables. Table 3.7b shows regression statistics in which it can be seen that there exists an identity relation

TABLE 3.6

Test for monotone trends in the continuation phase m_I vs session practice functions.

LEGEND:

SYMBOL	DESCRIPTION
N	number of sessions
τ	tau statistic

Subject	N	τ	
AK			
233	34	-0.21568	
367	47	-0.17483	
466	42	0.119628	
734	57	0.144110	
932	60	0.223728	*
1468	61	-0.11857	
LL			
175	15	-0.42857	*
233	20	0.057894	
367	31	0.135483	
466	31	-0.27526	*
734	67	0.189507	*
932	40	-0.15256	
1468	38	0.015647	
GF			
175	30	0.473563	**
233	53	-0.01814	
367	49	-0.06887	
466	23	-0.21739	
734	20	0.347368	*
932	20	-0.30526	
1468	22	-0.15151	

---

* $(p \leq .05)$
** $(p \leq .01)$

TABLE 3.7a

Continuation phase m_F and m_L for each subject and level of T.

T	AK m_F	LL m_F	GF m_F
175		179.79	175.89
233	235.05	230.02	237.41
367	374.94	358.73	370.59
466	457.32	470.12	474.43
734	729.37	709.55	725.80
932	915.16	948.78	967.46
1468	1495.66	1478.97	1484.04

T	AK m_L	LL m_L	GF m_L
175		174.78	178.14
233	223.38	230.67	234.06
367	369.43	360.52	367.63
466	476.13	461.00	459.40
734	740.07	728.33	750.99
932	945.24	928.80	946.87
1468	1436.70	1481.98	1456.23

TABLE 3.7b

Regression statistics for continuation phase m_L vs T function

Subject	Slope	Intercept	r^2
AK	0.9811	11.73	0.9990
LL	1.0108	-8.03	0.9999
GF	0.9965	4.81	0.9995

* significantly different from 1.0 for slope or from 0.0 for intercept, $p<.05$

between m_L and T. None of the slope coefficients differed significantly from 1.0 and none of the intercept coefficients differed significantly from zero. Thus unlike the similar analyses performed by Collyer et al. (1992) and for the PTDD experiment, the CP tapping analysis indicates an absence of linear bias.

The absence of linear bias means that it is appropriate to analyze bias rather than residual bias functions for the presence of oscillator signatures (Collyer et al., 1992). Figure 3.5 shows bias as a function of T. It is clear that the discrete timekeeper hypothesis proposed by Collyer et al. (1992) is at best only remotely supported by the shape of GF's function; his function oscillates about zero bias but the oscillations are very widely separated indicating that there are only two levels of discreteness over the entire range. In contrast, the functions of AK and LL bear little or no resemblance to what the discrete timekeeper hypothesis predicts should be the case. Their functions do not oscillate about zero bias.

In conclusion, the CP bias functions do not support the discrete timekeeper hypothesis. However, this conclusion is weak because the experimental procedure might have precluded the ability to detect the true shape of the oscillator signature pattern as a result of spacing successive values of T too far apart. Consequently it should be interpreted as being only cursory evidence against Collyer's discrete timekeeper hypothesis.

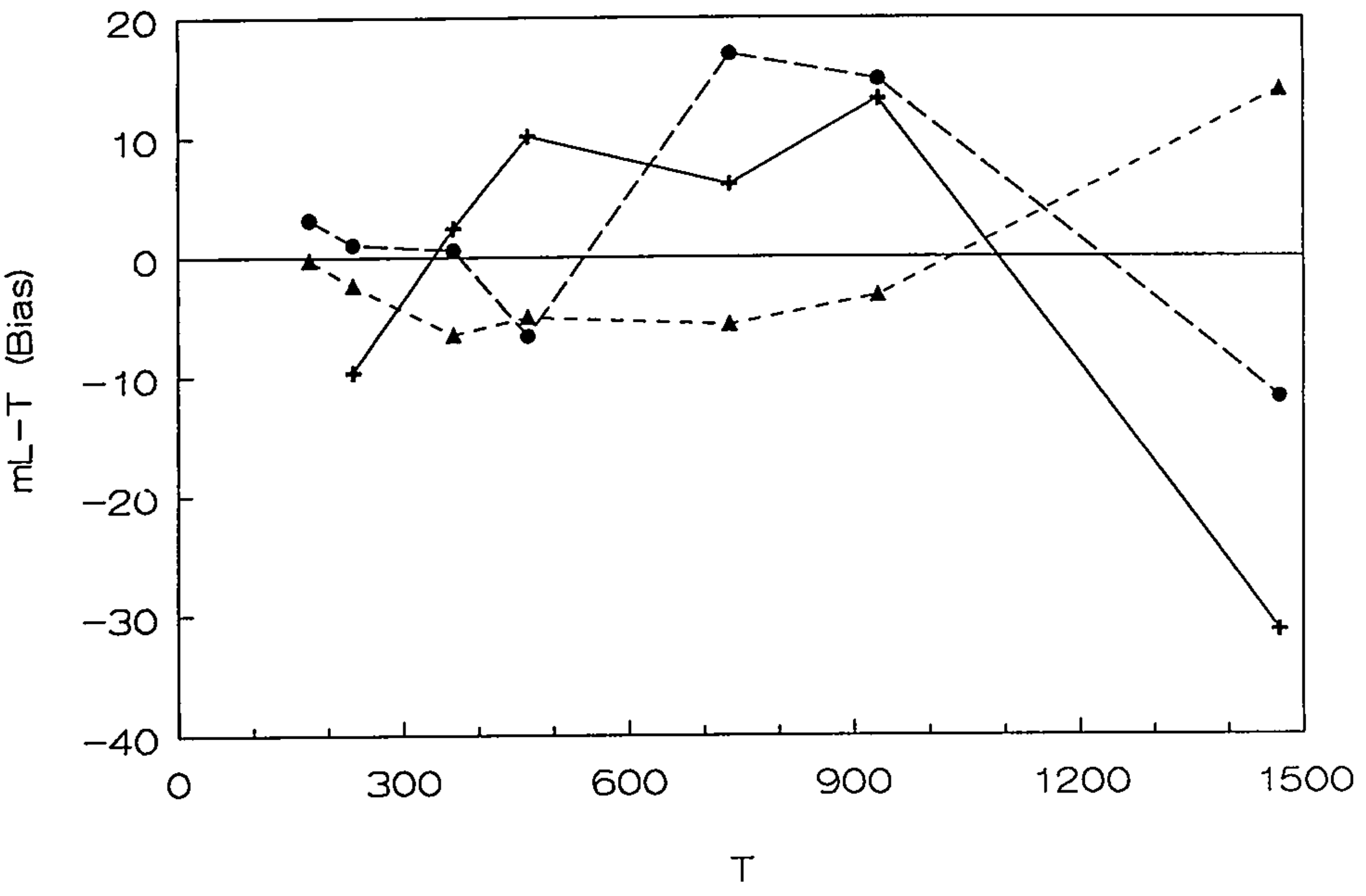
Although the analysis of oscillator signature patterns based on Collyer et. al (1992) failed to reveal much about the motor timekeeper, other information about the timekeeper is available in the tapping IRIs. One of the great benefits of the TPM is that it provides the rationale and the technique to partition s_I^2 into clock (s_C^2) and motor delay (s_D^2) variances. Knowing these variances one is placed in a much stronger position to make statements about the functioning of the component processes.

FIGURE 3.5

Continuation phase bias (m_L-T) as a function of T for AK, LL, and GF.

LEGEND:

SUBJECT	SYMBOL
AK	crosses
LL	triangles
GF	circles



20
10
0
−10
−20
−30
−40
0
300
600
900
1200
1500
mL−T (Bias)
T

PARTITIONING s_I^2 into s_D^2 AND s_C^2

In order to justify the use of the TPM to obtain s_D^2 and s_C^2, the CP IRI sequences must be shown to be stationary. Earlier it was established that small trends were present but because they were of such small magnitude relative to m_I it was concluded that they would present no serious problem for the analysis. Nevertheless, the existence of trends should be kept in mind throughout the following analysis.

A main prediction of the TPM is that $r_I(1)$ should range between -0.5 and 0. Instances when $r_I(1)$ is either greater than 0 or less than -0.5 would be evidence contrary to the TPM. Figure 3.6 shows mean $r_I(1)$ with the vertical bars indicating two standard errors to each side of the mean. Each point is the average $r_I(1)$ taken over all sequences within the last five sessions at T.

Because none of the intervals includes values outside the acceptable bounds for AK, all of his data are consistent with the TPM and inconsistent with any model that predicts $\rho_I(1)$ should be less than -1/2 or greater than 0. However, for GF and LL some estimates are inconsistent with the predictions of the TPM. For GF the three highest values of T generated mean $r_I(1)$ that are greater than zero by more than two standard errors. Only one similar value, T = 1468 msec, was computed for LL. Thus while these results are consistent with the TPM for T in the low range of durations, they indicate that the model might be inappropriate for T in the high range.

According to the TPM, $-G_I(1)$ equals s_D^2 and $G_I(0)$ plus $2G_I(1)$ equals s_C^2. Mean s_C^2 and s_D^2 are shown in Figs. 3.7 and 3.8 as functions of T for each S. From a glance at these s_D^2 functions one can see that the mean is less than zero for LL and GF whenever the mean $r_I(1)$ does not conform to the predictions of the model. When s_D^2 is negative s_C^2 is greater than s_I^2 by an amount equal to $2s_D^2$. Obviously that should never happen according to the TPM because σ_C^2 should be less than s_I^2. No irregularities of this kind occurred for AK.

FIGURE 3.6

Continuation phase mean lag 1 serial correlation, $\eta(1)$, plotted as a function of T. Two standard errors are shown to each side of the mean.

LEGEND:

SUBJECT	SYMBOL
AK	crosses
LL	triangles
GF	circles

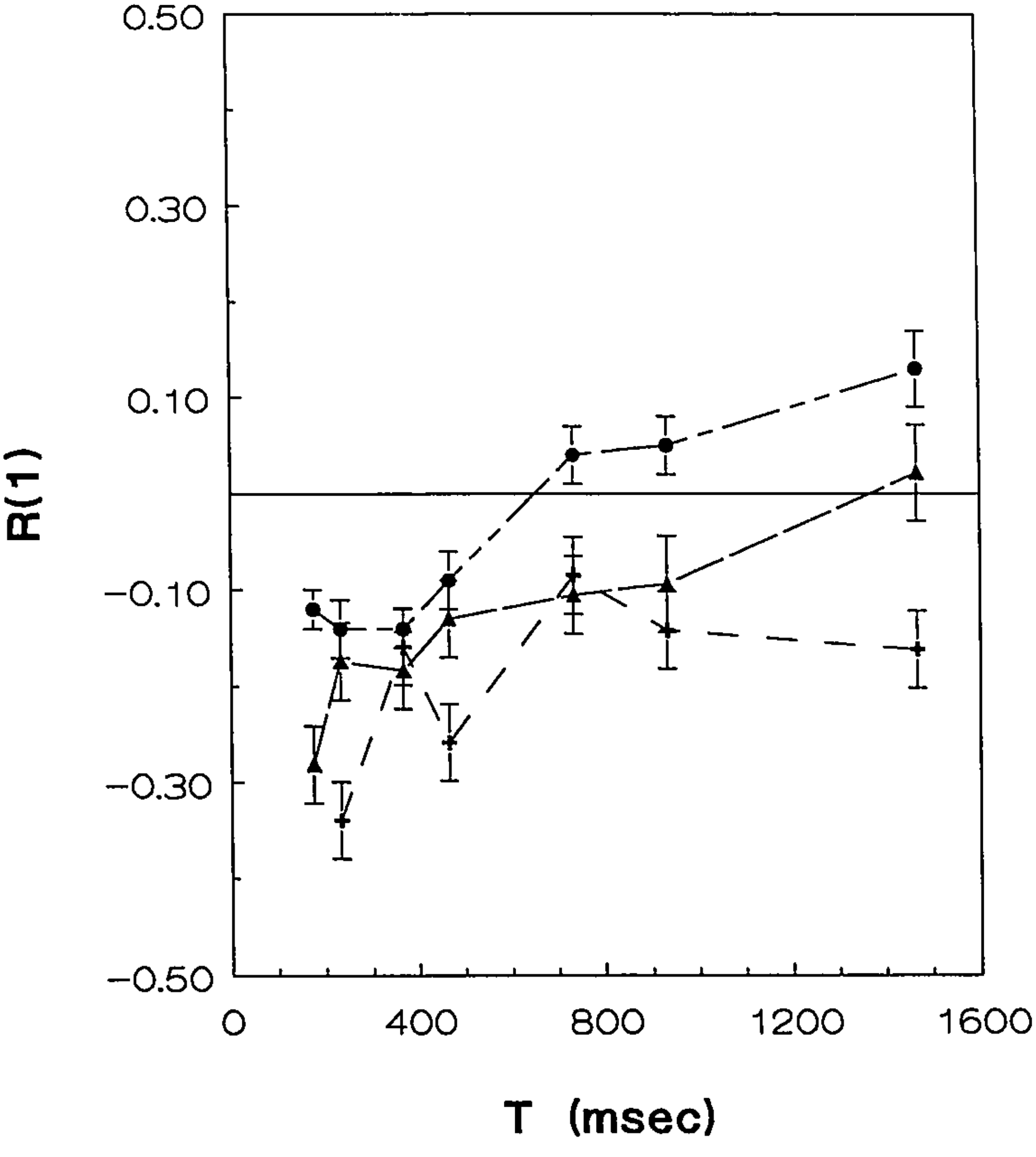

0.50
0.30
0.10
−0.10
−0.30
−0.50
R(1)
0
400
800
1200
1600
T (msec)

FIGURE 3.7

Continuation phase biased s_C^2 as a function of T for AK, LL, and GF.

LEGEND:

SUBJECT	SYMBOL
AK	crosses
LL	triangles
GF	circles

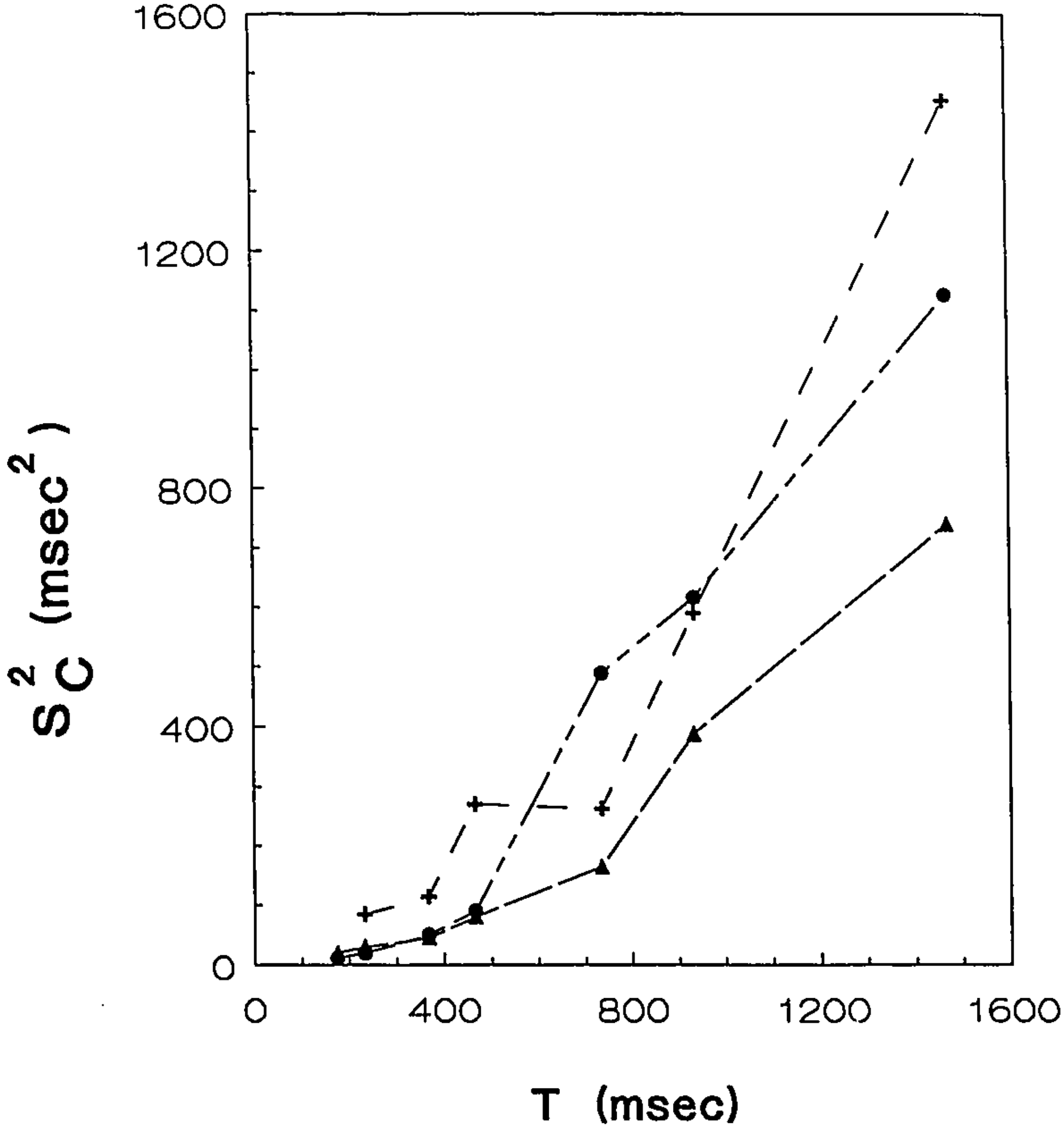
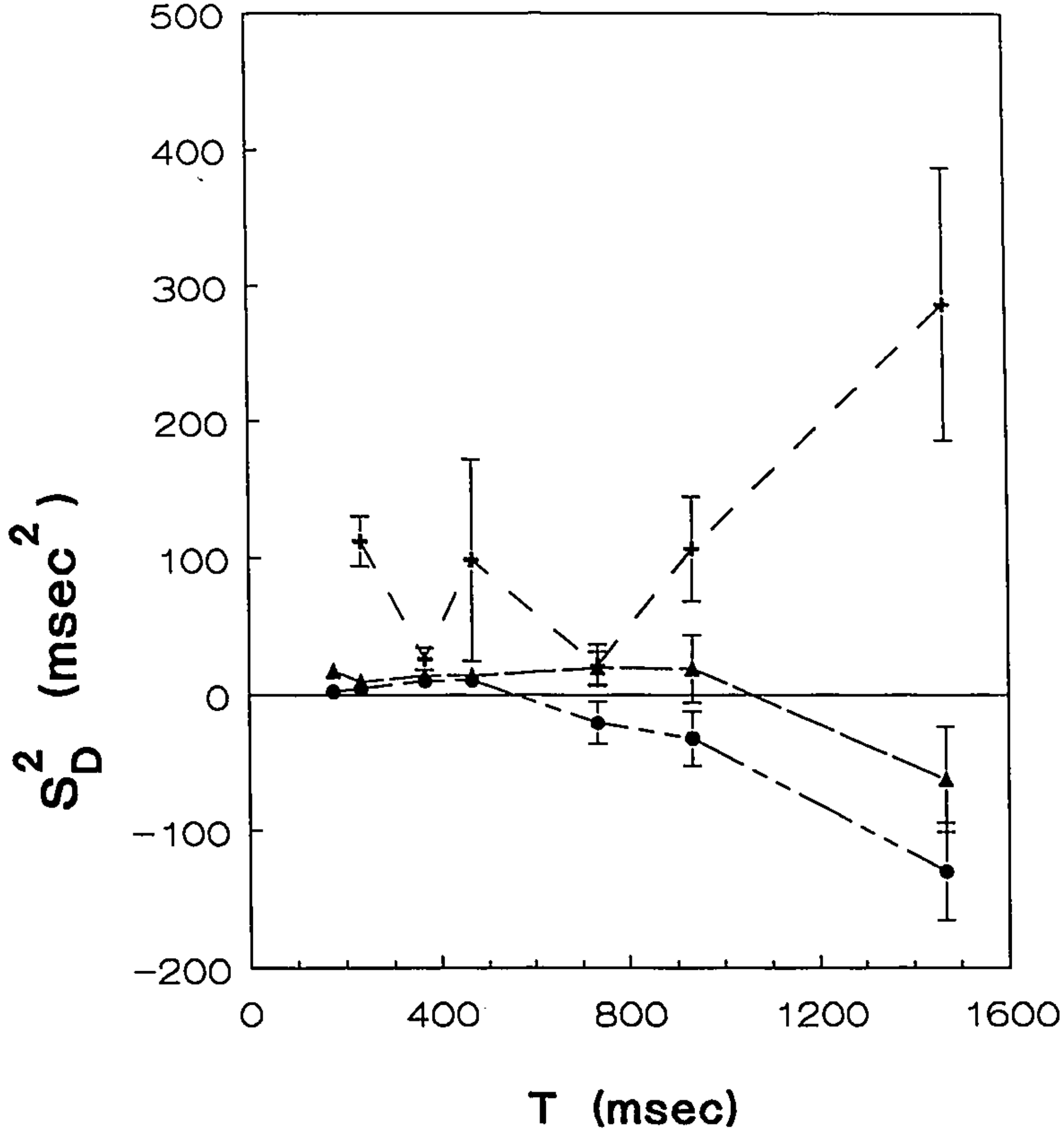

1600
1200
800
400
0
0
400
800
1200
1600
S_C^2 (msec^2)
T (msec)

FIGURE 3.8

Continuation phase biased s_D^2 as a function of T for AK, LL, and GF with error bars indicating two standard errors about the mean.

LEGEND:

SUBJECT	SYMBOL
AK	crosses
LL	triangles
GF	circles


500
400
300
200
100
0
−100
−200
0
400
800
1200
1600
S_D^2 (msec^2)
T (msec)

Of particular importance in the present context is to determine how biased s_C^2 and s_D^2 are related to m_I (biased estimates of s_C^2 and s_D^2 were analyzed in order to compare to Wing's (1973) analysis of biased functions). The TPM states that s_D^2 should be independent of m_I but it does not specify the form of the relationship between s_C^2 and m_I. Table 3.8 shows ANOVA results in which it can be seen that mean s_D^2 changes across target durations for AK and GF but not for LL.

Wing and Kristofferson (1973) reported s_D^2 estimates that were not constant over the range of values of T they used. The same is true of the present data. By way of an explanation they proposed that if muscle groups involved in the response operate with greater precision at different response rates, then s_D^2 estimates should vary accordingly (Wing & Kristofferson, 1973). But they also point out that this explanation cannot account for highly unstable estimates of s_D^2 at a given T between sessions.

For T greater than or equal to 734 msec, values of s_D^2 are often negative and highly variable both before and after practice. This result suggests that the TPM might be a poor model for CP tapping, especially at the three longest values of T. The model might become invalid at these long durations because cognitive factors such as attention may increasingly influence the timekeeper. At the target duration of 1468 msec, for example, there is sufficient time for one to momentarily become inattentive without having disastrous consequences on performance - the accuracy time-window in the CP equals 734 msec. Such a wide window of error gives considerable latitude for timing error. In any event, values of s_D^2 generally are incompatible with the TPM for T greater than 466 msec..

In addition to determining the range of durations over which the TPM is valid, one of the principle reasons for conducting the tapping experiment is to determine whether s_C^2 is better described as being a linear or quadratic function of m_I. Table 3.9 shows the analysis of variance (ANOVA) results in which the method of orthogonal

TABLE 3.8

Analysis of variance (ANOVA) results for mean s_D^2 over the last five sessions at each level of T for each subject.

LEGEND:

SYMBOL	DESCRIPTION
F	**F** statistic
df	degrees of freedom
p	significance level

	F	df	p
AK	11.46	(5,24)	<.01
LL	1.55	(6,28)	n.s.
GF	60.21	(6,28)	<.01

TABLE 3.9

ANOVA results for mean s_C^2 over the last five sessions at each level of T for each subject.

LEGEND:

SYMBOL	DESCRIPTION
F	**F** statistic
df	degrees of freedom
p	significance level

	Linear Component			Quadratic Component		
	F	df	p	F	df	p
AK	156.92	(1,5)	<.01	44.78	(1,5)	<.01
LL	44.17	(1,6)	<.01	13.19	(1,6)	<.01
GF	1186.34	(1,6)	<.01	219.65	(1,6)	<.01

polynomials was applied to determine the degree of the predictive relation between s_C^2 and m_I. In every case there were highly significant linear and quadratic components.

Wing (1973) found significant linear but no significant quadratic components in an analysis of the relationship between biased s_C^2 and m_I in three of four Ss. He interpreted that result to support the idea that a simple stochastic process, perhaps a Poisson pulse generator, formed the basis of the central timekeeper. However, data from the fourth subject revealed a significant quadratic component and, more importantly, a non-significant linear component. This result is inconsistent with a simple stochastic process hypothesis but it is not inconsistent with a process operating in accord with Weber's law.

Because all three Ss in the present experiment have highly significant linear and quadratic components in their biased s_C^2 vs m_I functions, the simple stochastic process hypothesis must be rejected.

As the biased s_C^2 vs m_I functions contain a quadratic component, we should not be surprised to find that when those functions are further analyzed in terms of the models presented in the Introduction (e.g., Weber's, Creelman's, Getty's, and Kristofferson's) that the three models based on Weber's law fit better. Had the number of pulses in the CP sequences been large (e.g., 200 or greater) bias would have been minimal and it would have been acceptable to use the biased s_C vs m_I functions for this analysis. But because the sequences are relatively short, the issue of bias must be addressed.

BIAS CORRECTED s_C^2 and s_D^2

As discussed in the Introduction, the magnitude of bias that is added to $G_I(k)$ as a result of using a particular sequence length is inversely proportional to N, the number of responses in the sequence (Anderson 1972; Vorberg, 1978; Wing, 1979). Since bias increases as N decreases, short sequences introduce more bias to $G_I(k)$ than long ones. Because CP sequences in the present experiment are short, especially for AK and LL, it is necessary to account for bias in $G_I(k)$ before modeling the functions. The introduction of bias in $G_I(k)$ has a tendency to generate values of $G_I(k)$ that are smaller than their unbiased counterparts. Thus, correcting for the effect of bias in $G_I(k)$ will generate s_C^2 that is larger, and s_D^2 that is smaller than their biased counterparts.

It turns out to be a relatively simple but tedious matter to determine the amount of bias in $G_I(k)$ that has been introduced as a result of using a specific sequence length. That quantity equals the sum of the second and third elements of Eq. 1.35. When that quantity is subtracted from the biased obtained autocovariance, the result will be called "bias corrected" autocovariance.

It should be noted that estimates of the parameters of the theoretical autocovariance function that are inserted into Eq. 1.35 were themselves obtained from the biased obtained functions. As a result they must not be the best estimates to begin with. A better, but more complex approach would be to find the parameters of the unbiased theoretical autocovariance function that minimize the sum of the squared deviations about the biased obtained autocovariances after bias is added to the theoretical autocovariances. Such an approach would eliminate the problem of estimating the parameters of the unbiased theoretical autocovariance function from the biased obtained function. But that problem must be considered not to be very serious because neither Vorberg (1978) nor Wing (1979), two other invesitgators who have addressed this issue, used this alternative approach. In the interest of maintaining consistency, their approach will be used for present purposes.

Bias corrected autocovariances for lags 0 to 5 were computed for each sequence in the last five sessions and were used to make bias corrected estimates of s_C^2 and s_D^2. These estimates are given in Table 3.10 and shown in Figs. 3.9 through 3.11 as a function of m_I.

TABLE 3.10

Bias corrected estimates of continuation phase s_C^2 and s_D^2 for each subject and T.

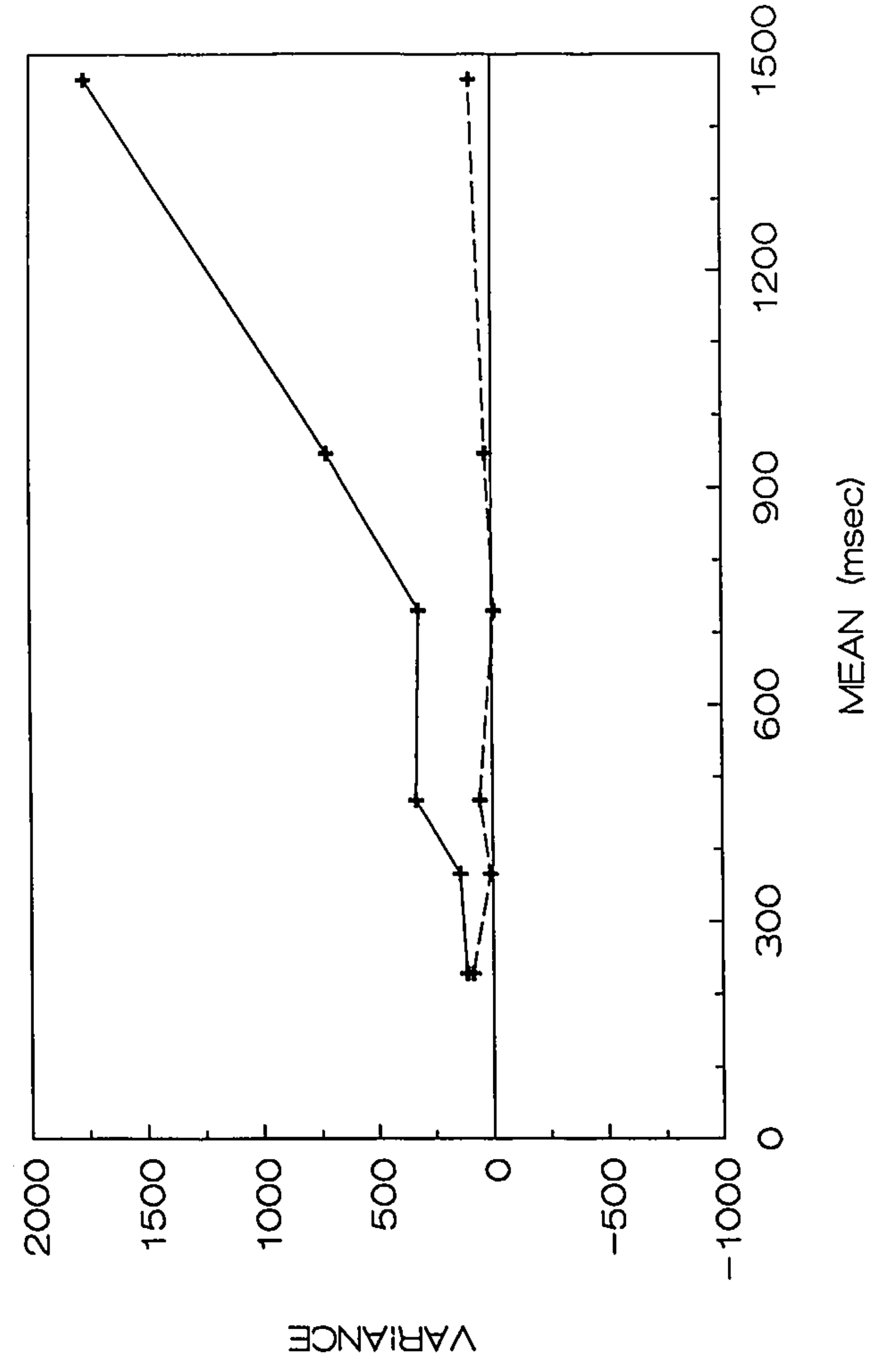
LEGEND:

SYMBOL	DESCRIPTION
TPM	Two process model
T	base interpulse interval
m_I	mean interresponse interval
s_C^2	bias corrected timekeeper variance estimate based on the TPM
s_D^2	bias corrected delay variance estimate based on the TPM

AK T (msec)		TPM	
	m_I	s_C^2	s_D^2
233	228.05	111.25	85.99
367	365.25	139.91	9.89
466	467.57	333.72	54.03
734	730.45	318.62	-10.59
932	946.41	718.57	25.77
1468	1464.49	1764.47	90.77
LL			
175	175.94	24.85	12.50
233	230.48	36.40	4.88
367	358.80	55.66	6.80
466	459.50	98.51	2.92
734	729.78	200.12	-1.32
932	929.49	468.24	-26.31
1468	1494.29	844.43	-120.27
GF			
175	178.60	12.40	1.61
233	236.31	21.48	3.46
367	367.66	54.54	7.91
466	465.12	97.58	6.50
734	746.39	520.55	-36.82
932	927.85	654.93	-51.88
1468	1450.67	1180.06	-157.93

FIGURE 3.9

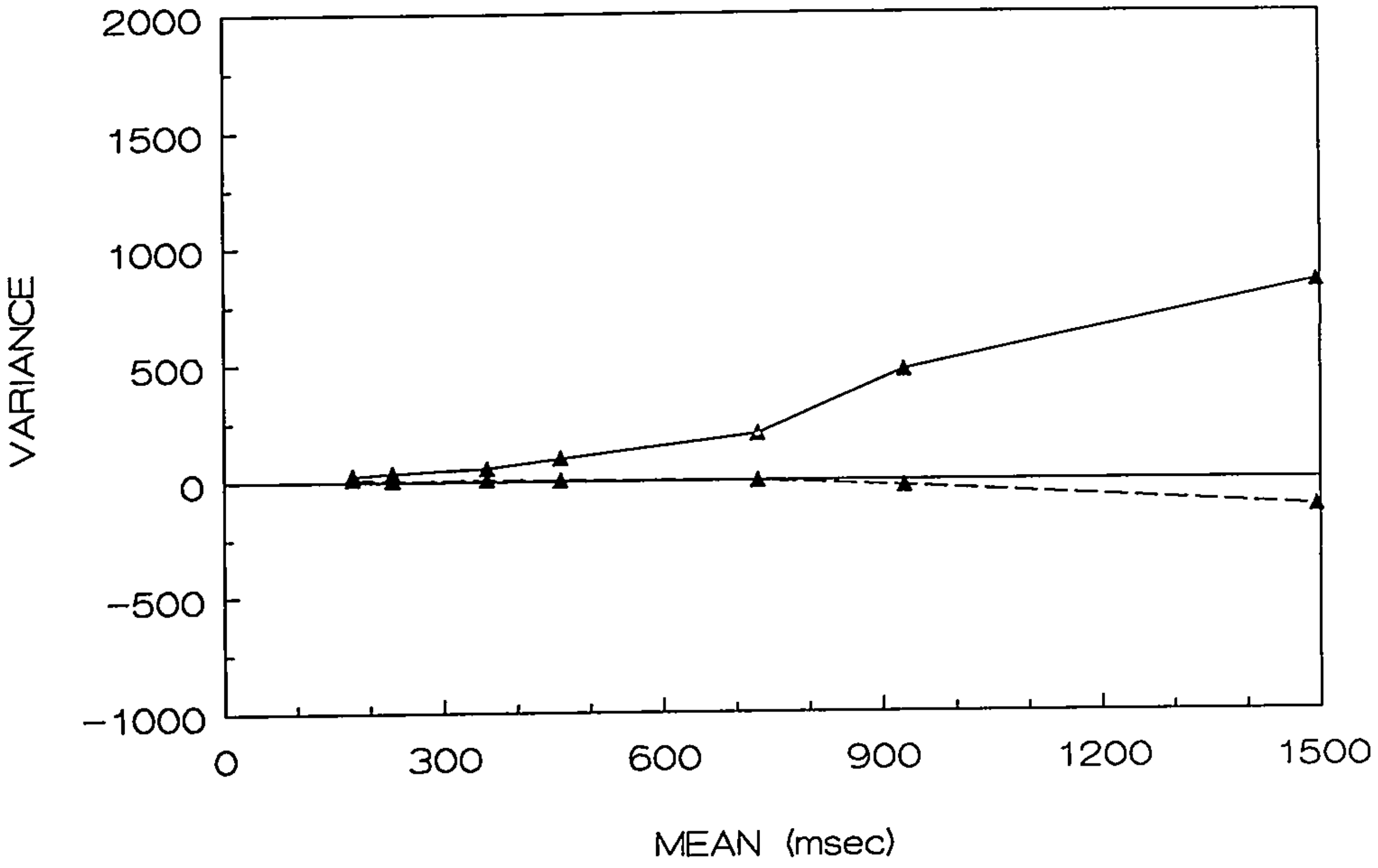
Continuation phase bias corrected s_C^2 (solid line) and s_D^2 (dashed line) plotted as functions of mean for AK.



VARIANCE
2000
1500
1000
500
0
−500
−1000
MEAN (msec)
0
300
600
900
1200
1500

FIGURE 3.10

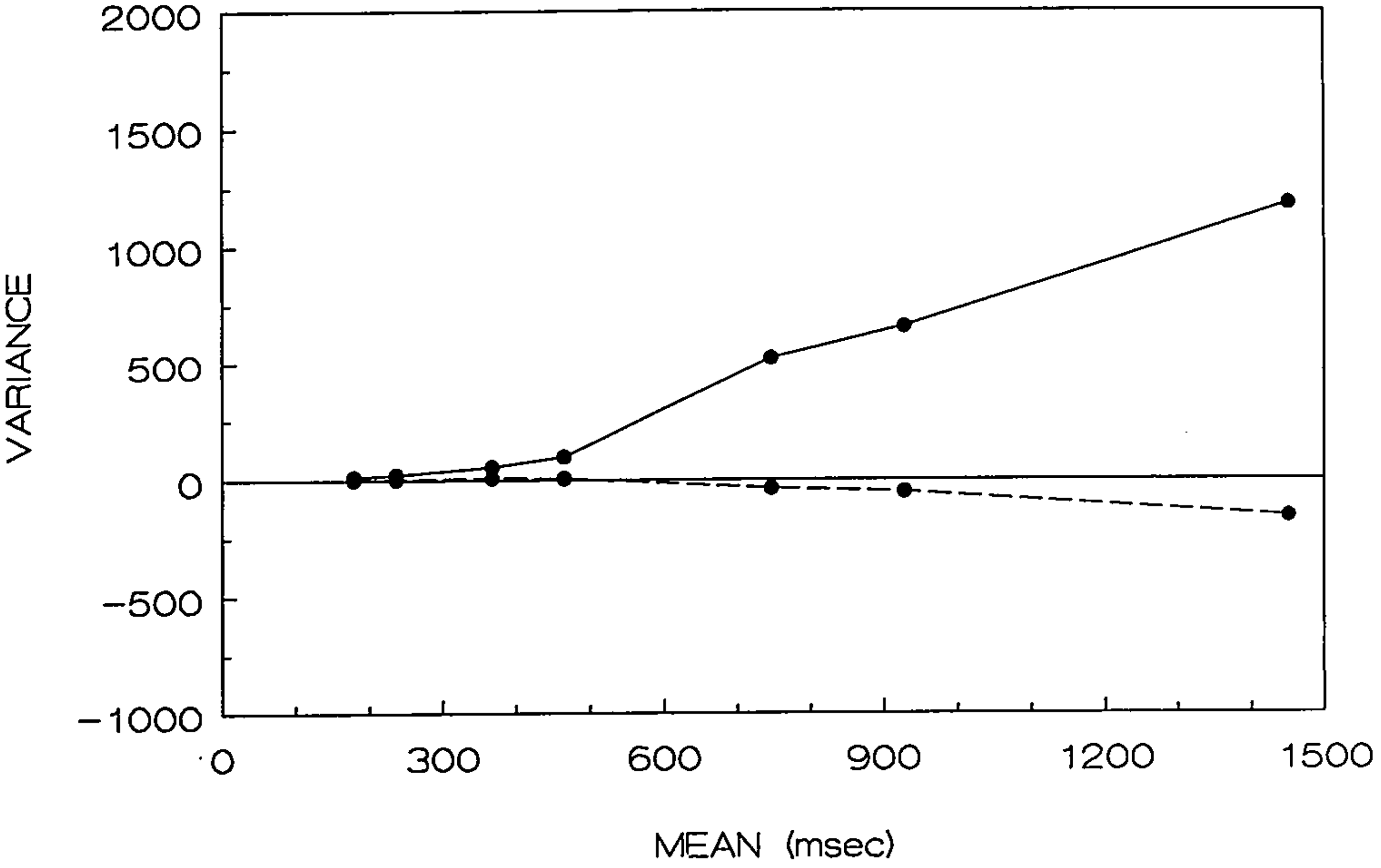
Continuation phase bias corrected s_C^2 (solid line) and s_D^2 (dashed line) plotted as functions of mean IRI for LL.



2000
1500
1000
500
0
−500
−1000
VARIANCE
0
300
600
900
1200
1500
MEAN (msec)

FIGURE 3.11

Continuation phase bias corrected s_C^2 (solid line) and s_D^2 (dashed line) plotted as functions of mean IRI for GF.



2000
1500
1000
500
0
−500
−1000
VARIANCE
0
300
600
900
1200
1500
MEAN (msec)

An analysis of the combined bias corrected CP s_D^2 indicates that there is no change in mean s_D^2 as a function of T [$F_{(6,13)} = 0.83$, $p > .05$]. This outcome supports the TPM prediction that s_D^2 is independent of T. For T less than or equal to 466 msec (the range studied by Wing, 1973) all bias corrected s_D^2 are small and positive. Mean s_D^2 for T in this range equals 50.6, 6.8, and 4.9 msec^2 for AK, LL, and GF respectively. Collapsing across subjects, mean s_D^2 equals 20.8 msec^2 which corresponds closely to Wing's (1973) estimates. However, bias corrected CP s_D^2 is frequently negative for T greater than 466 msec. This implies that the TPM is not valid for IRI timing for T greater than or equal to 734 msec. The exact value of T at which the model becomes invalid is located somewhere between 466 and 734 msec, but it cannot be more narrowly defined here because no values of T between 466 and 734 msec were studied.

When bias corrected values of s_C^2 are combined across Ss, ANOVA results indicate that mean s_C^2 changes as a function of T [$F_{(6,13)} = 13.27$, $p < 0.01$]. An analysis for a linear trend term reveals statistical significance [$F_{(1,6)} = 55.34$, $p < 0.01$]. Further analysis reveals a significant deviation from linearity [$F_{(5,6)} = 3.44$, $p < 0.05$], so the data were tested for a quadratic term. The quadratic term was highly significant [$F_{(1,6)} = 13.89$, $p < .01$] but the deviation from that term was not [$F_{(4,6)} = 0.55$, $p > 0.05$]. For the first time, these results provide evidence for the existence of a second order relationship between bias corrected CP s_C^2 and target duration. That relationship indicates that a simple stochastic central timekeeper is not involved with the timing of IRIs. Thus, the present analysis supports the interpretation based on the analysis of the biased CP s_C^2 vs m_I functions - both encourage an interpretation that is inconsistent with a simple stochastic timekeeper.

Although the simple stochastic model of the timekeeper can be rejected by these results, the results do not necessarily support a Weber's law interpretation. The main issue here is that the existence of a quadratic term in the s_C^2 function does not imply linearity in the s_C function. In order to support the Weber's law model one must also test for and demonstrate linearity in the s_C function. An ANOVA on the combined biased corrected s_C function reveals that mean s_C changes as a function of T [$F(6,13) = 20.33$, $p < 0.01$]. A statistically significant linear term exists [$F(1,6) = 104.2$, $p < 0.01$] and deviation from linearity was found not to be significant [$F(5,6) = 1.77$, $p > 0.05$].

Taken together, these results lead to the rejection of the proportional variance class of models <u>and</u> to the non-rejection of the proportional standard deviation class of models. This is a general level of support for Weber's law as it applies to motor timing and it is particularly important here because Weber's law generally has been shown to characterize DD data as well.

From figures 3.10 and 3.11 it is clear that extensive and specific practice does not result in the emergence of a step function for either LL or GF. Instead their functions increase throughout the entire range. It would be a fair description to say that there is a segment over the lower range of durations that has a relatively small slope compared to the segment over the upper range.

In contrast, a step function consisting of two steps did emerge in AK's bias corrected CP s_C^2 vs m_I function. Moreover, these steps appear to bear a striking resemblance to those found for the same subject in Kristofferson's (1980) DD experiment. They are located over the same temporal ranges as the two intermediate steps in Kristofferson (1980), and the ordinate at the higher tread is approximately twice that of the lower tread when converted into standard deviation or quantum units. The corresponding quantum values for these two steps are 27 and 44 msec.

The existence of these steps on AK's bias corrected s_C^2 vs m_I function could reflect the operation of a quantal timekeeper. But whether that is the case or not, the similarity of the two functions is of great importance for present purposes. At the very least this similarity indicates that the timekeeper(s) mediating MFDD (Kristofferson,

1980) and CP tapping have common psychophysical properties. This does not mean that one timekeeper mediates behaviour in both tasks but that is a distinct possibility. Having said that it must be pointed out that some significant differences in the two functions do exist. For example, only two steps are present in the tapping function, a clear departure from at least four steps shown to exist in the MFDD function (Kristofferson, 1980). This is in part due to the fact that tapping at the shortest base durations that were used in Kristofferson (1980) proved to be impossible. The demanding motor requirements of the task ruled out the opportunity to investigate AK's function over this low range of durations.

At the upper end of the temporal range, AK's tapping function differs in an important way from his DD function. The step that exists on the DD step function over the 800 to 1600 msec range does not exist on the tapping bias corrected s_C^2 vs m_I function. It is not clear how the tapping function changes over this upper range because only two durations were investigated within it.

The results of determining the best fitting case of each of Weber's, Creelman's, Getty's, and Kristofferson's models are reported in Table 3.11. Once again, Kristofferson's model provided the best fit and Creelman's model the worst fit in terms of minimizing the sum of squared deviations about the functions. This was the case even though special procedures were followed to estimate V_r for Getty's and Creelman's models. V_r was initially estimated by fitting the models to the first two data points on the functions. It was then entered into the procedure as a constant when the fitting procedure was applied to the entire set of points. Without this special procedure both models frequently returned a negative V_r.

Since all models based on Weber's law fitted the functions far better than Creelman's model, the proportional clock variance class of models must be rejected in

TABLE 3.11

Results of model fitting applied to the bias corrected continuation phase s_C vs m_I functions.

LEGEND:

SYMBOL	DESCRIPTION
SSE	sum of squared errors

All other symbols are parameter estimates of the respective models.

Model: Creelman

Subject	SSE	C	V_r (msec^2) (2)
AK	177	0.694	64
LL	92	0.374	0[a]
GF	223	0.530	0[a]

Model: Getty

Subject	SSE	K	V_r (msec^2)
AK(2)	29	0.027	93
LL(2)	10	0.020	9
GF(2)	35	0.025	1

Model: Weber

Subject	SSE	K
AK	51	0.029
LL	14	0.021
GF	36	0.025

Model: Kristofferson

Subject	SSE	K	V_o(msec^2)	L (msec)
AK	24	0.031	120	151
LL	10	0.020	13	0[a]
GF	34	0.026	0[a]	32

---

[a] would be negative if constraint not imposed

favour of the proportional clock standard deviation class of models. Furthermore, within the proportional standard deviation class of models, Kristofferson's model fitted the best.

There are substantial differences among the three subjects in all three of the parameters of Kristofferson's model so their results will be considered separately. For AK, K equals .031 which is identical to the value of K when the same model was fitted to his final PTDD Weber function. This is interesting because it suggests that the same Weber's law clock could be in operation over the upper range of durations for both PTDD and tapping. However, when V_0 and L are compared between these two paradigms important differences exist. The value of L for tapping (151 msec) is about half what it is for PTDD (301 msec). If L represents the upper limit on the duration of the deterministic interval then that interval is shortened in tapping. Furthermore, the shortening of L appears to coincide with a sixfold increase in V_0 (from 18.2 msec^2 in PTDD to 120 msec^2 in tapping). Thus a change in L appears to correspond with a change in V_0.

The situation is very different for LL. For her K and L are appreciably smaller for CP tapping than they are for PTDD. This could be interpreted to indicate that the Weber law and deterministic timekeepers are flexible and adaptable to the conditions to which S is exposed. The deterministic process appears to be flexible to the extent that a deterministic interval of 0 msec is possible (L equals 0 for LL's CP function). According to the deterministic interval hypothesis, this means that no deterministic interval is inserted into the timing chain of events for her in CP tapping. For the same S, L equals 361 msec for PTDD. If this equals the upper limit of L for LL, then it appears that the full range for L approaches 400 msec, in close agreement to the range identified by Kristofferson (1976) in R-SS.

V_0, on the other hand, is nearly the same for both paradigms for LL. It equals 15.5 msec^2 for PTDD and 13 msec^2 for CP tapping. This value, which here represents the minimum level of central timekeeper variance, is low in comparison to the values of V_o equal to 142 msec^2 (Kristofferson, 1976) and approximately 50 msec^2 (Hopkins & Kristofferson, 1980) in R-SS. The present value is probably lower than these because neither PTDD nor CP bias corrected clock variance functions have an efferent variance component included in them. In contrast, the efferent variance component had not been partitioned out of the R-SS estimates. This difference will be exploited in Chapter 4 in order to extract new efferent variance estimates.

When L equals 0 msec, as is the case for LL, Kristofferson's model becomes functionally, but not theoretically, equivalent to Getty's model. Both models should provide identical values of K, and V_o should equal V_r. However, due to the slight modification in the procedure to estimate V_r, V_r is slightly smaller than V_o. For both models K equals 0.02.

V_o, is here interpreted to be a measure of minimum central clock variance. For AK it equals 120 msec^2 and for LL it equals 13 msec^2 but for GF it equals 0 msec^2. It seems unlikely that central variance can reach the absolute minimum of 0 msec^2, but such a deterministic central timekeeper must be considered as a possibility. Extremely low variances in R-SS together with ongoing improvements after 80,000 trials prompted Hopkins and Kristofferson (1980) to ask whether the lower limit on variance is greater than zero. If a deterministic timekeeper exists for GF, it appears to operate over the very narrow range of 0 to 32 msec. Since no base durations were investigated in this range it is impossible to make a clear statement regarding this possibility.

The analysis provided 32 msec as the value of L for GF but that was partially due to the positive constraint that was placed on V_o. Since Vo would have been slightly negative, V_o and L must be considered as only close approximations in terms of describing GF's CP s_C vs m_I function. However, since L is very small, V_o would have been a very small negative number indicating that K is a fairly accurate representation of the rising portion of his function. This is further supported by the fact that K is 0.025 in both the original Weber's law model and Getty's generalization of it, a value extremely close to the value of K based on Kristofferson's model (0.026).

In this section the original TPM (Wing & Kristofferson, 1973) was used to generate s_C^2 and s_D^2 from the IRI tapping sequences in the CP. These parameters were then used to determine how clock and motor delay variances change as a function of m_I. In the next section several generalizations of the TPM will be evaluated and the impact on the clock and delay variance functions will be discussed.

GENERALIZATIONS OF THE TPM

BIAS AND AUTOCOVARIANCE FUNCTIONS

A main prediction of the TPM is that $\rho_I(1)$ (and hence $\gamma_I(1)$) should be negative. In fact the TPM goes further and states that all $\gamma_I(k)$, for k greater than 1, should equal zero. In contrast, none of the four generalizations of the TPM which have been derived by Wing (1977) makes that prediction. Each one predicts that some $\gamma_I(k)$ for k greater than 1 should differ from zero. Furthermore, since each has a uniquely shaped autocovariance function (the predicted shape for each was discussed in the Introduction) it should be possible to choose the one that best matches the obtained functions. In this section, autocovariance functions for lags k equal to 0 to 5 will be analyzed in an attempt to determine which predicted function best matches the obtained functions on the basis of minimizing the sum of squared errors.

It was reported above that on several occasions $G_I(1)$ was greater than zero, a result that casts doubt on the validity of the TPM for these data. The TPM also predicts that all $\gamma_I(k)$ for k greater than 1 should equal zero. Upon analysis of $G_I(k)$ for k greater than 1 it is clear that on many occasions it does differ from zero, and with rare exception, it is negative in value for these cases. Because several of the generalizations of the TPM predict that $\gamma_I(k)$ should be negative for k greater than 1, the IRI autocovariance functions were analyzed in terms of how well they conformed to the predictions of each of the four generalizations.

IRI autocovariance functions for k equal to 0 to 5 were computed for each sequence of the last five sessions for each T. Autocovariances with two standard errors of estimate about each mean $G_I(k)$ are shown in Fig. 3.12 as a function of k for each S and T. Estimates of the parameters of the best fitted theoretical autocovariance functions for the TPM and its four generalizations were determined for each obtained function. This was done initially by imposing constraints on all parameter estimates such that the absolute value of the correlation parameter was not allowed to be greater than 1 and variance parameters were not allowed to be less than zero. Table 3.12 summarizes the results of this analysis in which the roman numerals indicate the best fitting generalization for each combination of S and T.

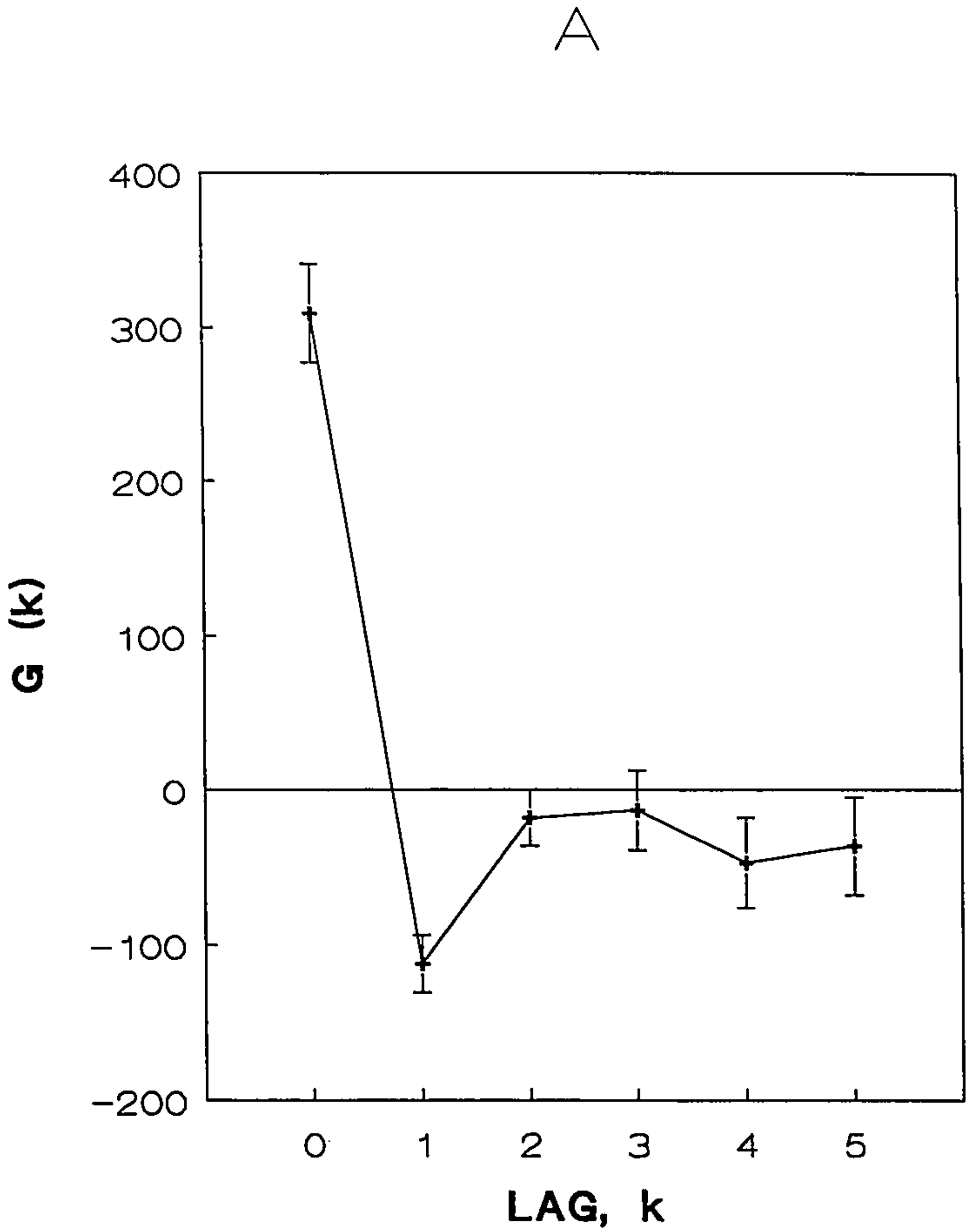
These results show that Model III describes the CP IRI autocovariance functions best overall; only the three highest values of T for GF and T equal to 466 for AK were better fitted by other generalizations. Overall they indicate that adjacent delay intervals (D_j) are correlated in the CP IRIs; only three of the twenty CP autocovariance functions analyzed provide evidence suggesting correlated clock intervals (C_j; Model I for GF). In addition, they suggest that the correlation takes a first order autoregressive (AR(1)) form.

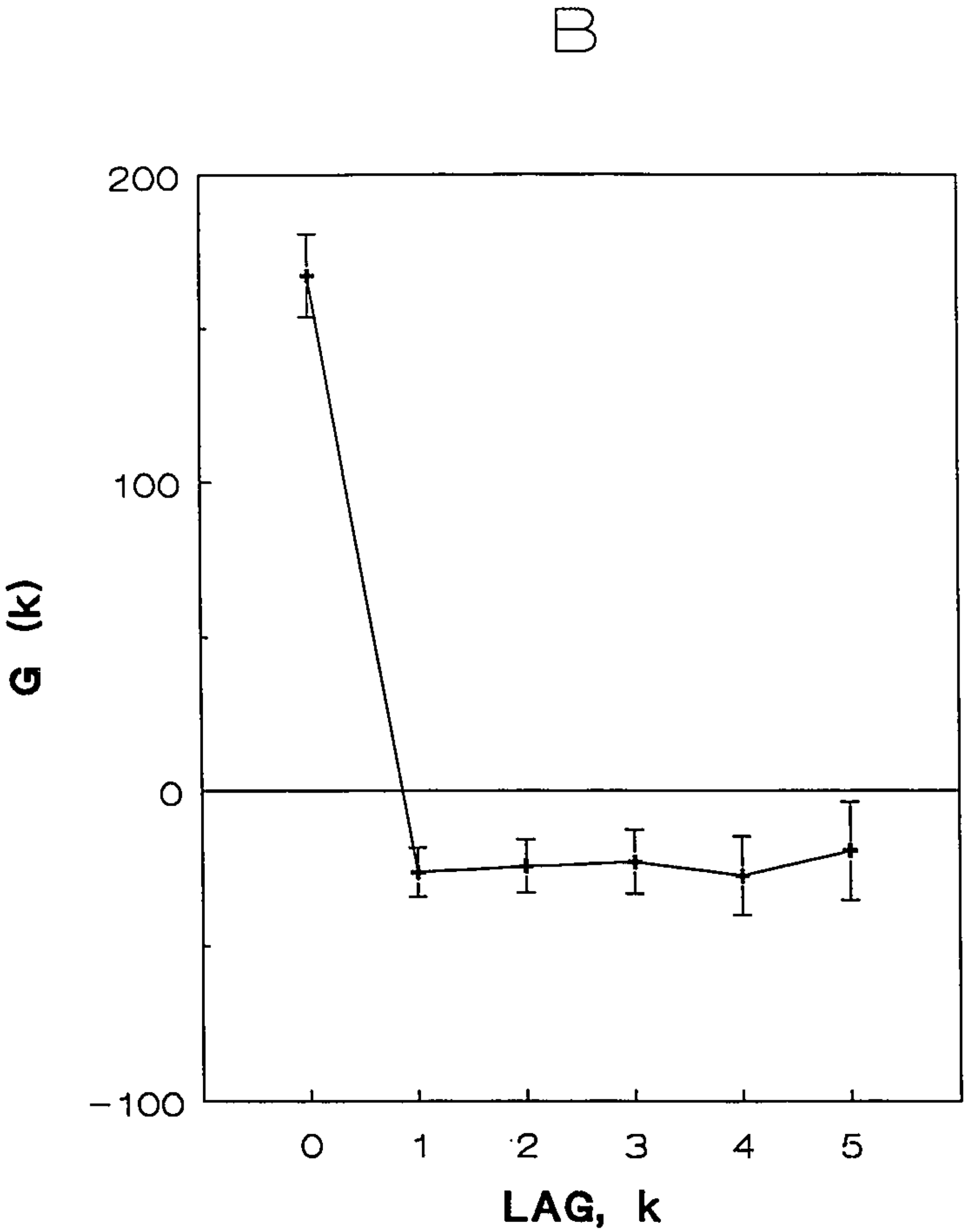
In two separate experiments Wing (1973; 1977) published results consistent with the interpretation that CP responses have AR(1) correlated D_j. Hence, the present results corroborate Wing's findings. However, as stated in the Introduction, Wing (1973; 1977) reported that estimates of the correlation parameter (θ) were negative for very short T and that they approached zero and became positive as T increased. This is not the case here. For both AK and LL estimates of θ are greater than zero and they slowly increase with T. The results for GF are consistent with Wing's in that estimates of θ are negative for three of the four short values of T and positive for the others. The conclusions that

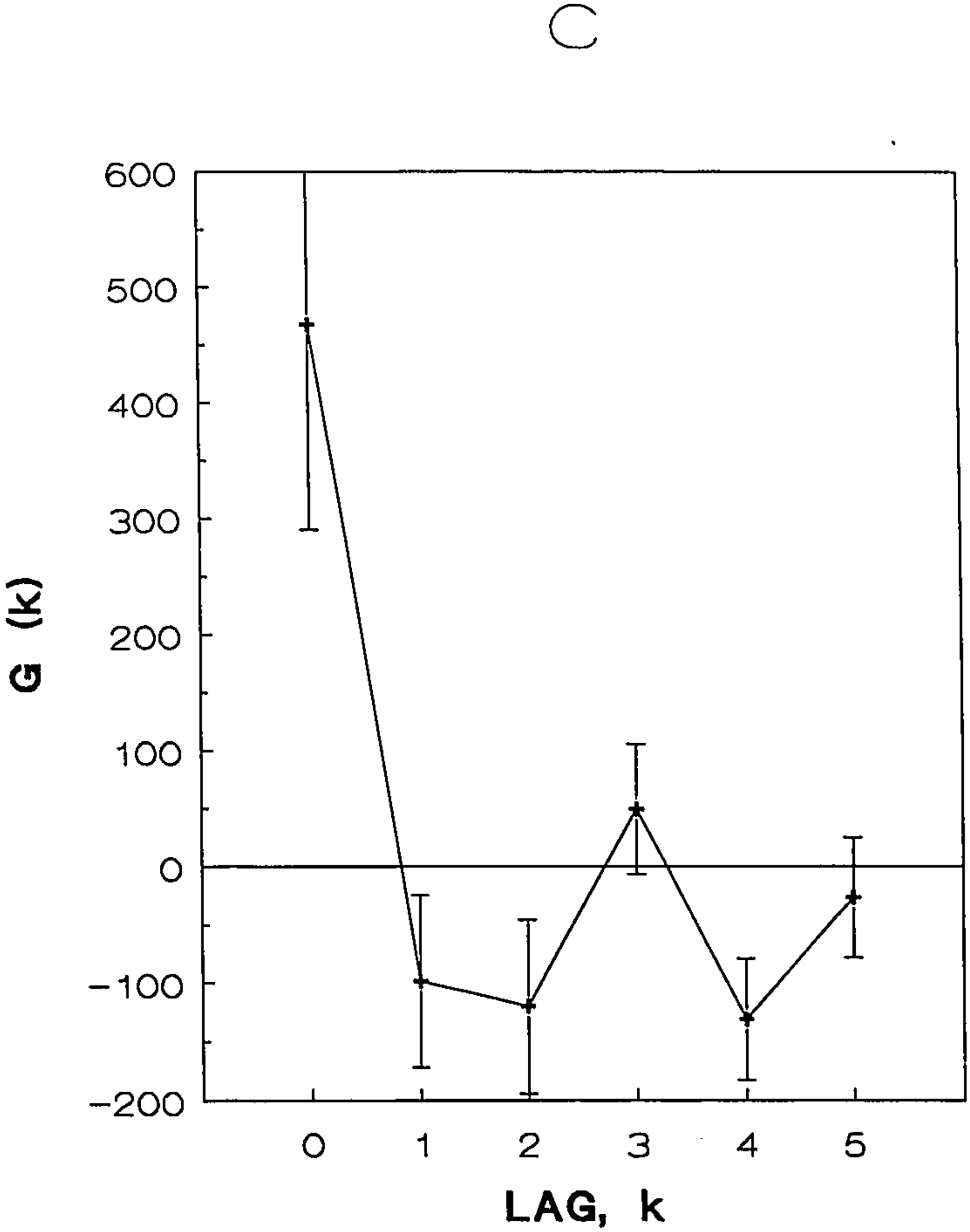
FIGURE 3.12

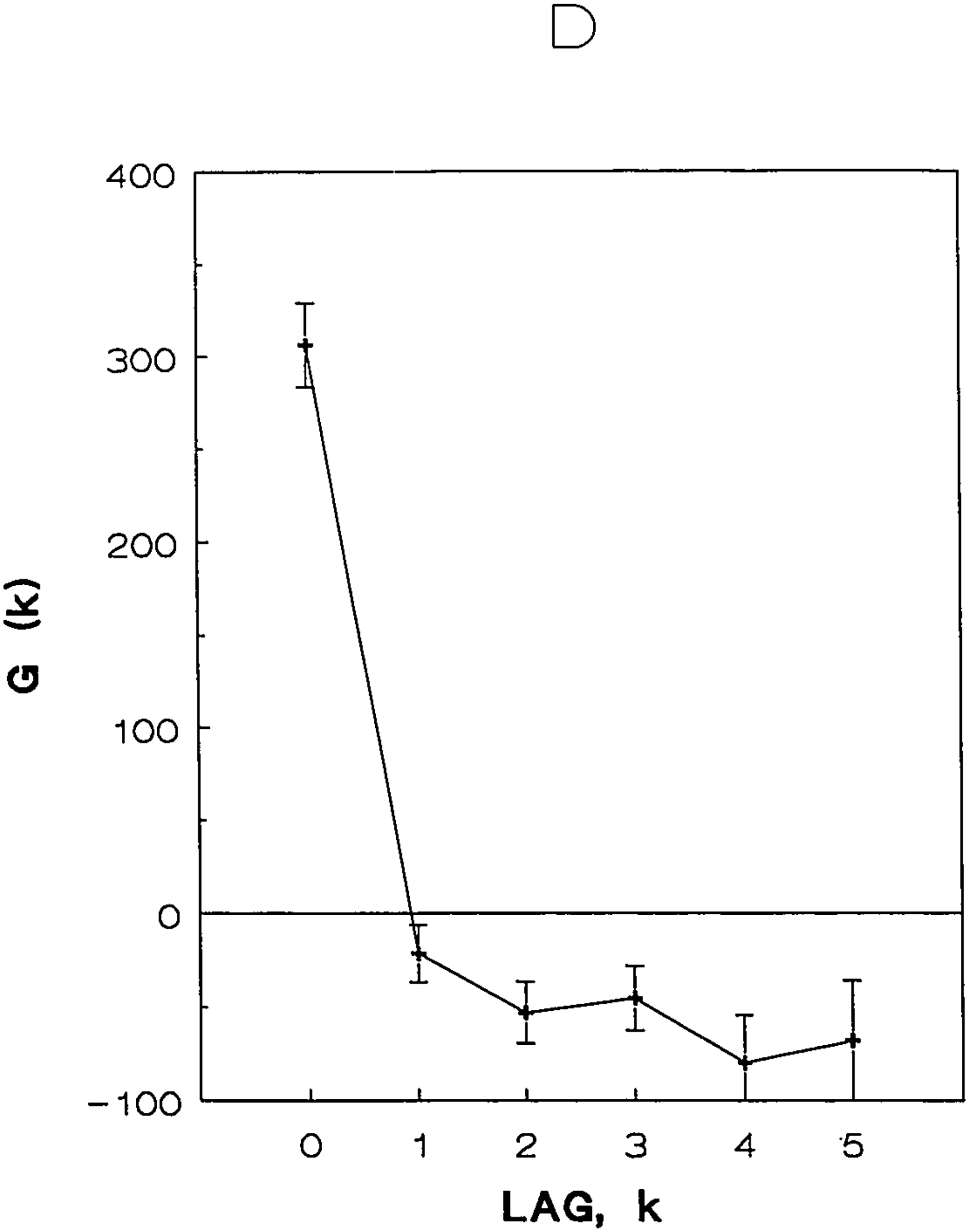
Bias corrected autocovariance functions, for lags 0 to 5, with two standard errors of estimate about each mean $G_I(k)$.

PANEL	SUBJECT	T (msec)
A	AK	233
B	AK	367
C	AK	466
D	AK	734
E	AK	932
F	AK	1468
G	LL	175
H	LL	233
I	LL	367
J	LL	466
K	LL	734
L	LL	932
M	LL	1468
N	GF	175
O	GF	233
P	GF	367
Q	GF	466
R	GF	734
S	GF	932
T	GF	1468

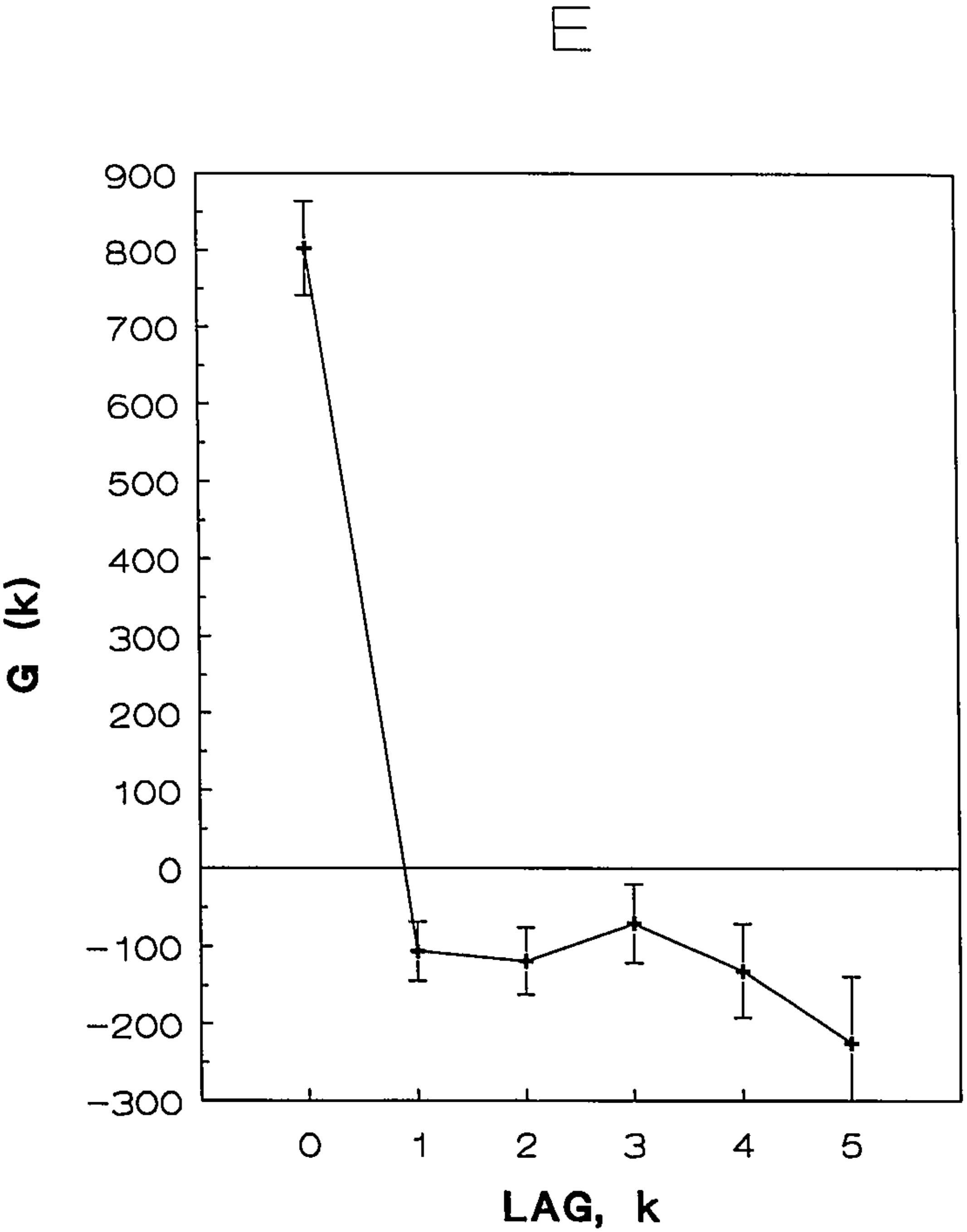

A
400
300
200
100
0
−100
−200
G (k)
0
1
2
3
4
5
LAG, k

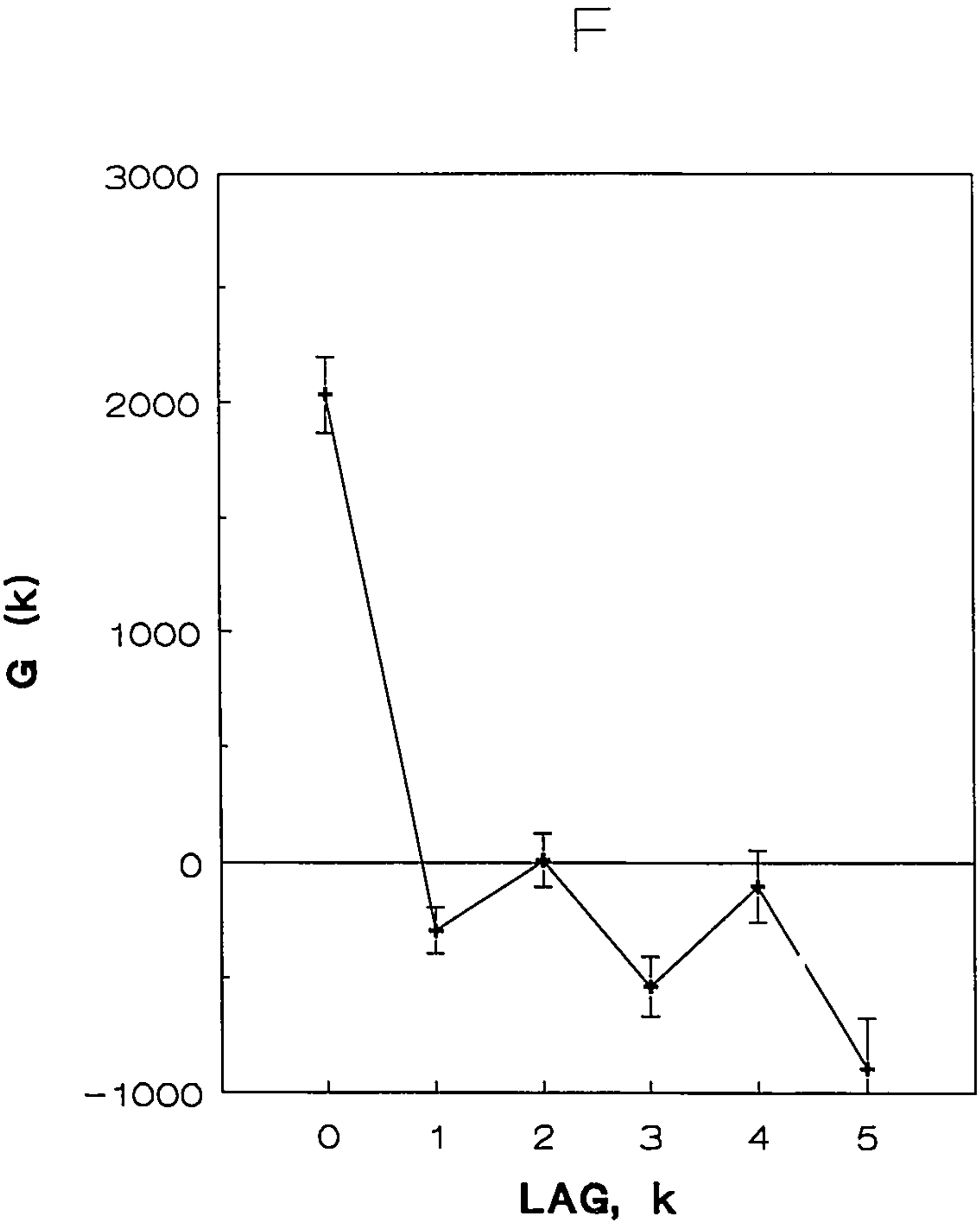

B
200
100
0
−100
G (k)
0
1
2
3
4
5
LAG, k

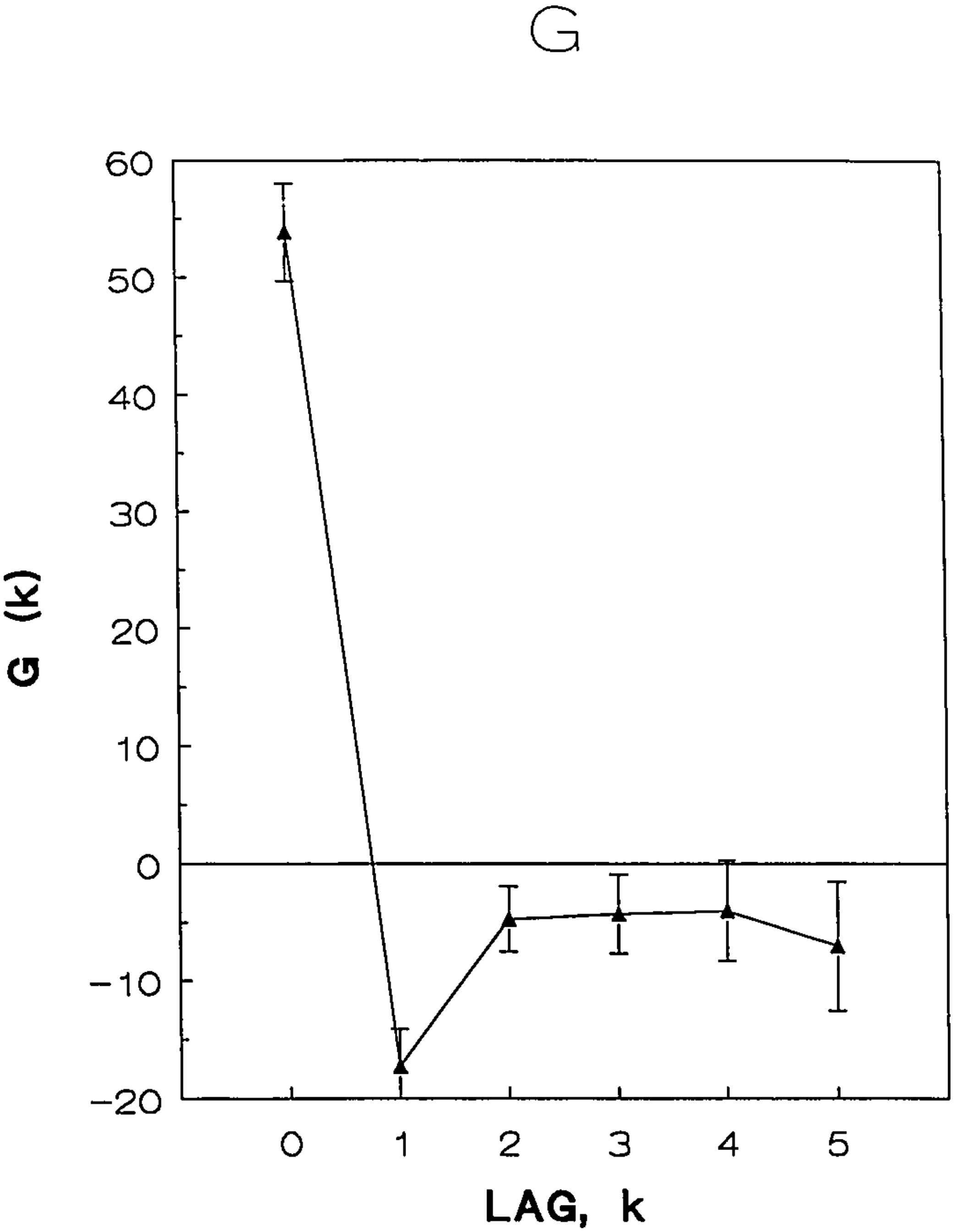

C
600
500
400
300
200
100
0
−100
−200
G (k)
0
1
2
3
4
5
LAG, k



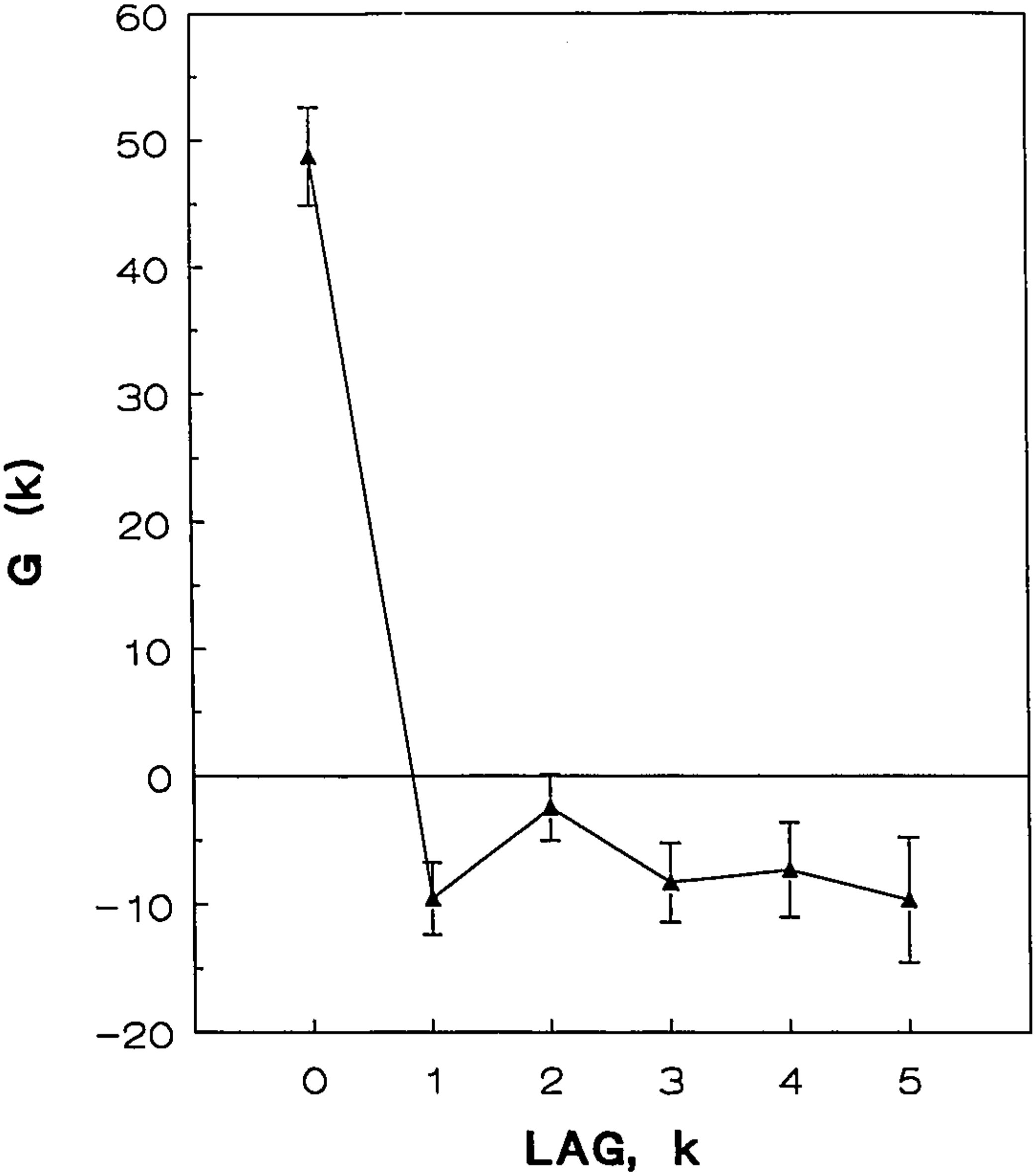
D
400
300
200
100
0
−100
G (k)
0
1
2
3
4
5
LAG, k

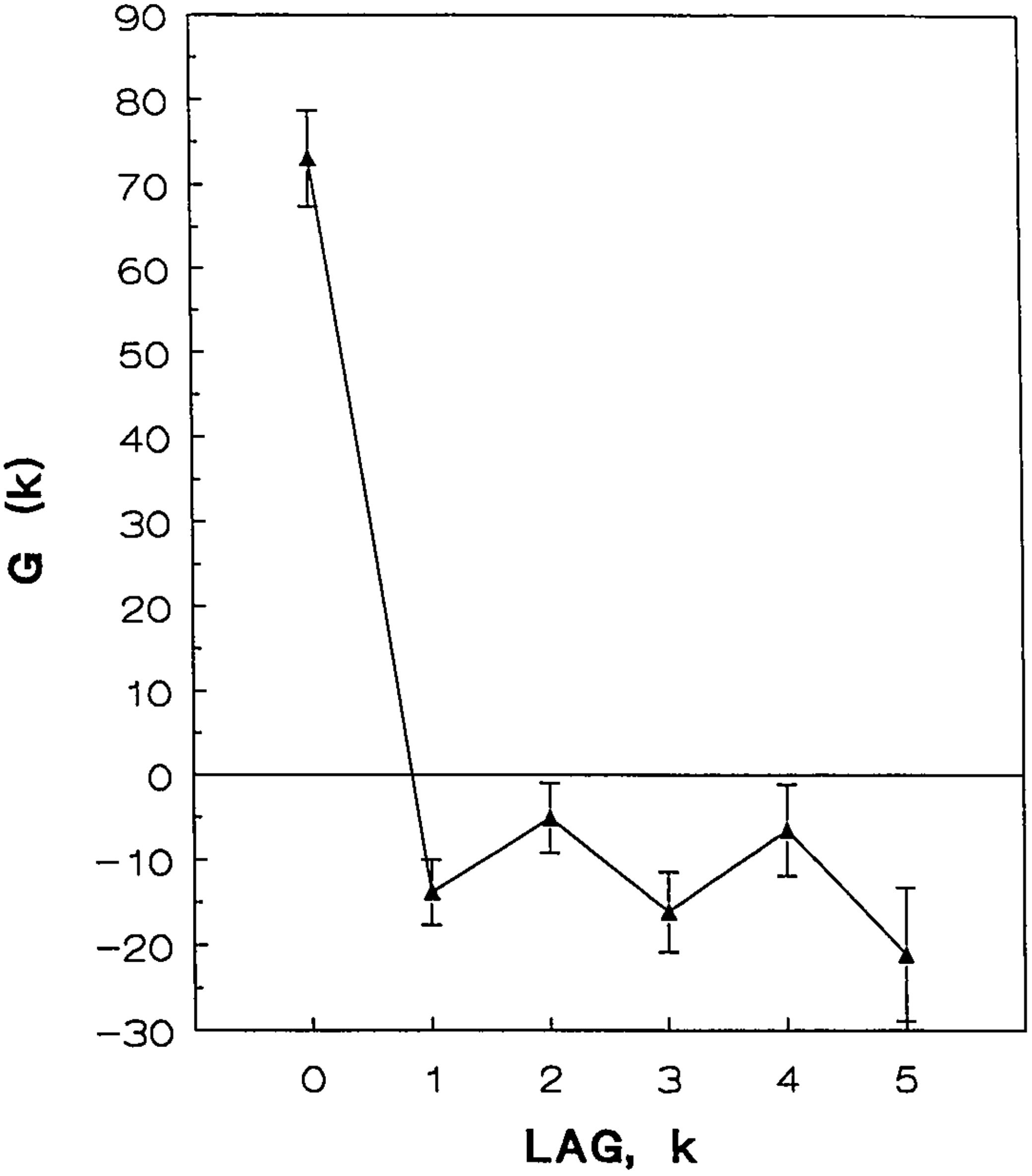

E
900
800
700
600
500
400
300
200
100
0
−100
−200
−300
G (k)
0
1
2
3
4
5
LAG, k


F
3000
2000
1000
0
−1000
G (k)
0
1
2
3
4
5
LAG, k

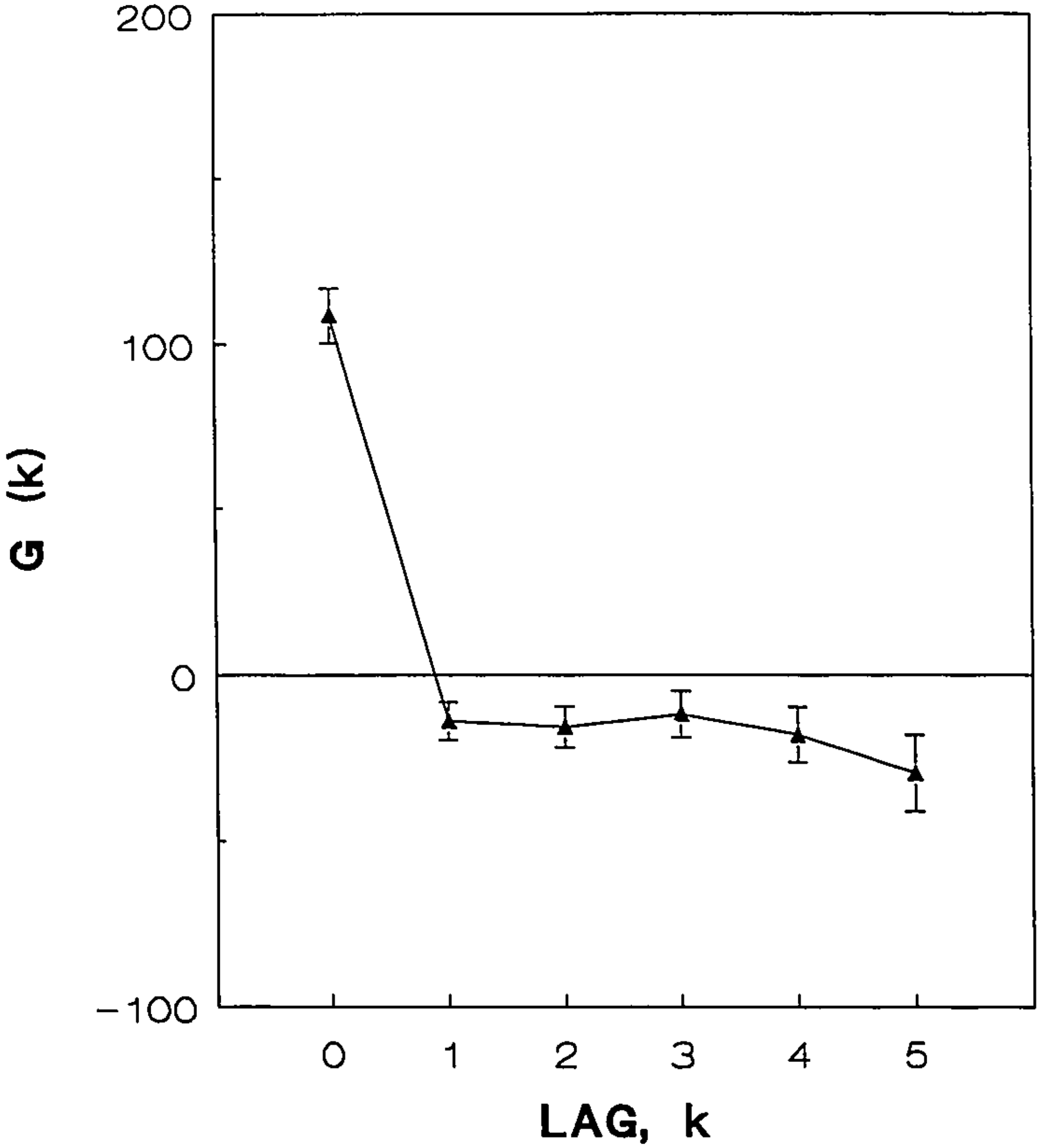

G
G (k)
60
50
40
30
20
10
0
−10
−20
0
1
2
3
4
5
LAG, k

H

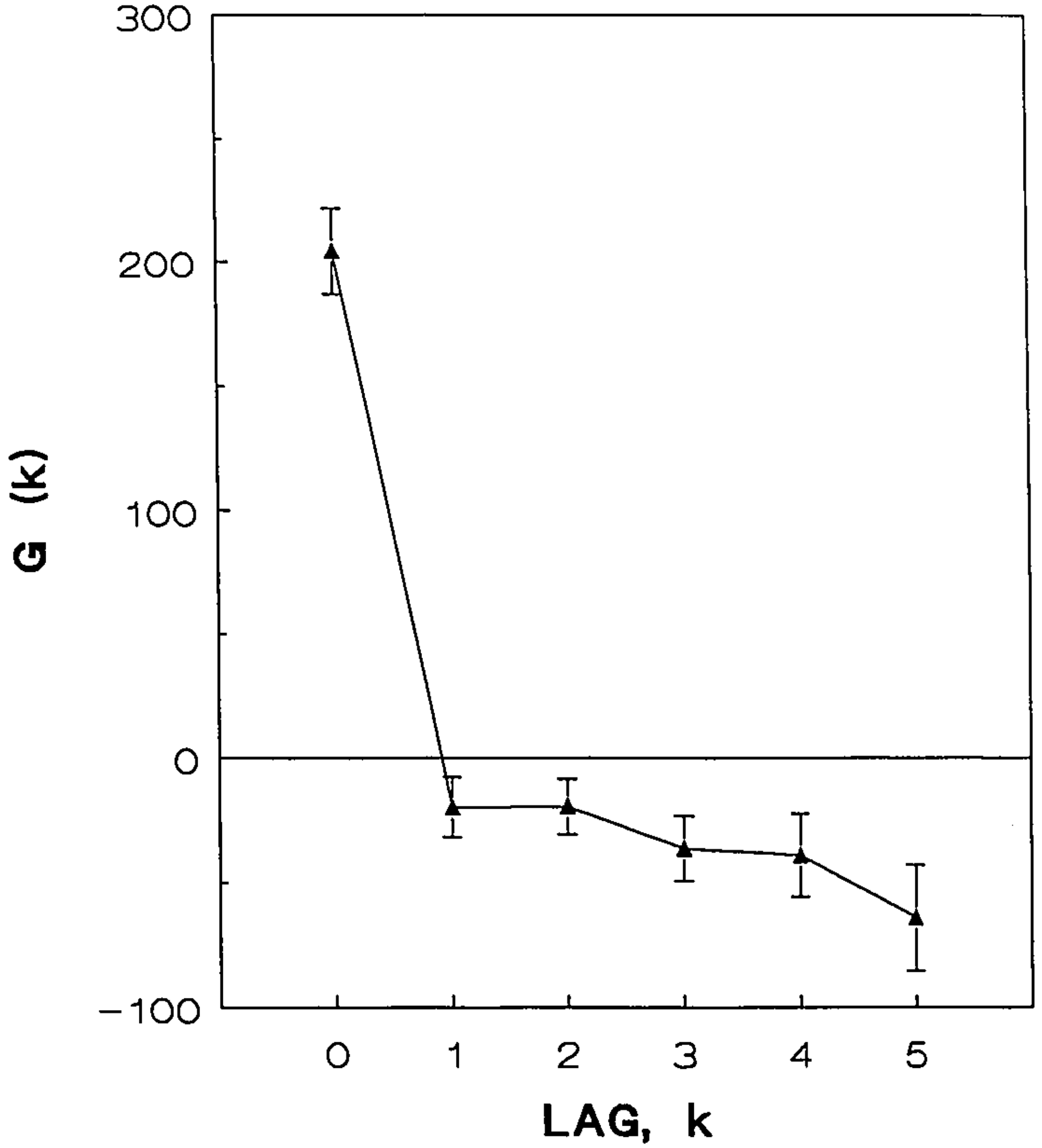



90
80
70
60
50
40
30
20
10
0
−10
−20
−30
G (k)
0
1
2
3
4
5
LAG, k

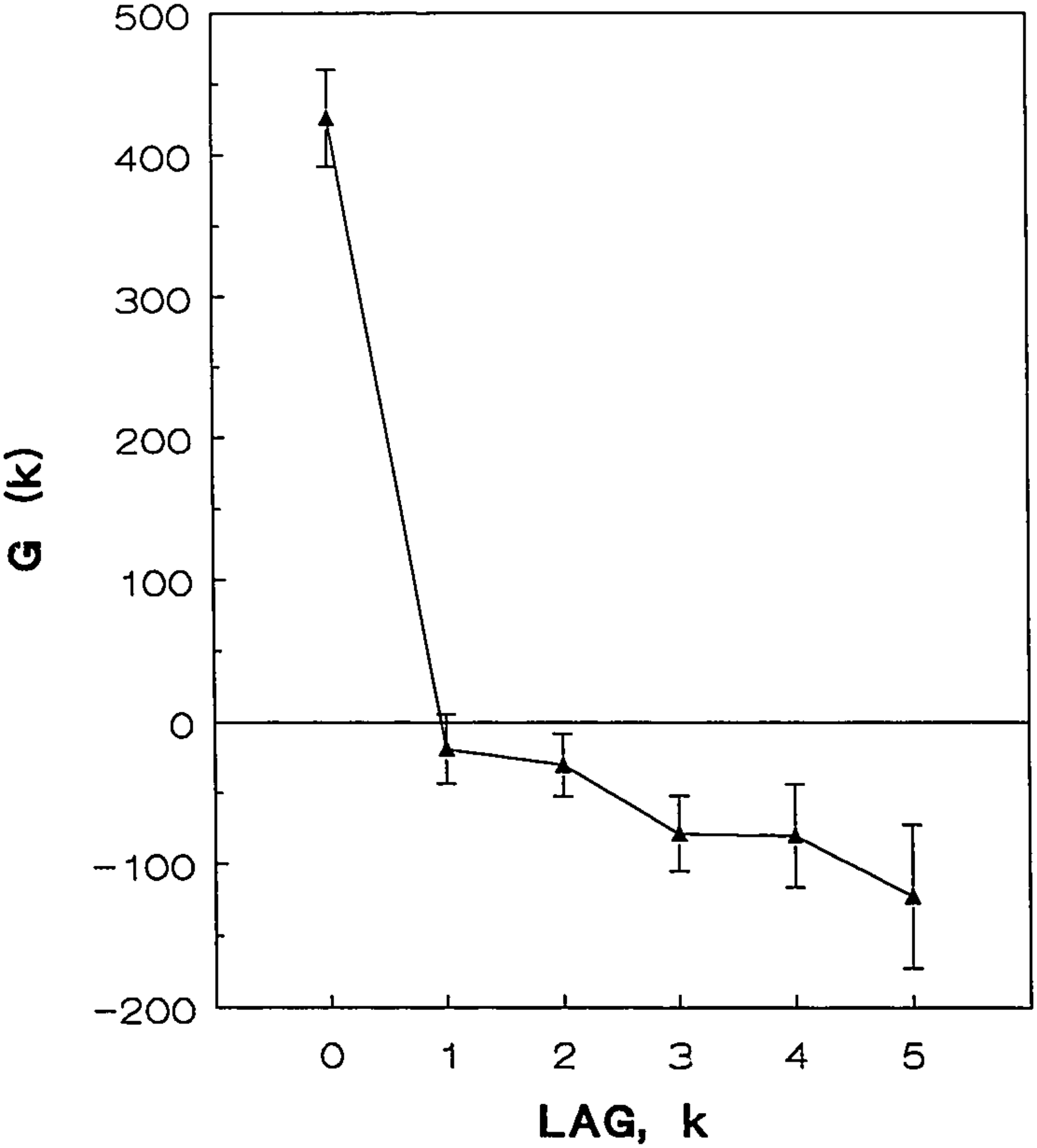
J



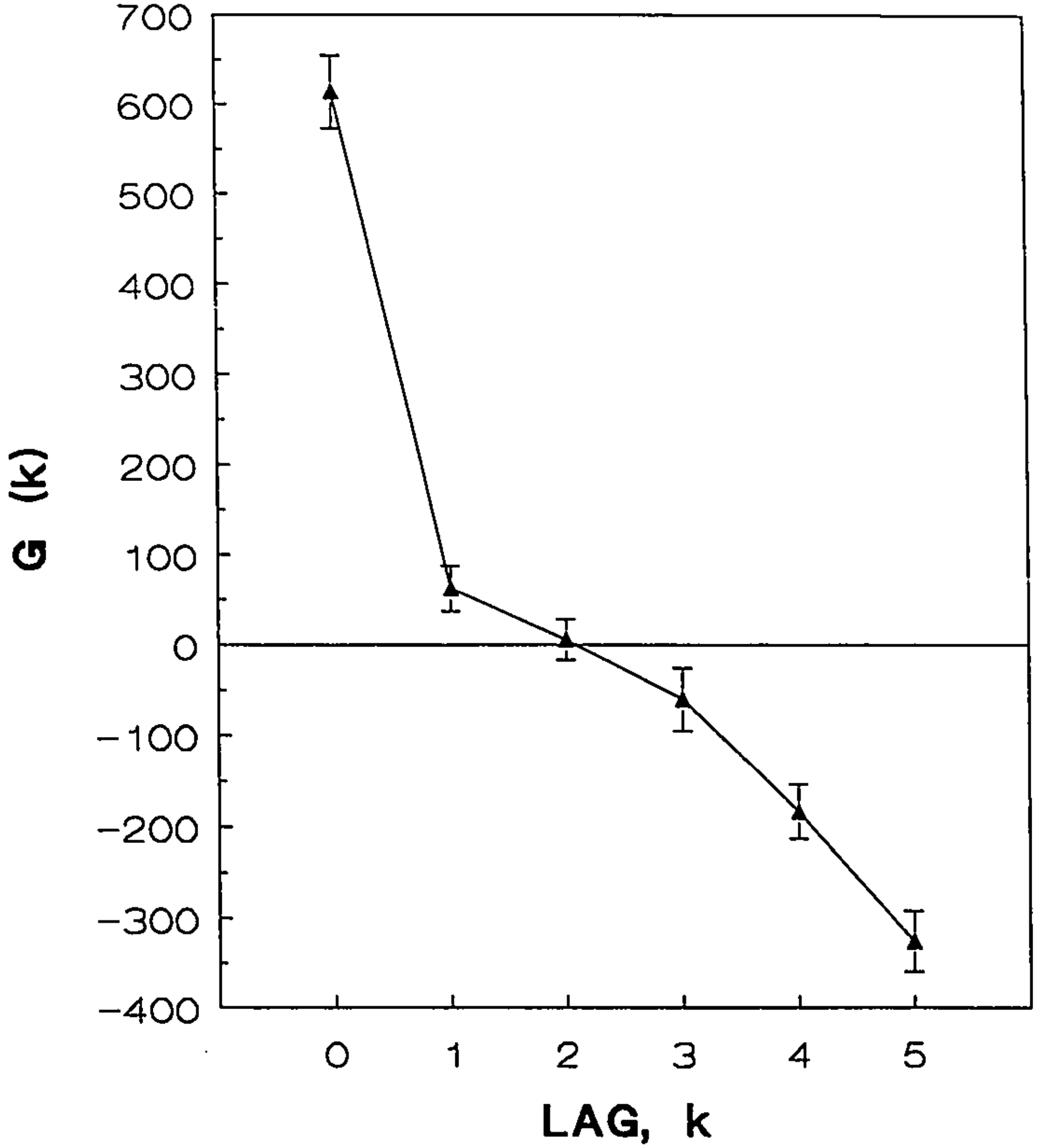
K



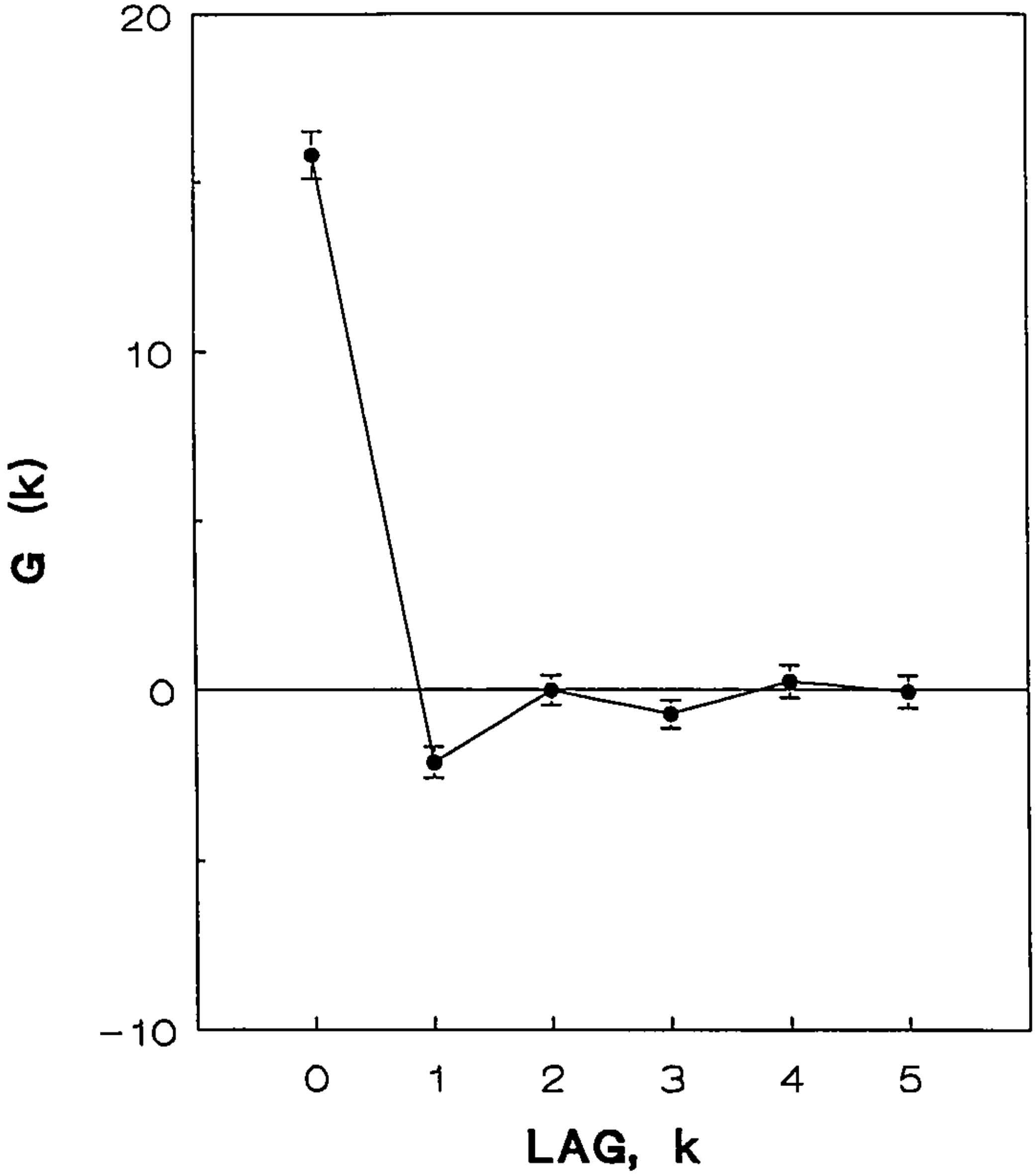
L

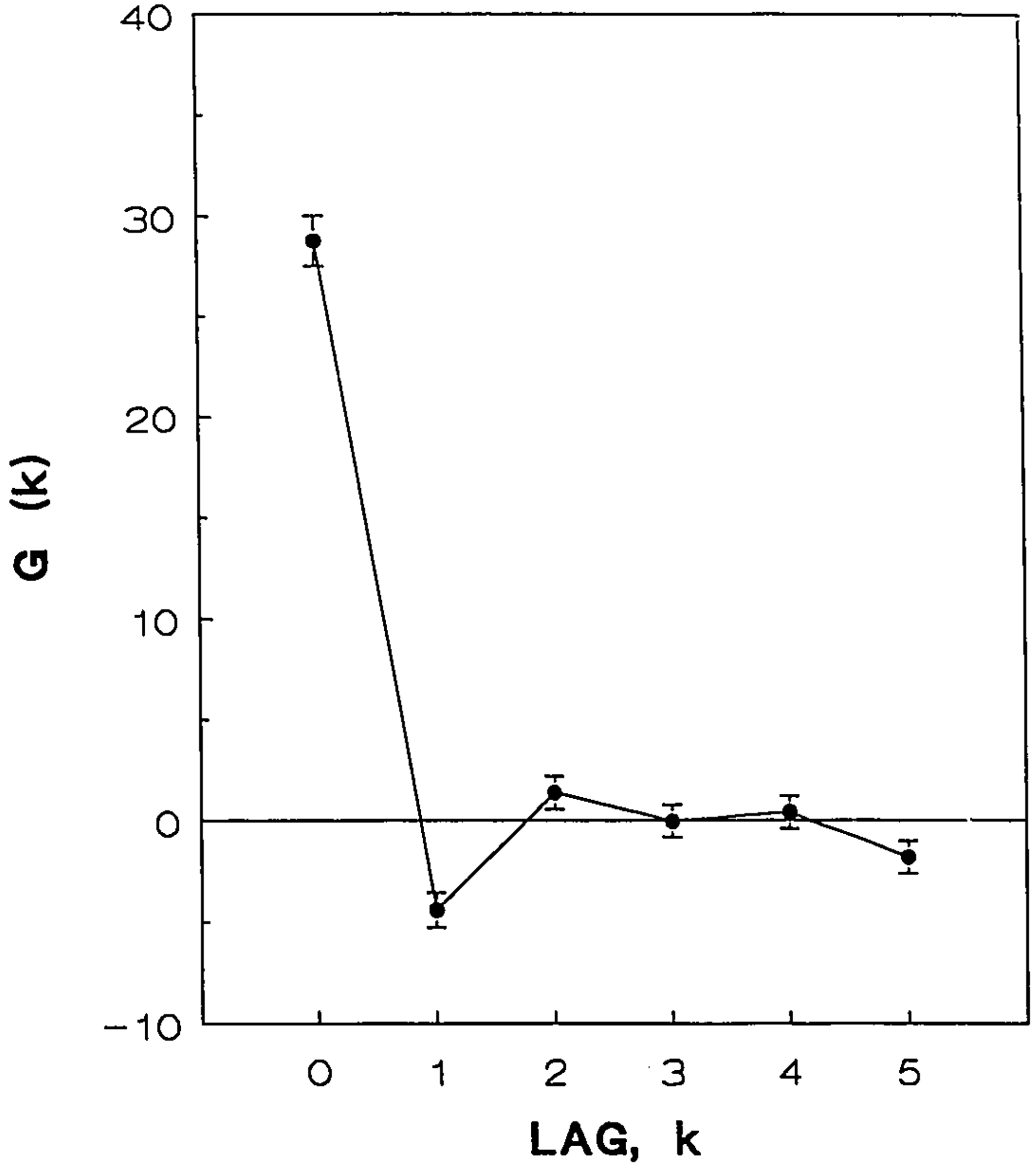


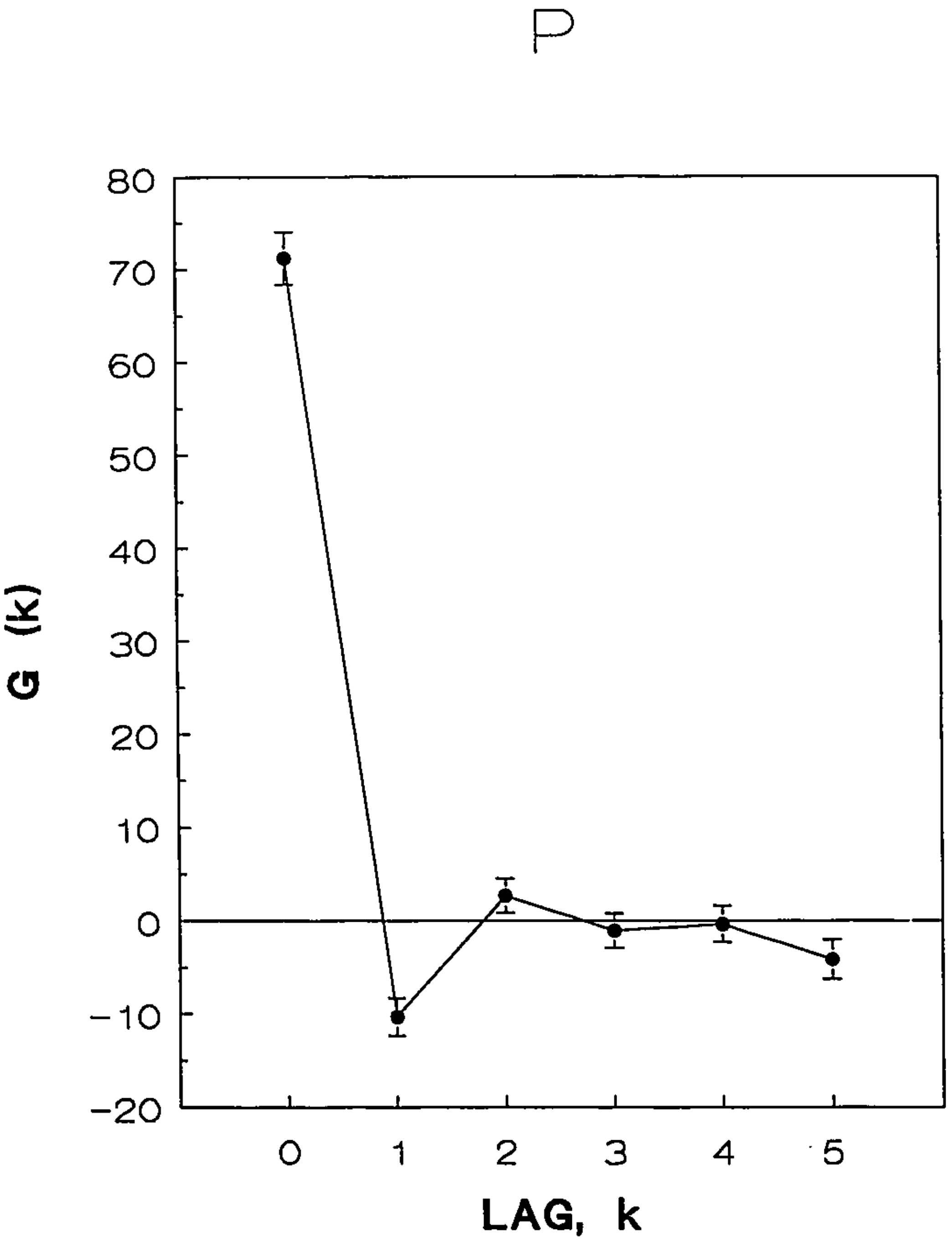
M

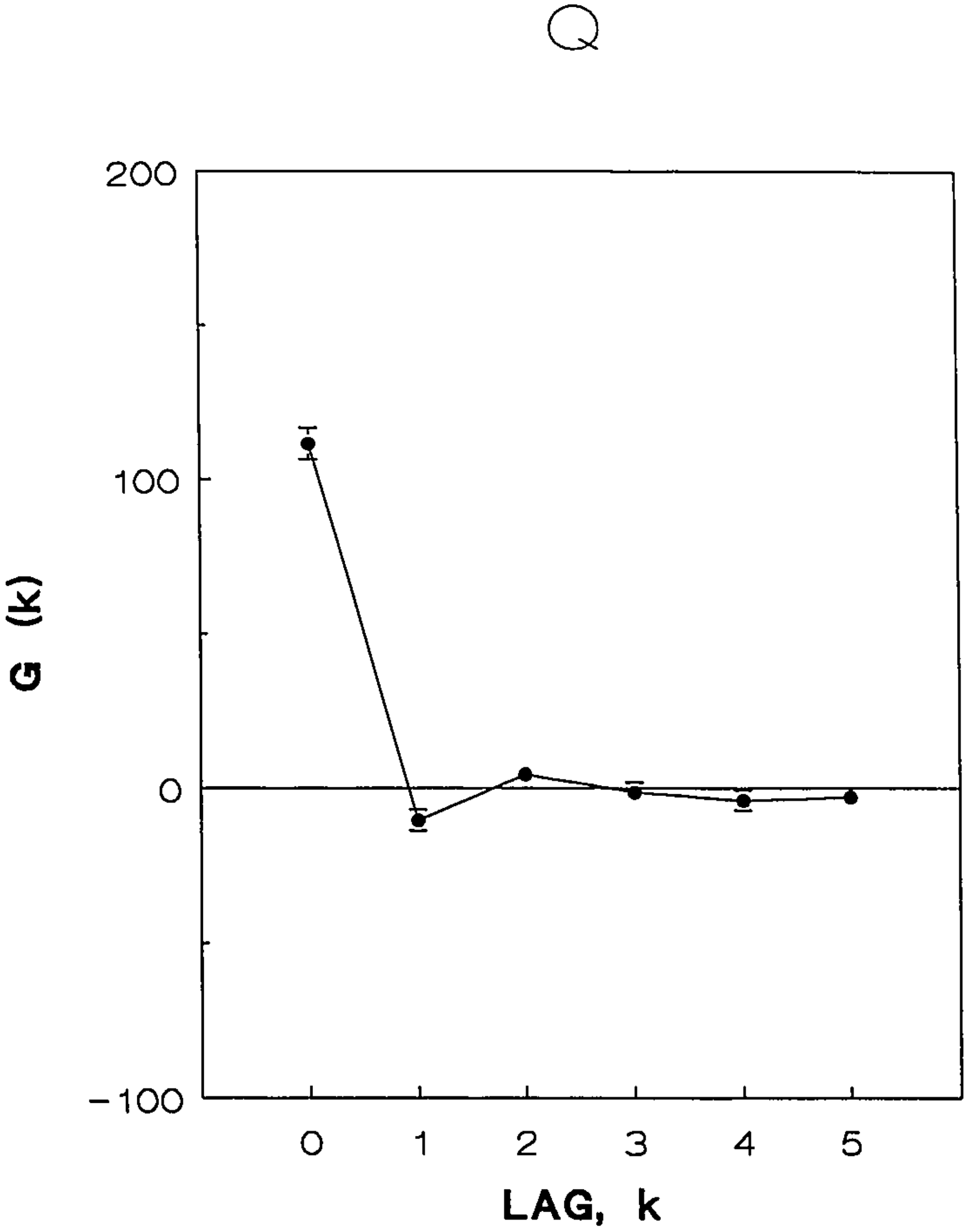


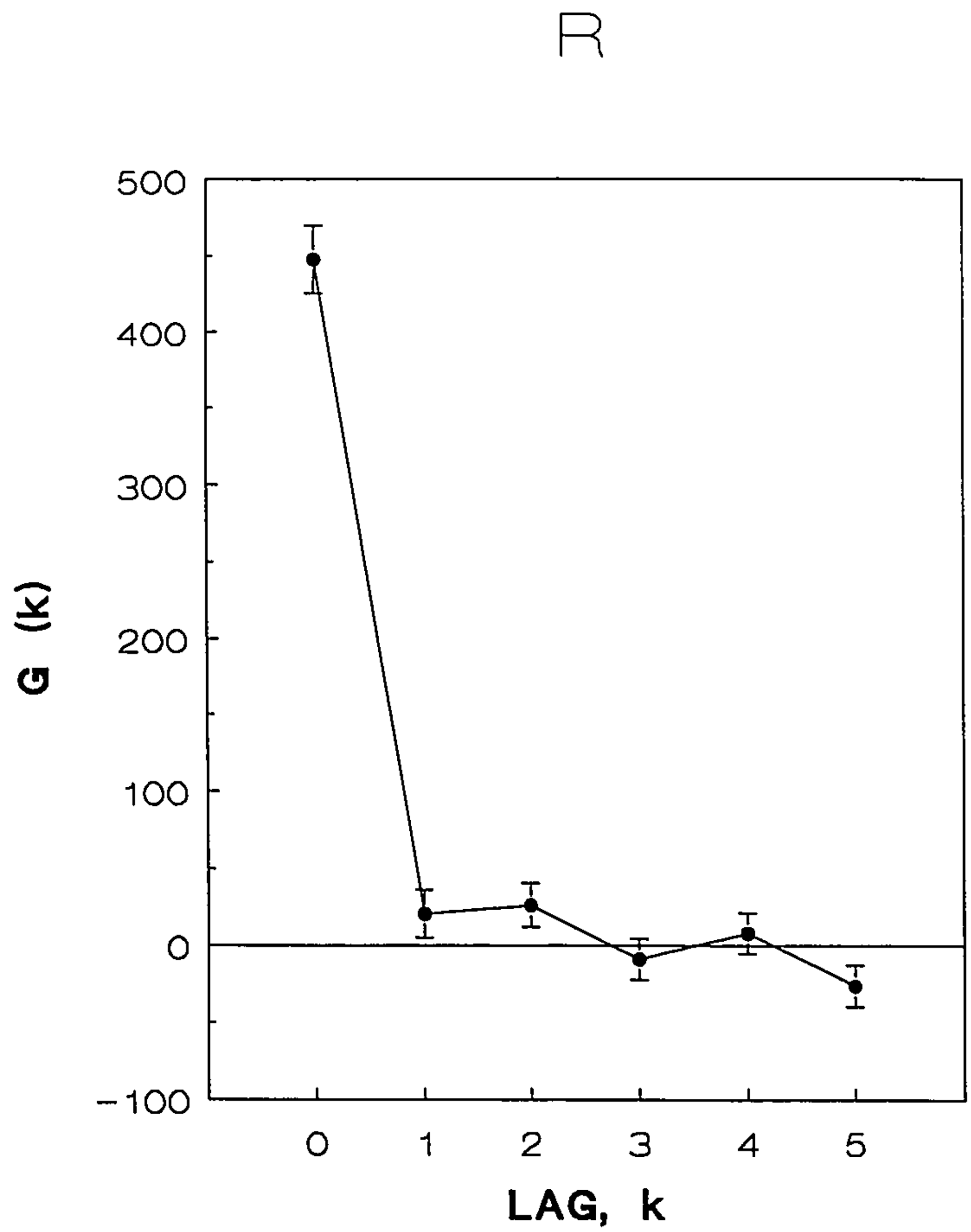
N

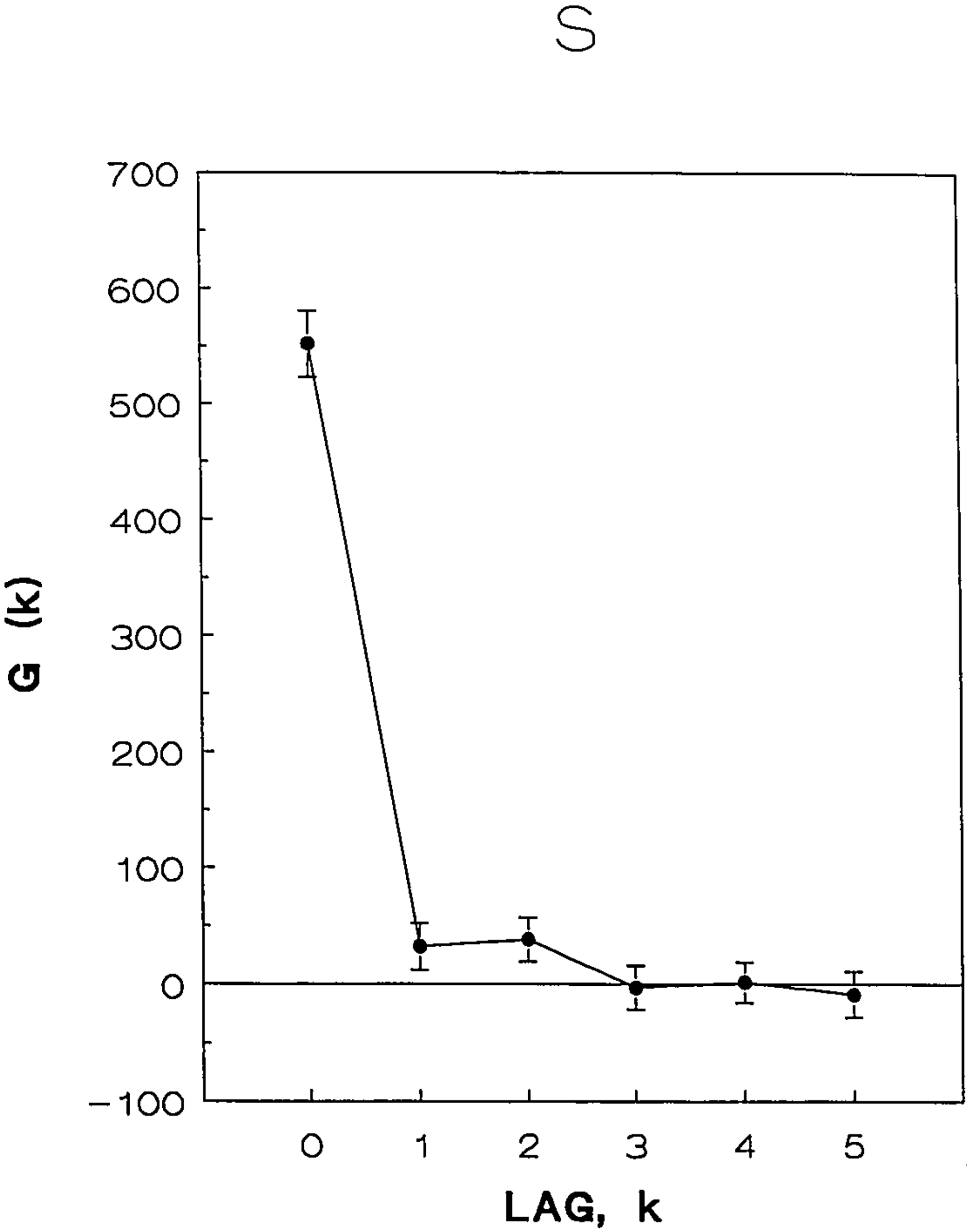



40
30
20
10
0
−10
G (k)
0
1
2
3
4
5
LAG, k


P
80
70
60
50
40
30
20
10
0
−10
−20
G (k)
0
1
2
3
4
5
LAG, k


Q
200
100
0
−100
G (k)
0
1
2
3
4
5
LAG, k


R
G (k)
500
400
300
200
100
0
−100
0
1
2
3
4
5
LAG, k


S
G (k)
700
600
500
400
300
200
100
0
−100
0
1
2
3
4
5
LAG, k

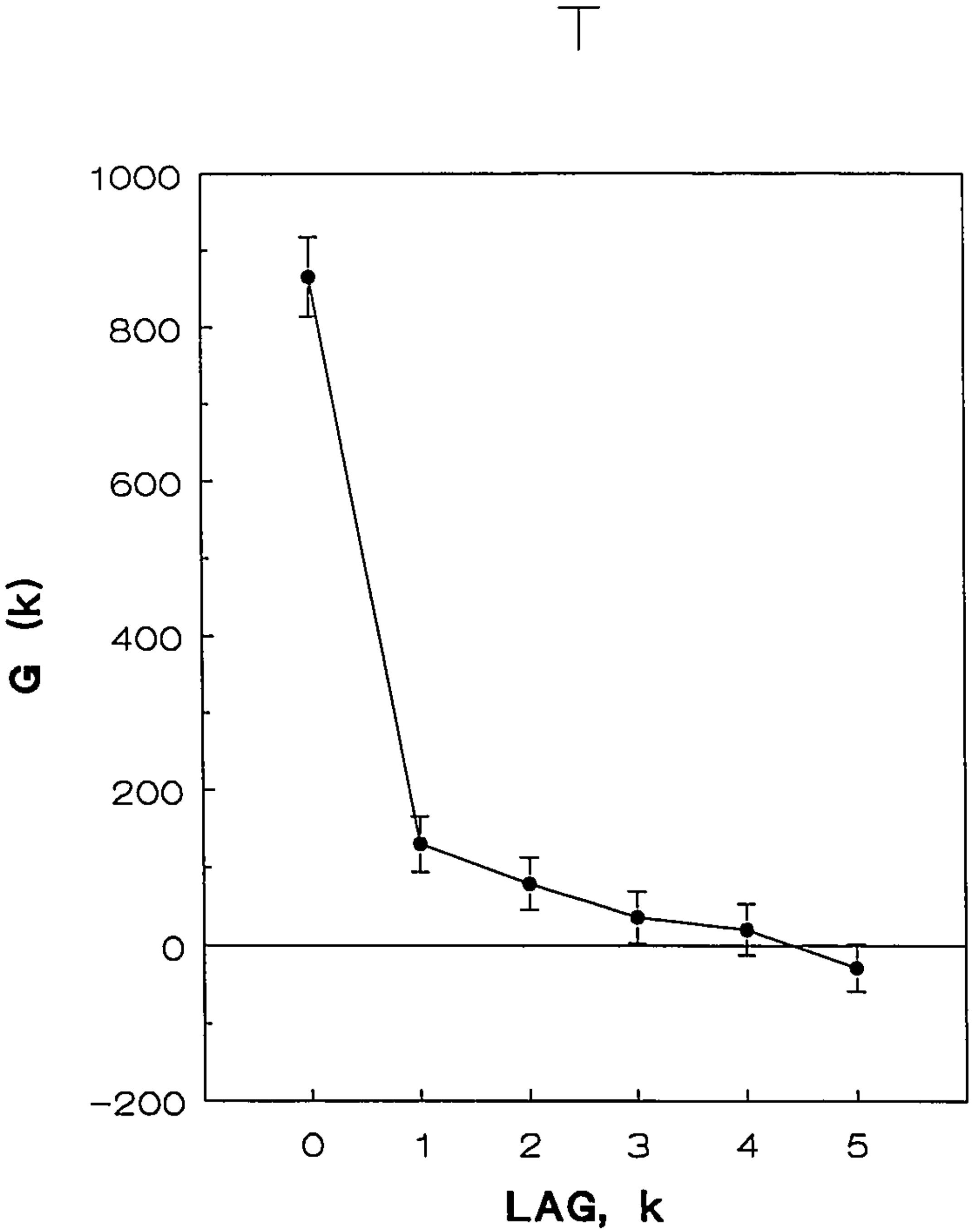

T
1000
800
600
400
200
0
−200
G (k)
0
1
2
3
4
5
LAG, k

TABLE 3.12

Results of fitting four generalizations of the TPM to the CP IRI autocovariance functions.

LEGEND:

SYMBOL	DESCRIPTION
I	Model I
II	Model II
III	Model III
IV	Model IV

T (msec)	AK	LL	GF
175		III	III
233	III	III	III
367	III	III	III
466	IV	III	III
734	III	III	I
932	III	III	I
1468	III	III	I

emerge from these comparisons are that D_j is correlated in the CP according to an AR(1) process for the full range of T tested and that θ increases with T.

When s_C^2 and s_D^2 are obtained by fitting Model III (or any of the other TPM generalizations) to the biased obtained autocovariance functions, often they are large and negative when the procedure does not place constraints on them. Since negative variance makes no sense its existence casts doubt on the validity of the Model that generates it. When constraints are placed on these statistics, all s_C^2 are zero for LL and AK when Model III fits the CP autocovariance functions the best. This contrasts with Wing's (1977) estimates which he graphically shows to be between 50 and 100 $msec^2$ for T = 400 msec. However, values of s_D^2 are on the same order of magnitude as those reported by Wing (1977) (between 150 and 300 $msec^2$ approximately). The results of AK and LL indicate that all the variance in the IRI times arises from variance in D_j. This suggests that if there is a central process involved in the timing of IRIs there is no variance associated with the timing of intervals by that process. However, there is an alternative explanation to the invariant timekeeper hypothesis and it is one that is associated with bias in $G_I(k)$.

In order to assess how bias due to sequence length alters the degree to which the four generalizations of the TPM fit the obtained autocovariance functions, the approach suggested by Vorberg (1978) and used by Wing (1979) was adopted. Their approach, which was discussed earlier, consists of generating what will be called biased predicted theoretical autocovariance functions for each model. The biased predicted theoretical functions will be compared to the biased obtained functions. A model is rejected if any of the biased theoretical autocovariance estimates fall outside two standard errors of the biased obtained autocovariances.

The results of this analysis indicate that Model III is still superior to the others; a smaller number of biased theoretical autocovariance estimates fall outside two standard errors of the biased obtained autocovariances for Model III than for any of the other generalizations. The fit is not perfect as several of the biased theoretical autocovariance estimates fall outside two standard errors of the obtained autocovariances. Nevertheless, the evidence supports the idea that the correlation in response delays is of the AR(1) form.

SUMMARY

Extensive practice greatly reduces CP s_I^2 but no steps were found on the s_I^2 vs m_I functions. Thus the idea that the timing of IRI in the CP is under the control of a quantal process is not supported. Evidence consistent with a deterministic timekeeper was identified in the Weber functions in the form of the flat segment over small values of T for AK and GF. However, the length of the intervals identified were different than those identified by Kristofferson (1976) in R-SS. In general those functions lowered in position such that the Weber parameter, K, in Kristofferson's model was reduced to nearly half its original value. Partitioning s_I^2 according to the TPM reveals that s_D^2 is negative for large T and positive, and in the expected range, for small T. This result supports the position that the TPM is valid for T less than about 466 msec and invalid for T greater than about 734 msec. It is impossible to state where between 466 and 734 msec the transition takes place because no base intervals between those two values were used. Lastly, and of paramount importance for the present investigation, the s_C^2 vs m_I relationship has a significant quadratic component which leads to the rejection of the proposition that s_C^2 increases linearly with m_I. Thus the idea that a simple stochastic timekeeper is in operation must be rejected. For one S (AK) two steps were identified on the s_C^2 vs m_I function. The existence of these steps suggests the possibility that under certain circumstances timekeepers that mediate MFDD and CP IRI timing have common psychophysical properties. Based on the current data it is not possible to conclude that these steps on AK's Weber function reflect the operation of a quantal timekeeper that exhibits deterministic properties. However, because steps do not exist on either LL's or GF's function it appears that, if the steps do reflect a quantal timekeeper, that such a timekeeper is not generally available to all Ss. A quantal timekeeper should not be ruled out by these findings because we know that steps emerge only after very extensive and specific practice. Of the three Ss AK has had by far the most experience with psychophysical procedures.

Initially the tapping investigation set out to test several hypotheses regarding the operation of the CP motor timekeeper. The SP was included in the procedure as a means to set the motor clock in order to generate CP IRIs. There was no intention to test hypotheses regarding timekeeping of SP IRIs because no model for repetitive synchronization was available at that time. During the course of experimentation that gap has been filled to some extent with the development of the SCM.

The SCM is a generalization of the TPM to SP IRI timing. It involves a re-interpretation of the two component processes and it offers a new framework for the analysis of repetitive synchronous IRI timing. This is important first because it may provide insight on the validity of the assumption that the SP timekeeper sets the IRI timekeeper for the timing of repetitive responses in the CP. Second, it is important because it might provide new knowledge on how repetitive responding is accomplished in the presence of exogenous auditory stimulus pulses.

SYNCHRONIZATION PHASE: RESULTS AND DISCUSSION

INTERRESPONSE INTERVAL TREND ANALYSIS

Figure 3.2 shows SP and CP m_I, computed over the last five sessions, as a function of position in the response sequence. The error bars represent two standard errors about the mean. From these figures it is immediately evident that the means of the first few SP IRIs differ from the rest. This difference represents the stage of responding during which synchronization is being established. Being interested only in those intervals for which synchronization has already been established, the first five SP IRIs will not be considered.

There is a marked difference between the SP and CP m_I vs sequence position curves. Most importantly the SP sequences are much more stationary. The following table lists the proportion of SP sequences within the last five sessions that contain statistically significant monotone trends. First, the results shown in Table 3.13 indicate that the proportion of sequences that contain monotone trends is lower than that which is expected to occur under the null hypothesis. Second, there is a higher probability that a sequence will contain a monotone trend when T is smaller than 466 msec than when T is greater than that. In summary, a highly stationary process underlies IRI generation in the SP, and this is especially true for T in the upper range studied.

In terms of the differences between the means of the first and second halves of the SP IRI sequences, the results parallel those of the CP. Many of the cases examined reveal that a band defined by two standard errors about the mean difference in means does not include zero. Only 50% of the SP cases gave this result in comparison to 80% for the CP. This further supports the idea that there is a smaller tendency toward non-stationarity within SP IRI sequences. Also, since the magnitude of the differences are at most only 1% of m_I, and usually much less, responding in the SP is considered to be controlled by a stationary process.

INTERRESPONSE INTERVAL DISTRIBUTIONS

Figure 3.3 shows relative frequency polygons of the distributions of SP IRIs within the last five sessions for each S and T. As a general description, SP IRI response frequency distributions are more sharply peaked than their CP counterparts. Also, the latter are broader and more irregular in shape than the former, and the modal bin of the SP distributions are positioned more directly over T. The modal

TABLE 3.13

The proportion of synchronization phase seqences within the last five sessions at each T for each subject that contain statistically significant monotone trends. Analyses based on Mann's test for trend with significance level set at .05.

T (msec)	AK	LL	GF
175		.112	.036
233	.016	.084	.007
367	.020	.096	.018
466	.008	.020	.000
734	.008	.024	.000
932	.000	.000	.000
1468	.004	.004	.000

bins of the CP distributions were often displaced to the right or left of T by a small amount, but they too were often positioned directly over T. In summary, the SP distributions are centered more closely over T and are less variable than their CP counterparts.

INTERRESPONSE INTERVAL VARIANCE ESTIMATES AND PRACTICE EFFECTS

Mean within session SP IRI standard deviation, s_I, generally reduced as a subject gained more practice. Figures 3.13 through 3.15 illustrate this trend by plotting SP mean s_I as a function of session number. Just as was the case for the CP s_I practice curves, the reduction in SP s_I is gradual and an asymptotic level of variance takes many sessions to achieve. Applying Mann's test for monotone trend indicates that 80% (16 out of 20) of the SP s_I practice curves contain a negative monotone trend. This too is consistent with the CP analysis which leads to the conclusion that SP IRI variability decreases with practice.

The initial (s_F) and final (s_L) levels of SP variability were obtained using the same procedure that was used to estimate CP s_F and s_L. The best fitted logarithmic, power, and exponential functions were determined for each of the SP s_I practice curves. Using the best of these three functions, the predicted point at the first session yielded s_F and the predicted point at the last session, s_L. Table 3.14 shows SP s_F and s_L for each subject.

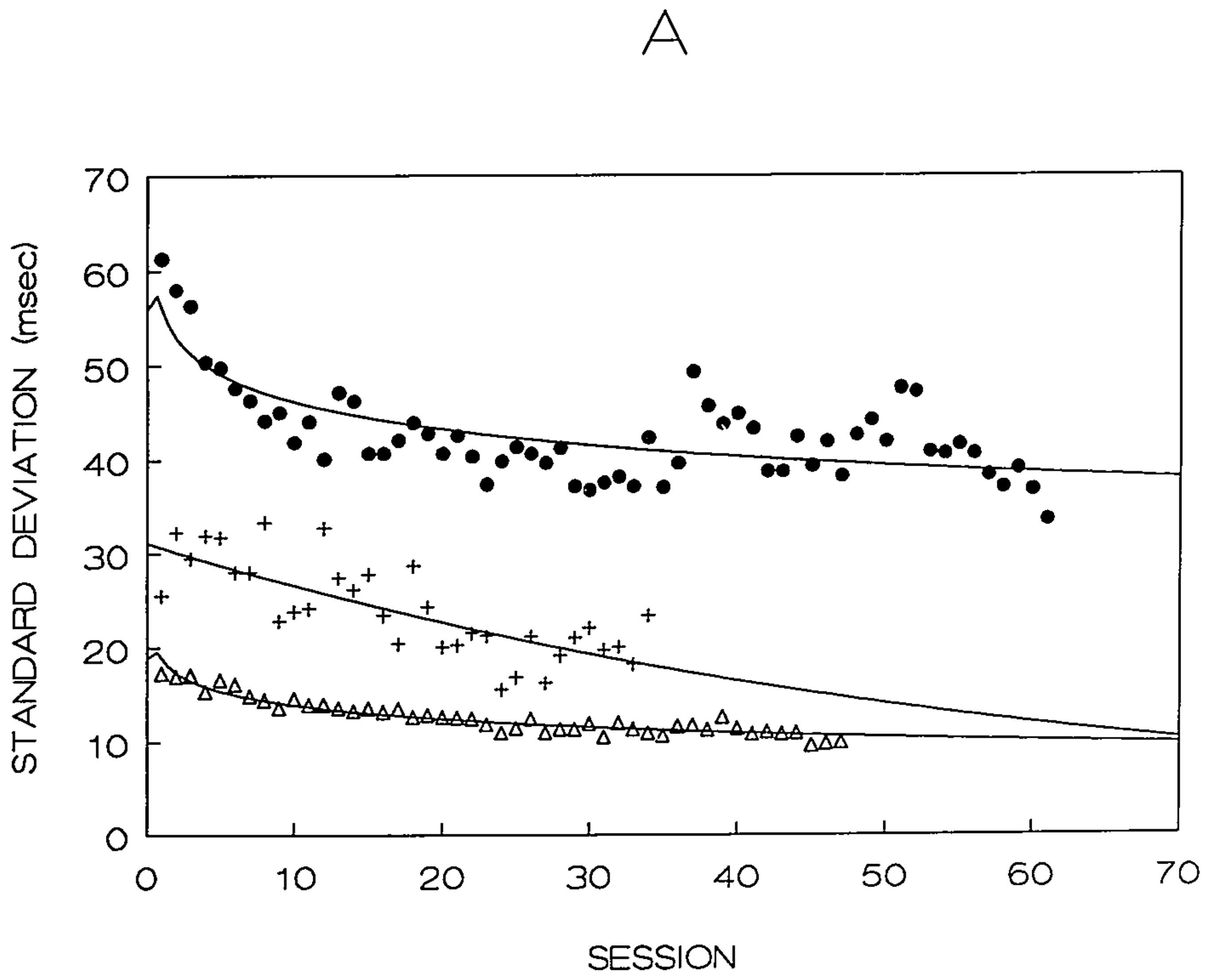
INTERRESPONSE INTERVAL MEAN ESTIMATES AND PRACTICE EFFECTS

The SP m_I vs session number functions for each S and T are remarkably stable and flat. Thus, there is no reason to believe that a trend analysis would reveal any significant trends especially since so few such trends were found in the CP. Consequently, the Mann test for trend was not carried out.

FIGURE 3.13

Mean within session synchronization phase s_I shown as a function of session number for AK.

PANEL	T (msec)
A	233 (triangles), 367 (plusses), 1468 (dots)
B	466 (diamonds), 734 (plusses), 932 (triangles)


A
STANDARD DEVIATION (msec)
0
10
20
30
40
50
60
70
SESSION
0
10
20
30
40
50
60
70

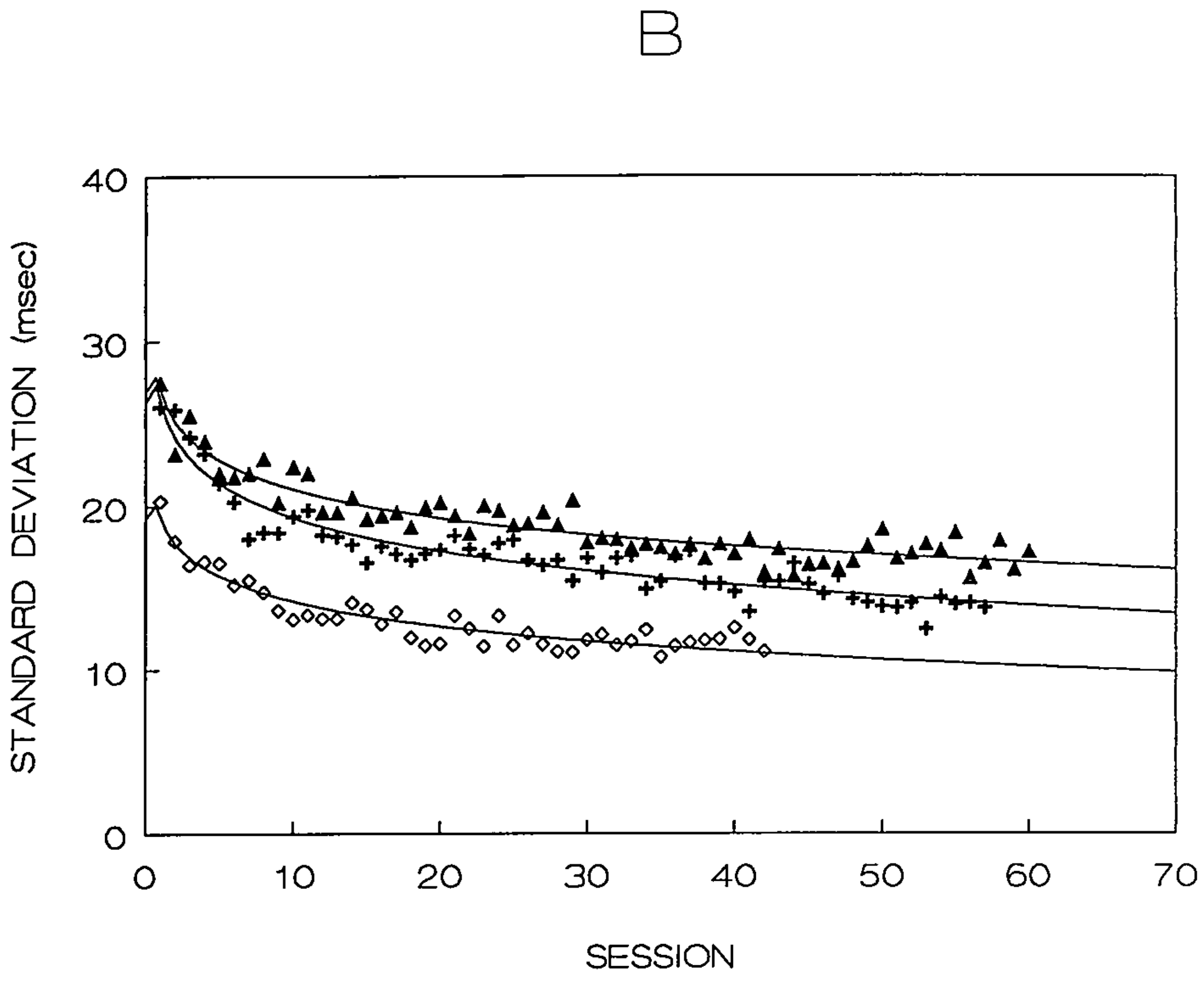
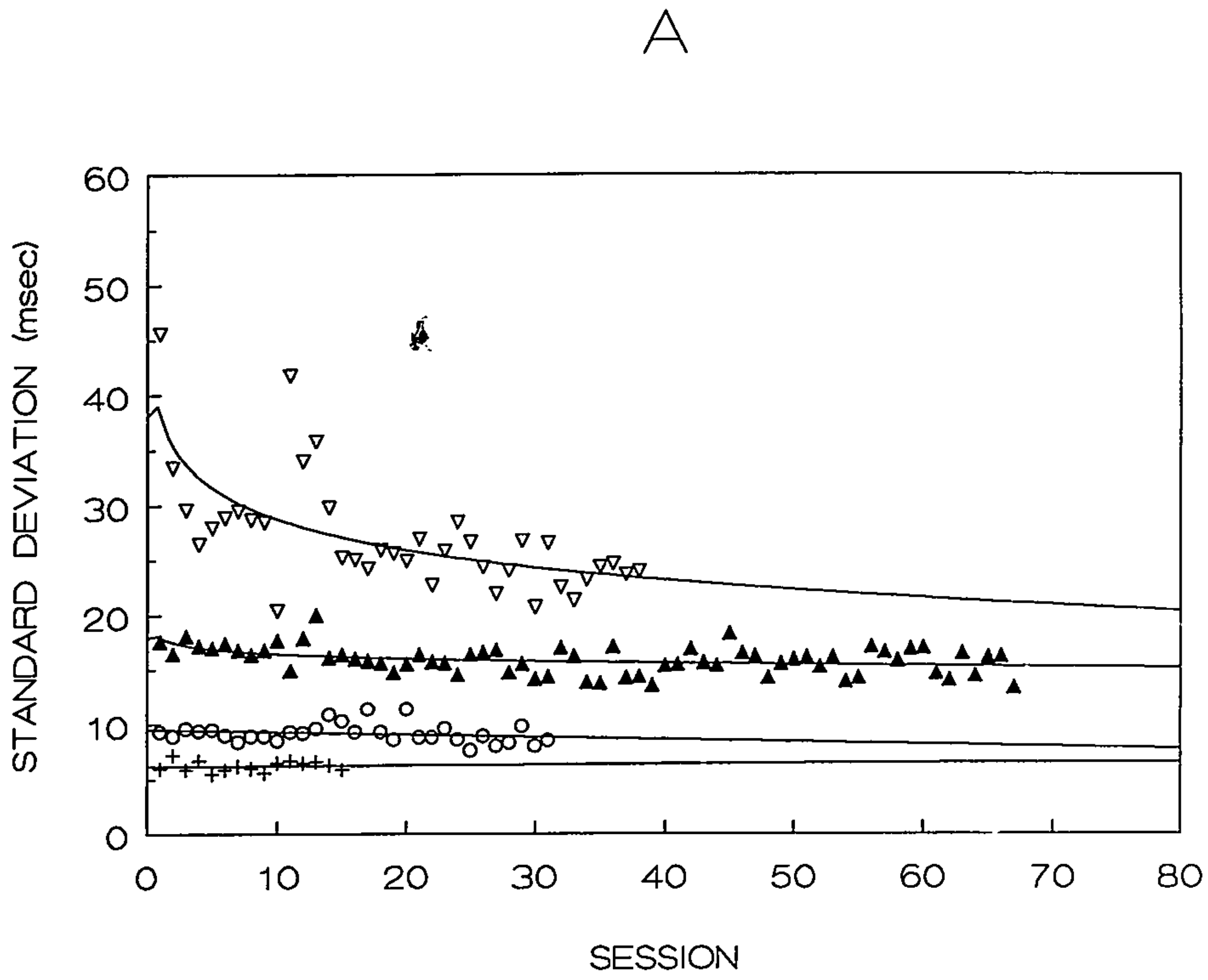

B
STANDARD DEVIATION (msec)
40
30
20
10
0
0
10
20
30
40
50
60
70
SESSION

FIGURE 3.14

Mean within session synchronization phase s_I shown as a function of session number for LL.

PANEL	T (msec)
A	175 (plusses), 367 (circles), 734 (filled triangles), 1468 (open triangles)
B	233 (triangles), 466 (plusses), 932 (dots)


A
STANDARD DEVIATION (msec)
0
10
20
30
40
50
60
0
10
20
30
40
50
60
70
80
SESSION

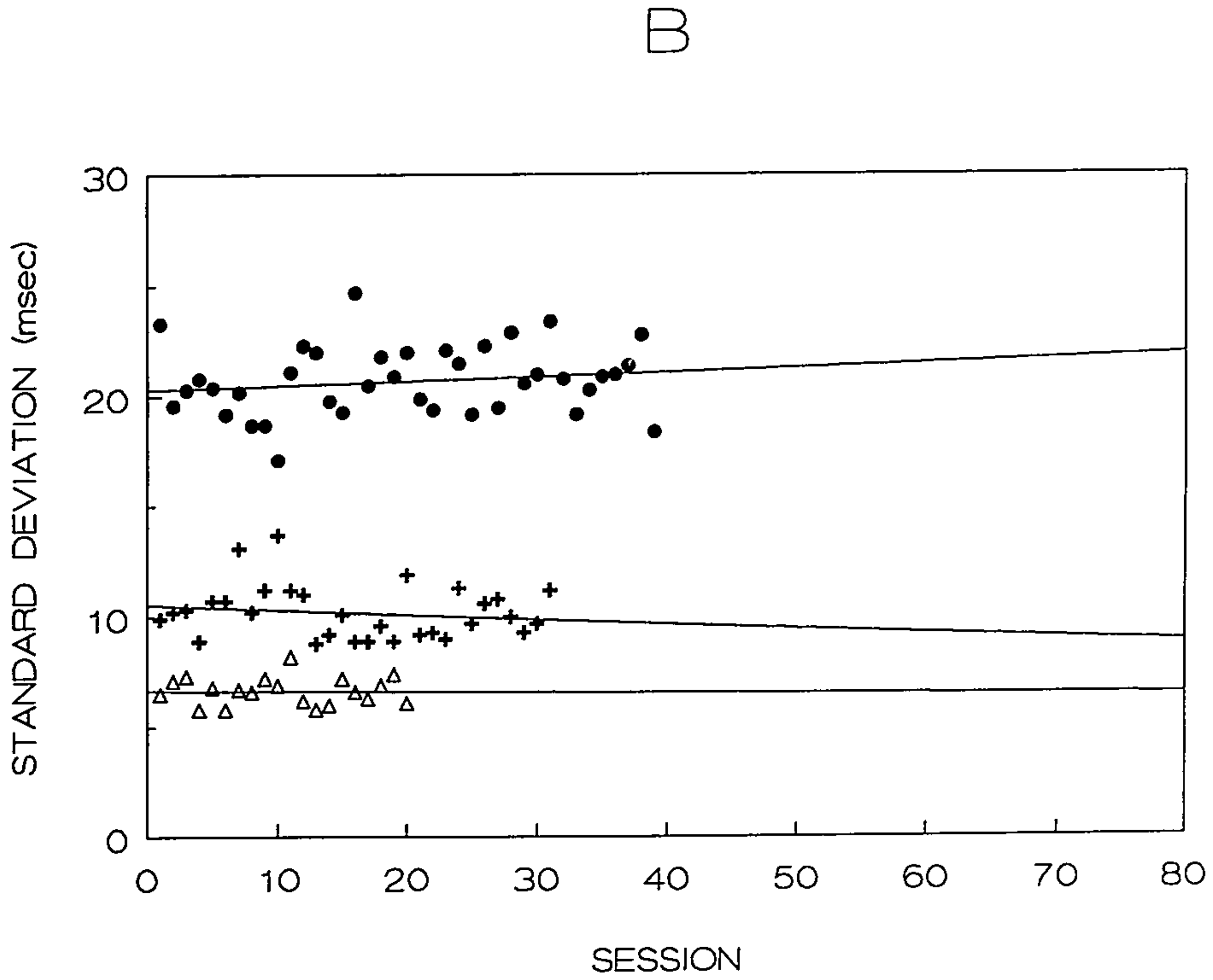
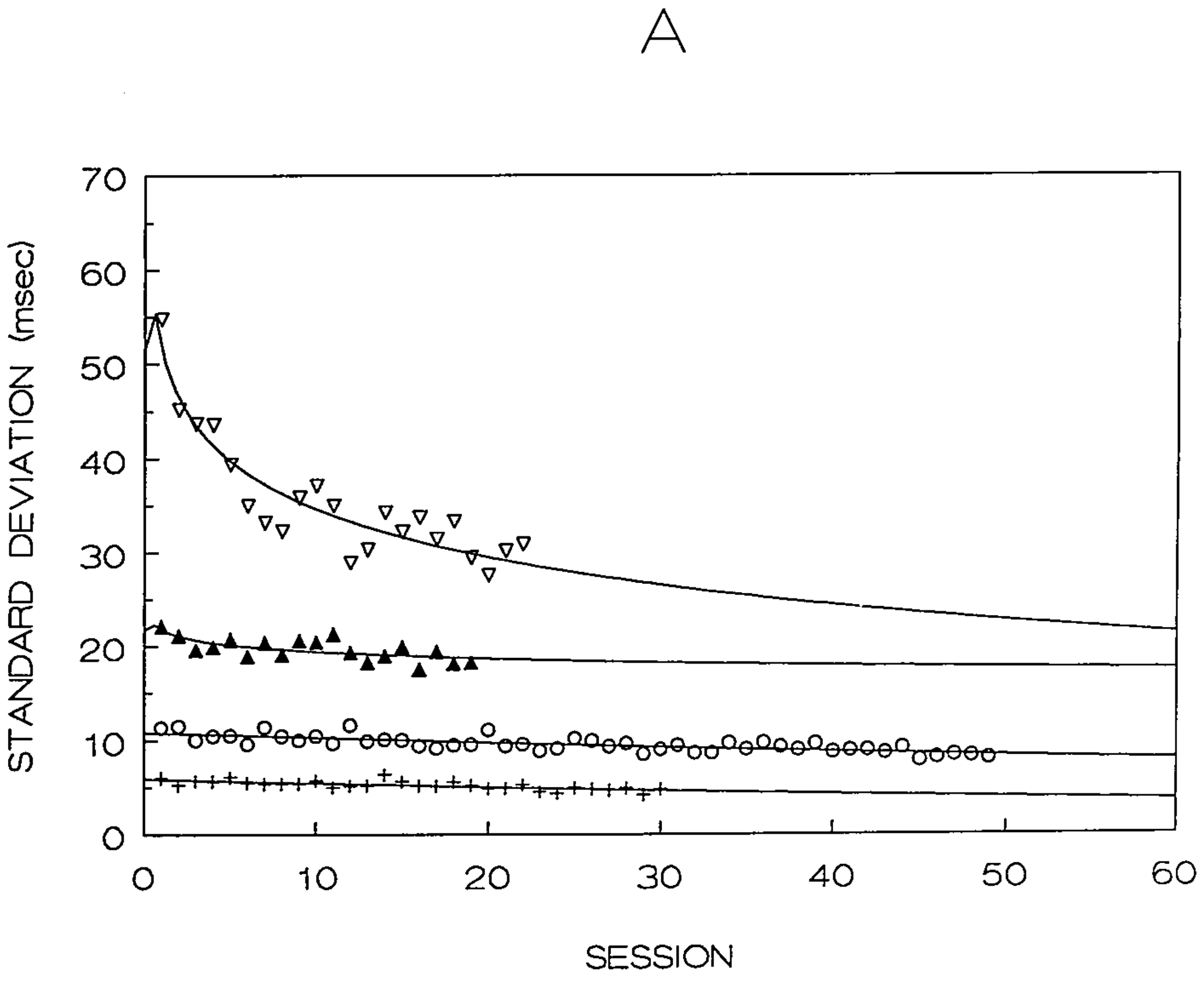

B
STANDARD DEVIATION (msec)
30
20
10
0
0
10
20
30
40
50
60
70
80
SESSION

FIGURE 3.15

Mean within session synchronization phase s_I shown as a function of session number for GF.

PANEL	T (msec)
A	175 (plusses), 367 (circles), 734 (filled triangles), 1468 (open triangles)
B	233 (triangles), 466 (plusses), 932 (dots)


A
STANDARD DEVIATION (msec)
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
SESSION

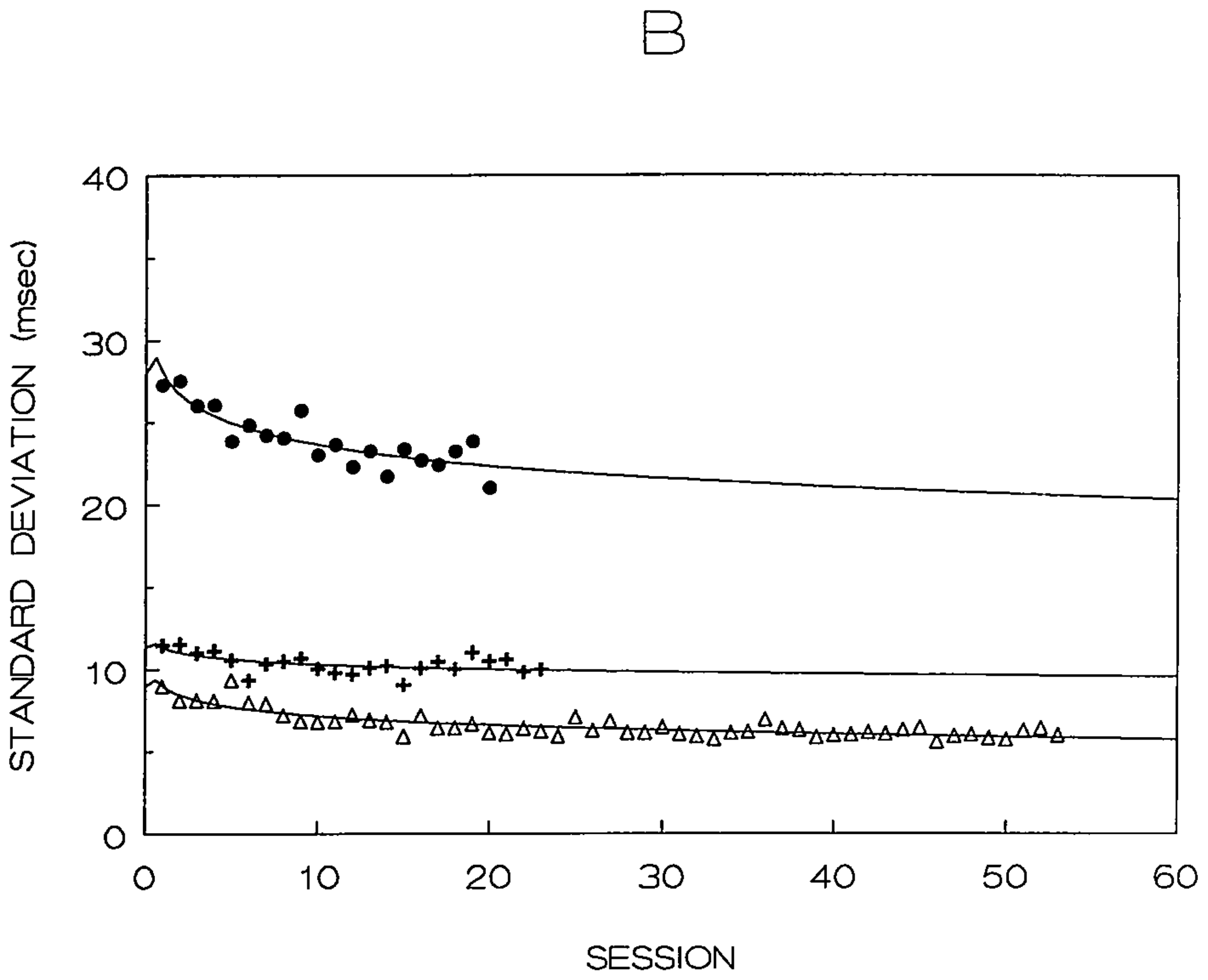

B
STANDARD DEVIATION (msec)
40
30
20
10
0
0
10
20
30
40
50
60
SESSION

TABLE 3.14

Synchronization phase s_F and s_L for each subject and level of T.

T	AK sF	LL sF	GF sF
175		6.19	5.85
233	30.60	6.66	8.97
367	18.84	9.51	10.77
466	19.27	10.50	11.36
734	26.32	17.96	21.77
932	26.97	20.32	27.98
1468	55.88	38.12	51.48

T	AK sL	LL sL	GF sL
175		6.250	4.63
233	18.19	6.630	5.8
367	10.67	8.790	8.47
466	10.98	9.620	9.95
734	14.01	15.27	18.75
932	16.44	21.08	22.36
1468	38.63	23.37	28.82

However initial (m_F) and final (m_L) means were computed in the usual manner to remain consistent with CP procedures. Those estimates are presented in Table 3.15 from which it is evident that the mean of the IRIs in the SP deviates very little from the target duration, T.

BIAS AND OSCILLATOR SIGNATURE PATTERNS

In order to determine if oscillator signature patterns are present in the SP data the m_L vs T function was first analyzed to see if there was an identity relation between m_L and T. Table 3.16 shows regression statistics in which it can be seen that an identity relation between m_L and T does not always exist; the slope coefficient differs significantly from unity for LL and the intercept coefficient differs significantly from zero for GF. These results are consistent with those obtained by Collyer et al. (1992) and with those reported in the PTDD experiment but they do not correspond to that which was found as a result of the same analysis of the CP. Linear bias, or a non-identity relation between mL and T, exists in the SP whereas it does not exist in the CP.

Because linear bias was detected on some occasions residual bias functions were analyzed for the presence of oscillator signature patterns. Figure 3.16 shows residual bias functions, in which residual bias is expressed as a percentage of T. It is very clear that none of the three functions oscillates about zero in a manner consistent with Collyer's et al (1992) discrete timekeeper hypothesis.

The absence of an oscillator signature pattern in the SP residual bias function means that Collyer's et al. (1992) discrete timekeeper hypothesis must be rejected. Thus, evidence suggesting the existence of a discrete timekeeper, as hypothesized by Collyer et al. (1992), does not emerge in either the SP or the CP. However, this does not mean that evidence of timekeepers with discrete or quantal characteristics is completely absent from the data. An analysis of the s_L vs m_L might lead to evidence in support of a quantal step function such as the one reported by Kristofferson (1980).

TABLE 3.15

Synchronization phase m_F and m_L for each subject and level of T.

T	AK	LL	GF
	m_F	m_F	m_F
175		176.79	172.51
233	230.42	231.75	229.68
367	362.83	365.4	367.98
466	465.07	463.62	463.38
734	732.21	730.95	732.25
932	927.51	929.145	929.85
1468	1464.98	1462.54	1466.39

T	AK	LL	GF
	m_L	m_L	m_L
175		174.45	172.56
233	226.36	230.75	229.89
367	363.11	364.96	363.93
466	462.18	464.25	462.94
734	731.88	731.26	731.48
932	928.33	929.53	929.24
1468	1460.79	1463.02	1465.8

TABLE 3.16

Regression statistics for synchronization phase m_L vs T function

Subject	Slope	Intercept	r^2
AK	0.9989	-3.762	0.9999
LL	0.9974**	-0.756	0.9999
GF	1.0005	-3.043**	0.9999

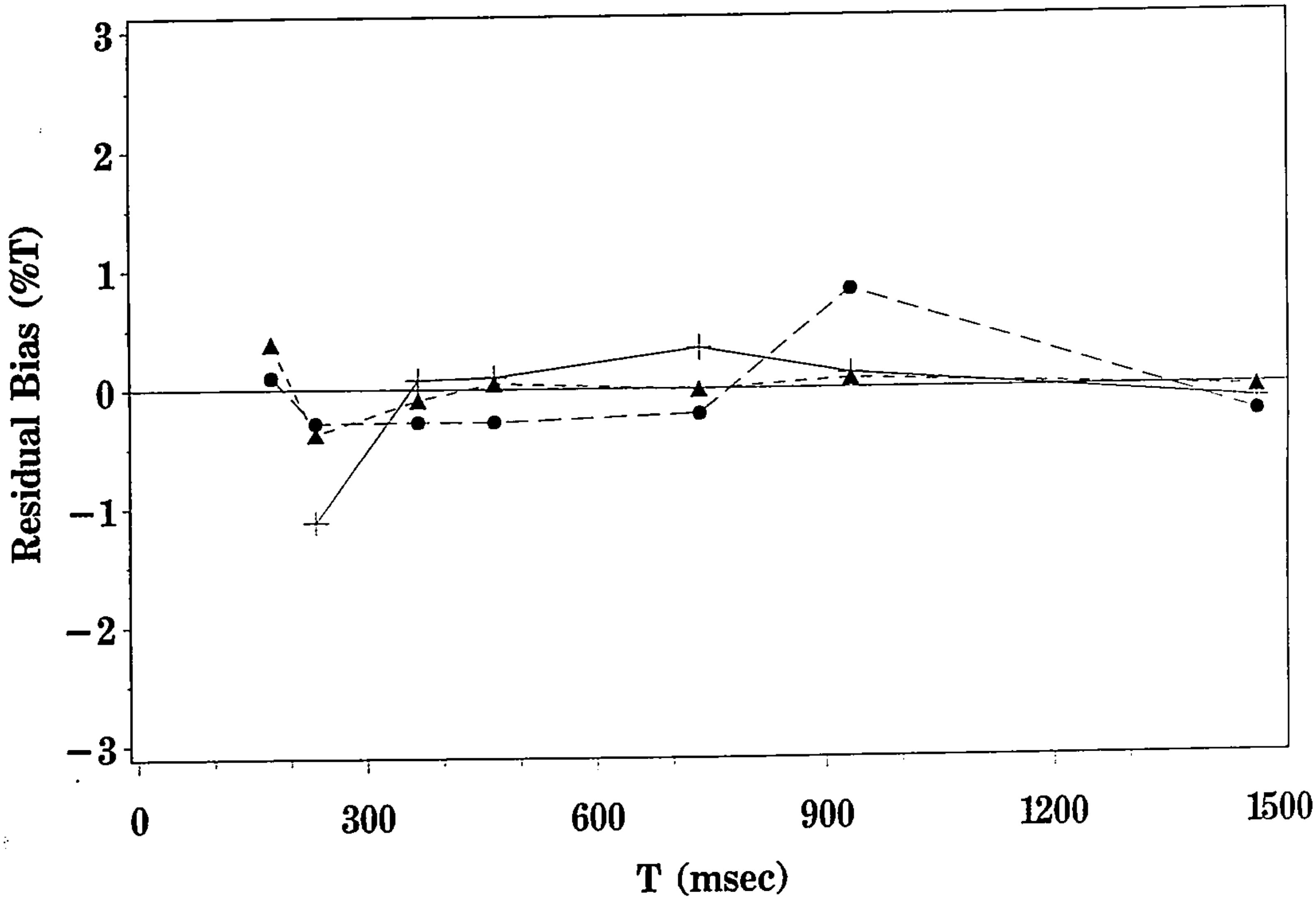
** significantly different from 1.0 for slope or from 0.0 for intercept, $p<.01$

FIGURE 3.16

Synchronization phase residual bias, expressed as a percentage of T, plotted as a function of T for all three subjects.

LEGEND:

SUBJECT	SYMBOL
AK	crosses
LL	triangles
GF	circles


Residual Bias (%T)
3
2
1
0
−1
−2
−3
0
300
600
900
1200
1500
T (msec)

s_F vs m_F AND s_L vs m_L FUNCTIONS

Figure 3.17 shows the relationship between s_F and m_F and the relationship between s_L and m_L. Common to all three subjects is the lowering of the functions with practice. Furthermore, the post-practice functions maintain the basic shape of the pre-practice functions; s_L increases with an increase in m_L. Finally, none of the functions appears to increase in a stepwise manner.

The best fitting cases of the proportional variance and standard deviation models will not be determined because there is no model available at present by which to interpret such results. Instead SP s_I^2 will be partitioned into s_C^2 and s_D^2 variances which will serve the basis for modeling analyses.

PARTITIONING s_I^2 INTO s_D^2 AND s_C^2

It was determined in an earlier section that the SP IRI sequences are adequately stationary for the purposes of partitioning s_I^2 into s_C^2 and s_D^2 according to the SCM. Because SP IRI sequences are relatively short only bias corrected s_C^2 and s_D^2 are reported in Table 3.17.

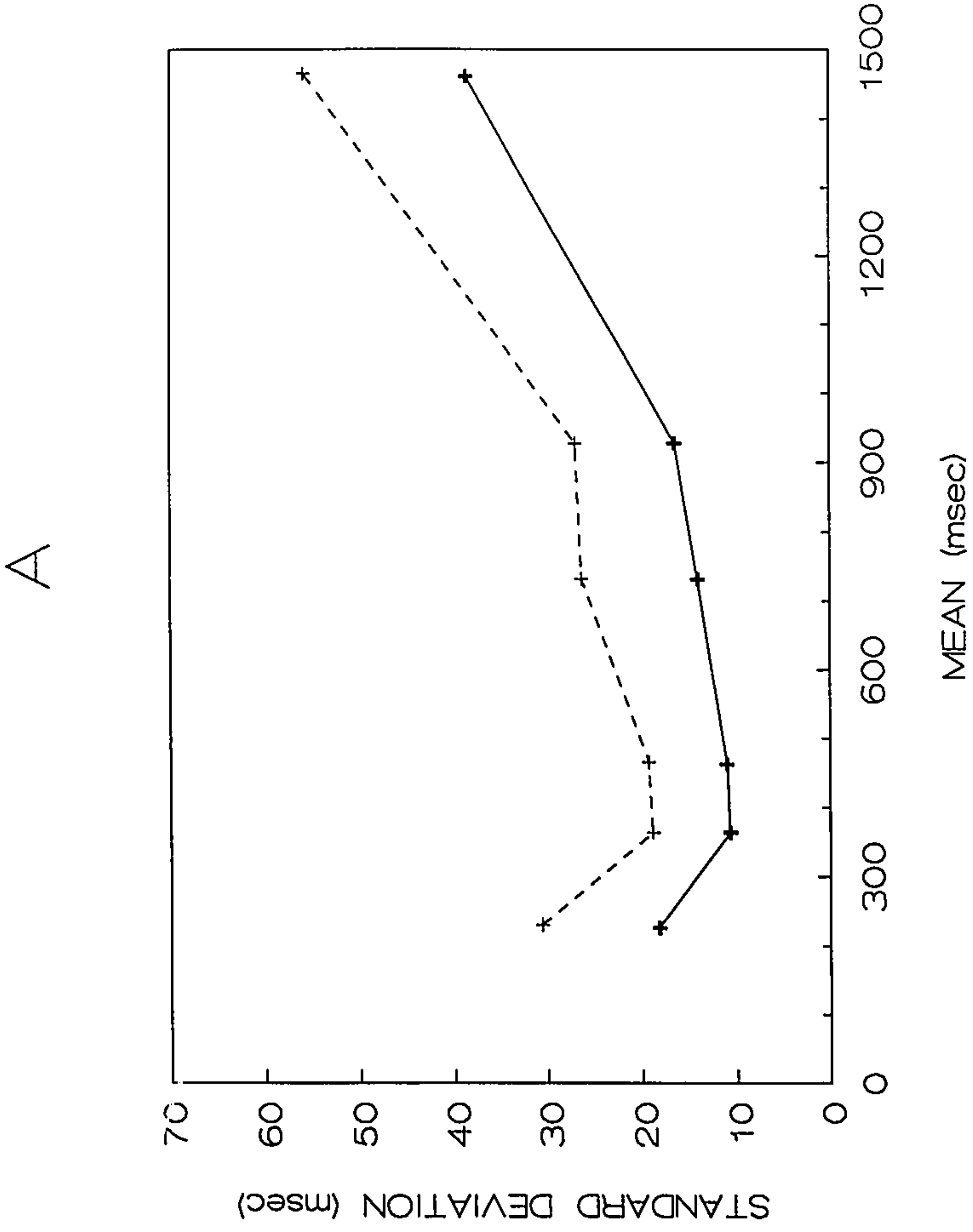
The functional relationships between bias corrected s_C^2 and m_I, and s_D^2 and m_I for the SP are shown in Fig. 3.18. The functions for AK and LL appear to be qualitatively different from GF's function. AK's function is U-shaped and LL's appears to be linear in shape. s_C^2 appears to be unrelated to m_I for GF.

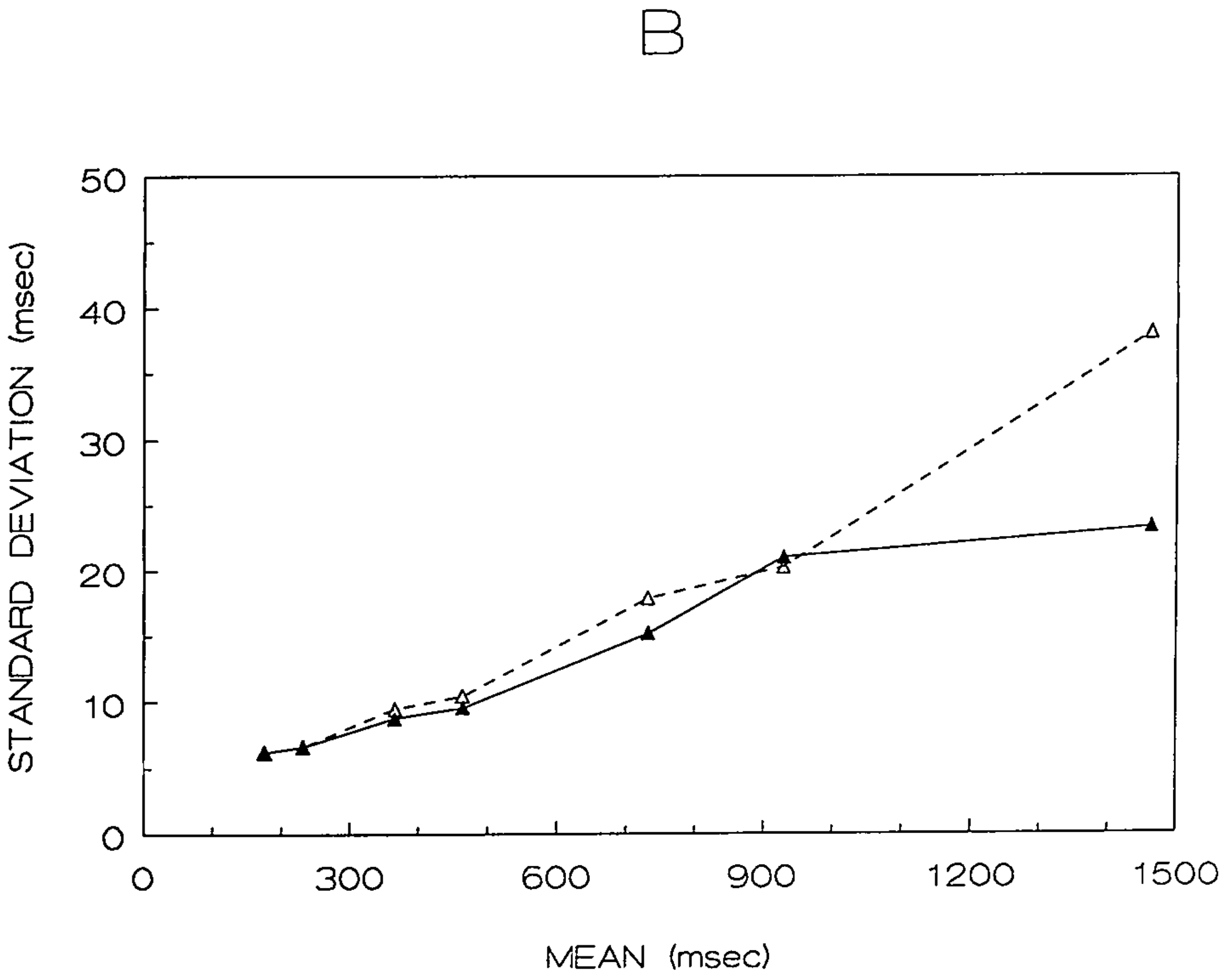
According to the SCM, s_C^2 should represent interpulse interval (IPI) variance. IPI variance should be a very small number approaching zero since all timing is carried out by the computer's clock. Thus, one prediction of the model is that s_C^2 equals zero. Moreover, IPI variance is expected to be independent of m_I because there is no reason to believe that the timing accuracy of the computer's clock changes for different values of T

FIGURE 3.17

Synchronization phase mean within session IRI standard deviation shown as a function of mean IRI. Open symbols on dashed line shows function for first five sessions (s_F vs m_F) and filled symbols on solid line shows function for last five session (s_L vs m_L).

PANEL	SUBJECT
A	AK
B	LL
C	GF


A
STANDARD DEVIATION (msec)
0
10
20
30
40
50
60
70
MEAN (msec)
0
300
600
900
1200
1500


B
STANDARD DEVIATION (msec)
50
40
30
20
10
0
0
300
600
900
1200
1500
MEAN (msec)

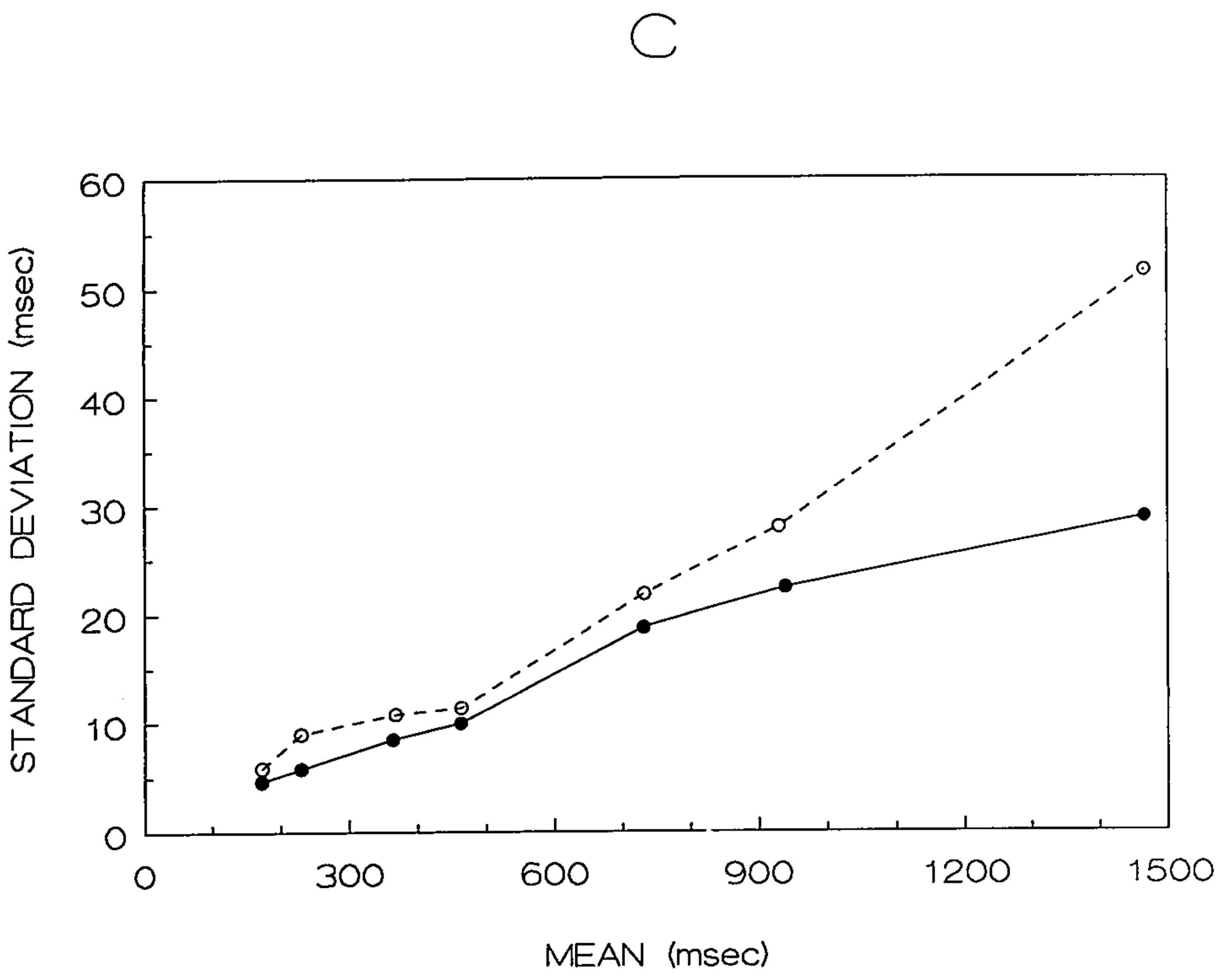

C
STANDARD DEVIATION (msec)
60
50
40
30
20
10
0
0
300
600
900
1200
1500
MEAN (msec)

TABLE 3.17

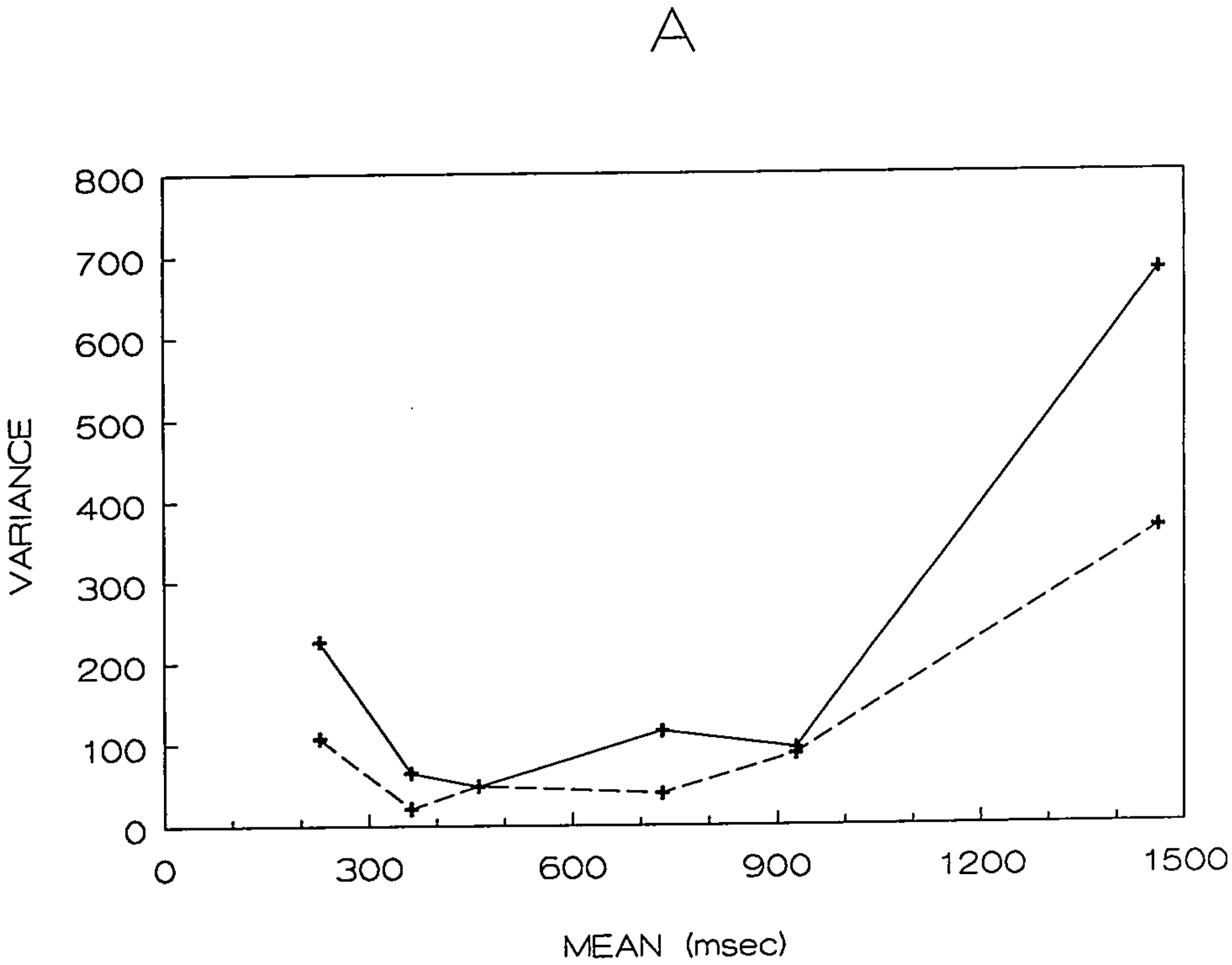
m_I, and bias corrected estimates of synchronization phase s_C^2 and s_D^2, for each subject and T.

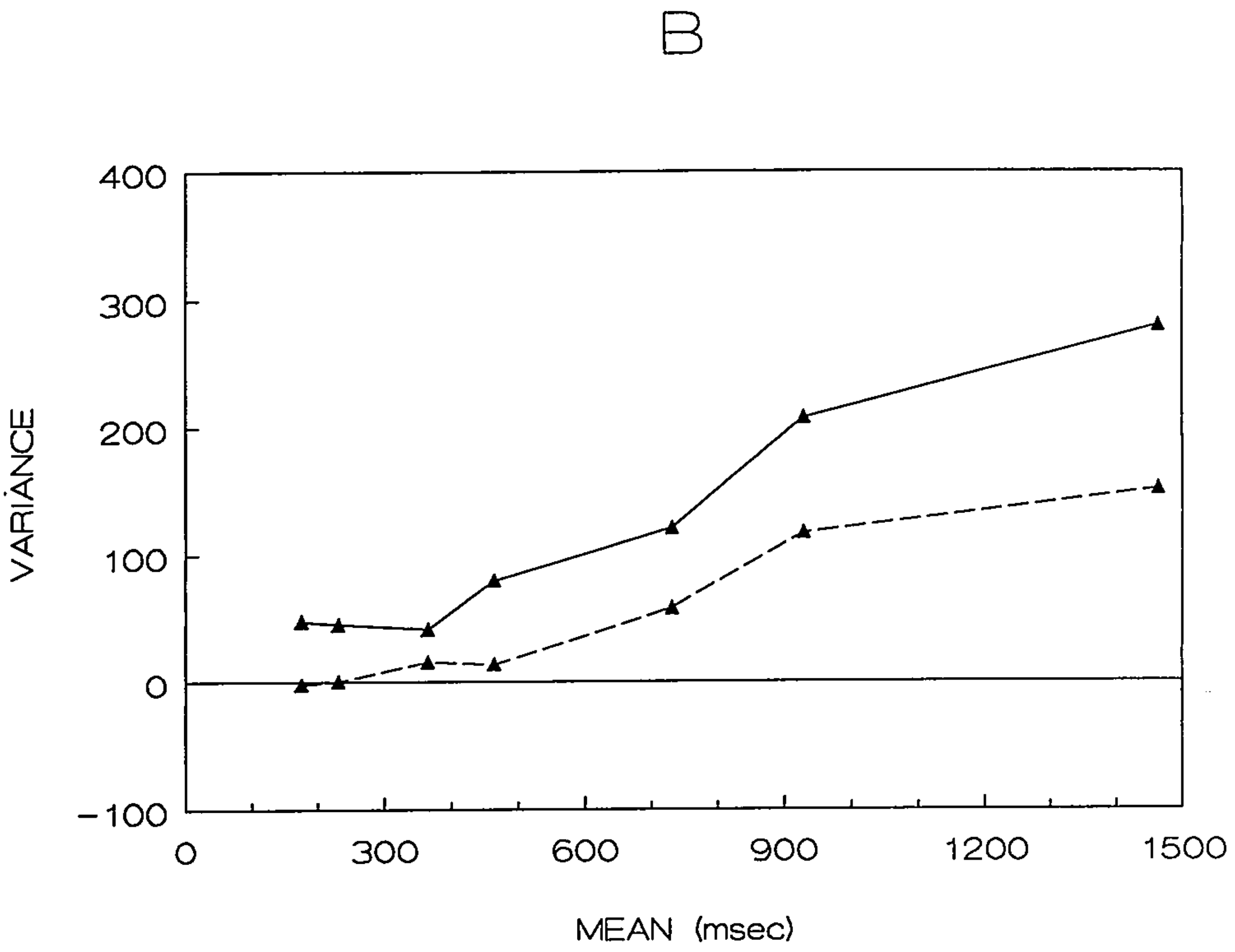
T (msec)	m_I	s_C^2	s_D^2
AK			
233	227.53	225.44	106.77
367	362.64	64.58	20.76
466	462.02	47.78	48.20
734	731.84	115.24	38.76
932	928.21	94.48	87.52
1468	1461.34	680.44	364.45
LL			
175	174.73	48.21	-2.16
233	231.00	45.75	0.28
367	364.86	42.04	16.09
466	464.18	79.93	14.26
734	731.18	121.36	58.44
932	929.50	207.46	117.30
1468	1463.58	279.96	151.26
GF			
175	173.57	30.43	-3.97
233	231.02	34.07	1.56
367	364.36	33.54	17.15
466	463.8	36.20	50.22
734	732.25	49.08	146.25
932	930.01	11.70	214.01
1468	1465.73	-11.66	468.18

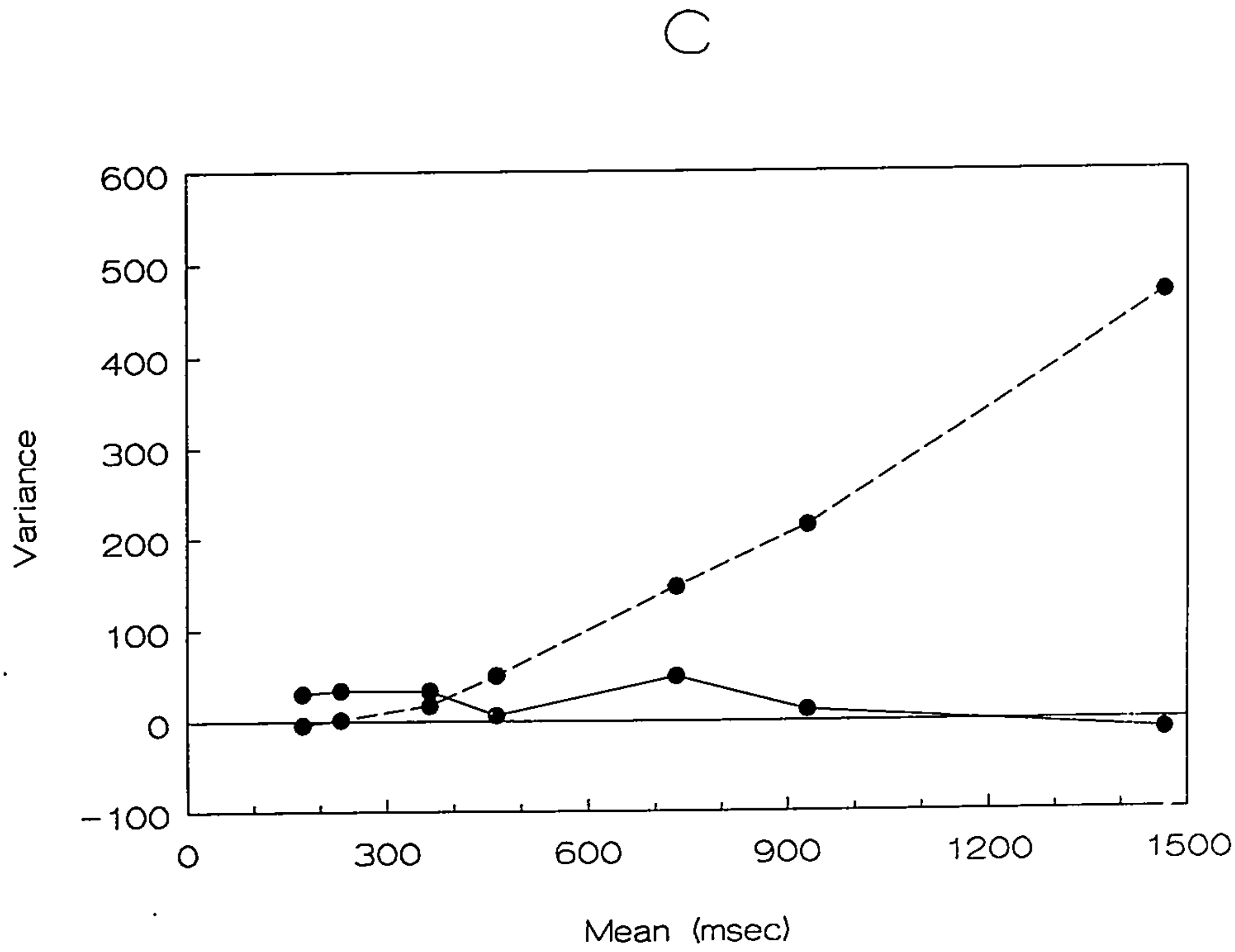
FIGURE 3.18

Bias corrected s_C^2 (solid line) and s_D^2 (dashed line) plotted as functions of m_I.

PANEL	SUBJECT
A	AK
B	LL
C	GF


A
VARIANCE
800
700
600
500
400
300
200
100
0
0
300
600
900
1200
1500
MEAN (msec)


B
400
300
200
100
0
−100
VARIANCE
0
300
600
900
1200
1500
MEAN (msec)


C
Variance
600
500
400
300
200
100
0
−100
0
300
600
900
1200
1500
Mean (msec)

within the range studied. Therefore, a second prediction of the model is that s_C^2 is orthogonal to m_I.

There is weak evidence to suggest that GF's SP s_C^2 vs m_I function conforms to the second of these two predictions. An analysis of the slope of the best fitting straight line reveals that there is a trend between bias corrected SP s_C^2 and m_I [slope = -0.033, $t_{(5)} = -2.68$, $p > .01$]. However, when mean s_C^2, computed over all values of T, is tested for departure from zero the results reach significance. Mean s_C^2 equals a low 26.2 msec^2 which is significantly greater than zero [$t_{(6)} = 3.74$, $p < .01$].

Estimates of combined bias corrected m_I and s_C^2 are shown in Table 3.18. When bias corrected SP s_C^2 data are combined by averaging over the three Ss the hypothesis of independence cannot be rejected [$F_{(6,13)} = 1.22$, $p > 0.05$]. The conclusion arising from this analysis is that s_C^2 does not change systematically with T. This conclusion supports the SCM as it is consistent with the prediction that s_C^2 should be independent of T. However, a glance at the individual s_C^2 vs m_I functions suggests that such support for the SCM is weak.

Bias corrected SP s_D^2 vs m_I functions appear to be of the same basic shape as the bias corrected SP s_C^2 functions for AK and LL but the former are slightly lower in position than the latter. For GF, however, s_D^2 increases monotonically as a function of m_I and the s_D^2 vs m_I function lies above the s_C^2 vs m_I function for the most part.

The hypothesis of independence between s_D^2 and m_I is rejected for combined bias corrected SP sD2 data, [$F(6,13) = 6.48$, $p < 0.01$] and both linear [$F(1,6) = 25.25$, $p < 0.01$] and quadratic [$F(1,6) = 7.38$, $p < 0.05$] trend components are statistically significant. These results indicate that there is a quadratic relationship between SP bias corrected s_D^2 and m_I . The SCM does not lead to a prediction of how changes in T should affect s_D^2 but it does imply that if a change in SP IRI variability occurs as a result of a change in T that that change should reflect a change in s_D^2 (a change in Ss

TABLE 3.18

Combined mean synchronization phase m_I and s_D for each T.

T (msec)	MEAN m_I (msec)	MEAN s_D (msec)
175	174.2[a]	0[b]
233	229.9	4.04
367	364.0	4.24
466	463.3	5.94
734	731.8	8.75
932	929.2	11.60
1468	1463.6	17.78

---

[a] computed over LL and GF only

[b] square root of negative number

responding), and not a change in s_C^2 (the computer's clock). In this sense the SCM is supported but further interpretations are impossible at this time because the SCM does not provide a procedure to decompose s_D^2 into its component parts.

A quadratic increase in bias corrected SP s_D^2 means that any model of the underlying process that gives rise to this pattern of change is not likely to be a member of the proportional variance class of models. Table 3.19 reports the relevant statistics for each of the three Weber's law models and Creelman's model when they are fitted to the combined bias corrected SP s_D vs m_I functions. It should be emphasized that in the context of the SCM s_D does not necessarily represent a single (central or motor delay) theoretical component, as was the case in the CP analysis, so the results must be interpreted with caution.

Of the three Weber-law-based models and Creelman's proportional variance based model, Kristofferson's model fits the best and Creelman's model the worst. This is the same result obtained for the CP s_C vs m_I function analysis. Thus, once again Weber's law models describe the functions better than Creelman's model. But at this point it is impossible to state with certainty what it is that is conforming to Weber's law in this case. It may be that the central timekeeper is the single component that is primarily responsible for the changing shape of the function. But since that has yet to be determined one can only speculate about the similarity or dissimilarity of the central or motor timekeepers in the two phases of a sequence.

Although it is somewhat difficult to interpret the meaning of s_C^2 and s_D^2 estimates obtained from the SCM, the SCM may itself be evaluated by examining the autocovariance functions from which the above estimates are generated.

AUTOCOVARIANCE FUNCTIONS

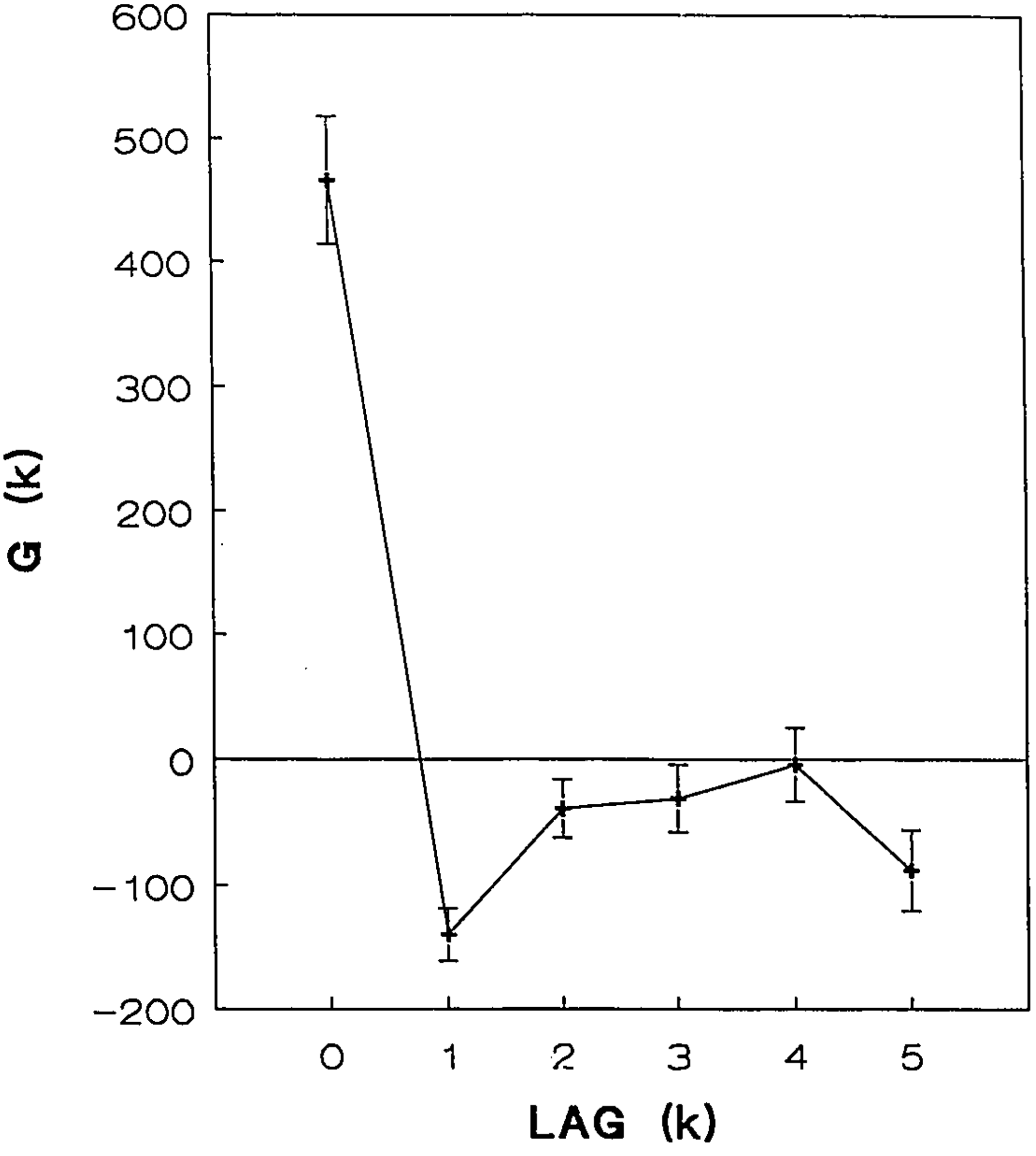
According to the SCM autocovariance function (see Equation 1.35) $\lambda_I(k) = 0$ for $k > 1$. Similarly, $\lambda_I(1)$ should equal $-0.5\ \lambda_I(0)$. Figure 3.19 shows that while such a

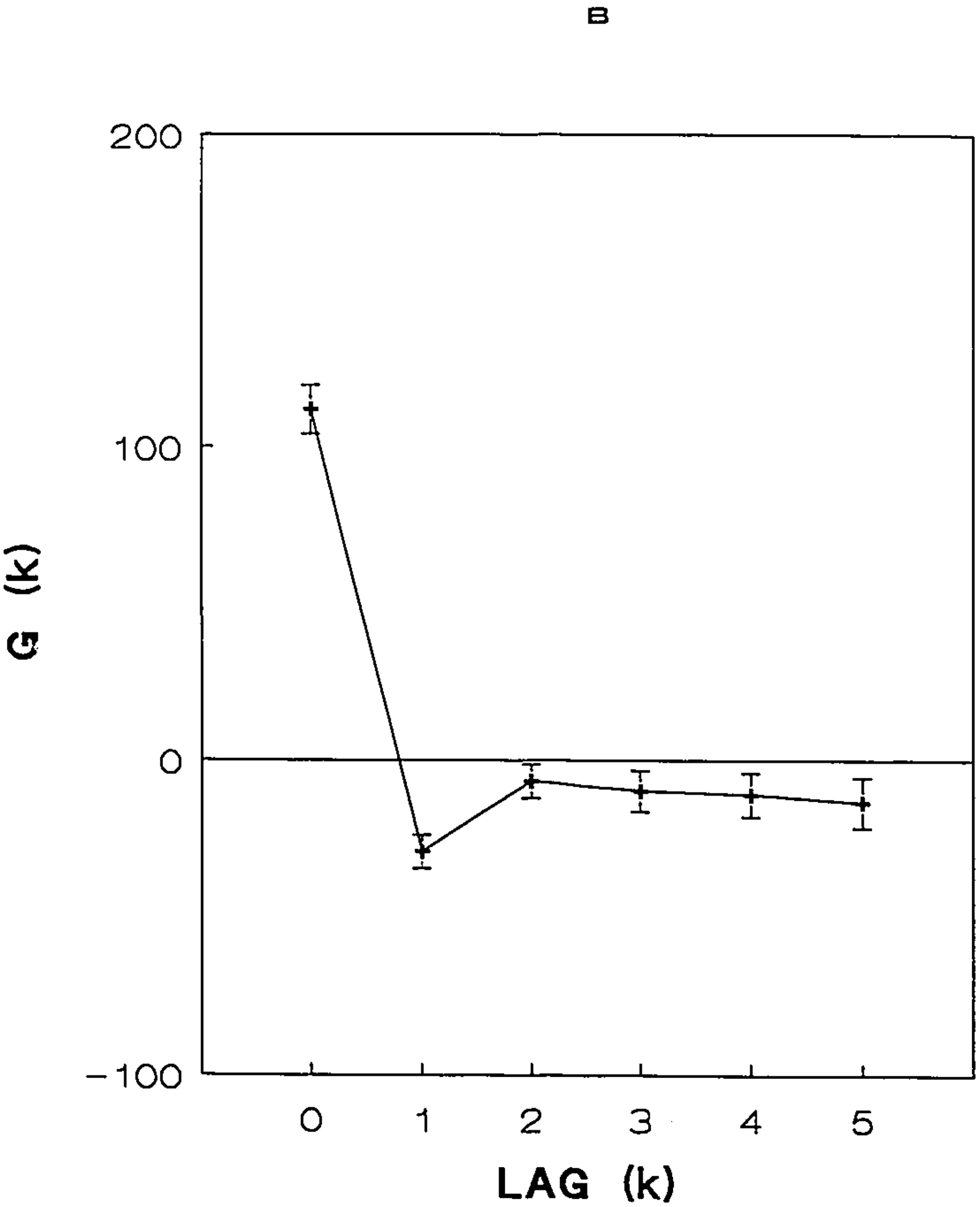
FIGURE 3.19

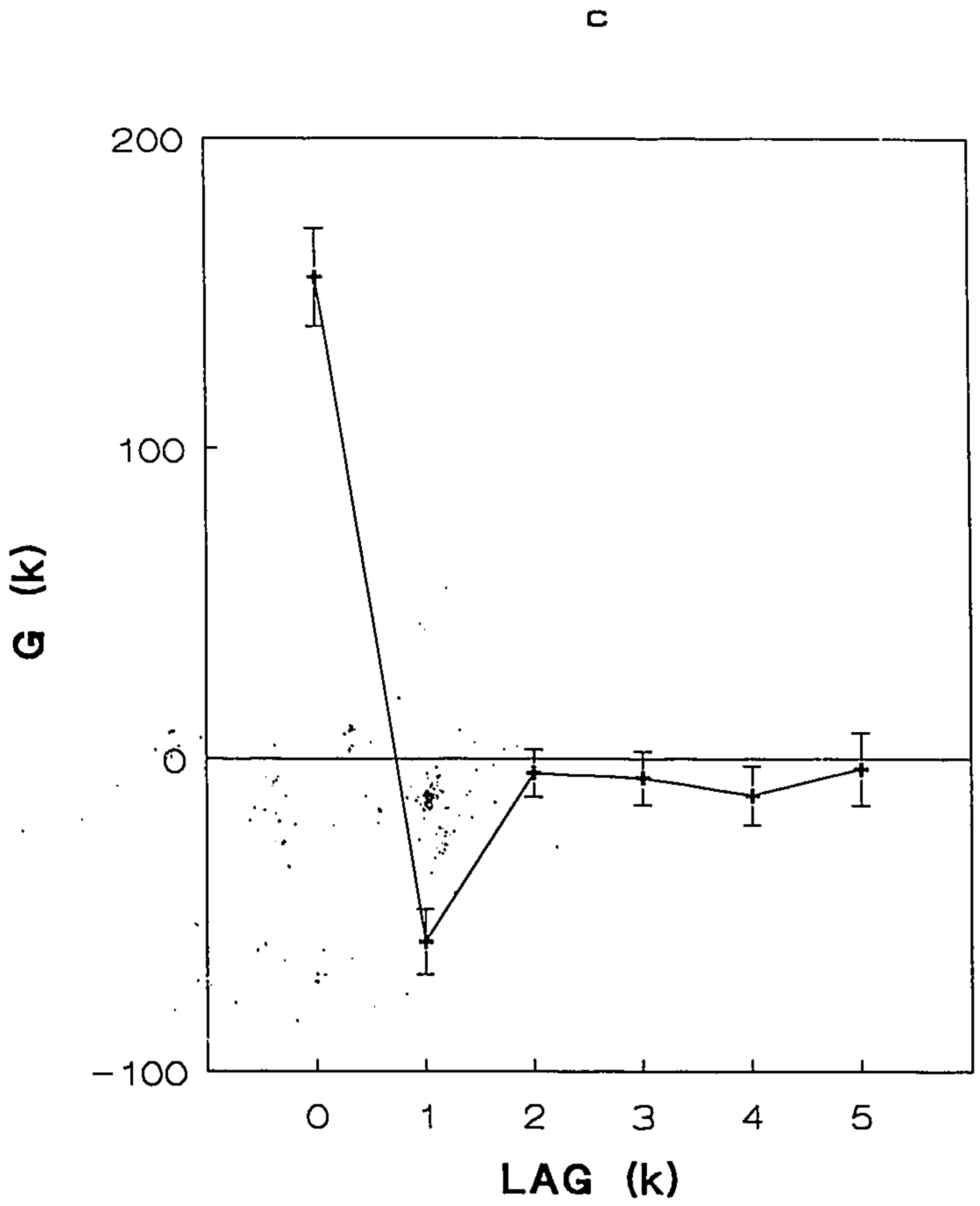
Synchronization phase bias corrected autocovariance functions, for lags 0 to 5, with two standard errors of estimate about each mean $G_I(k)$.

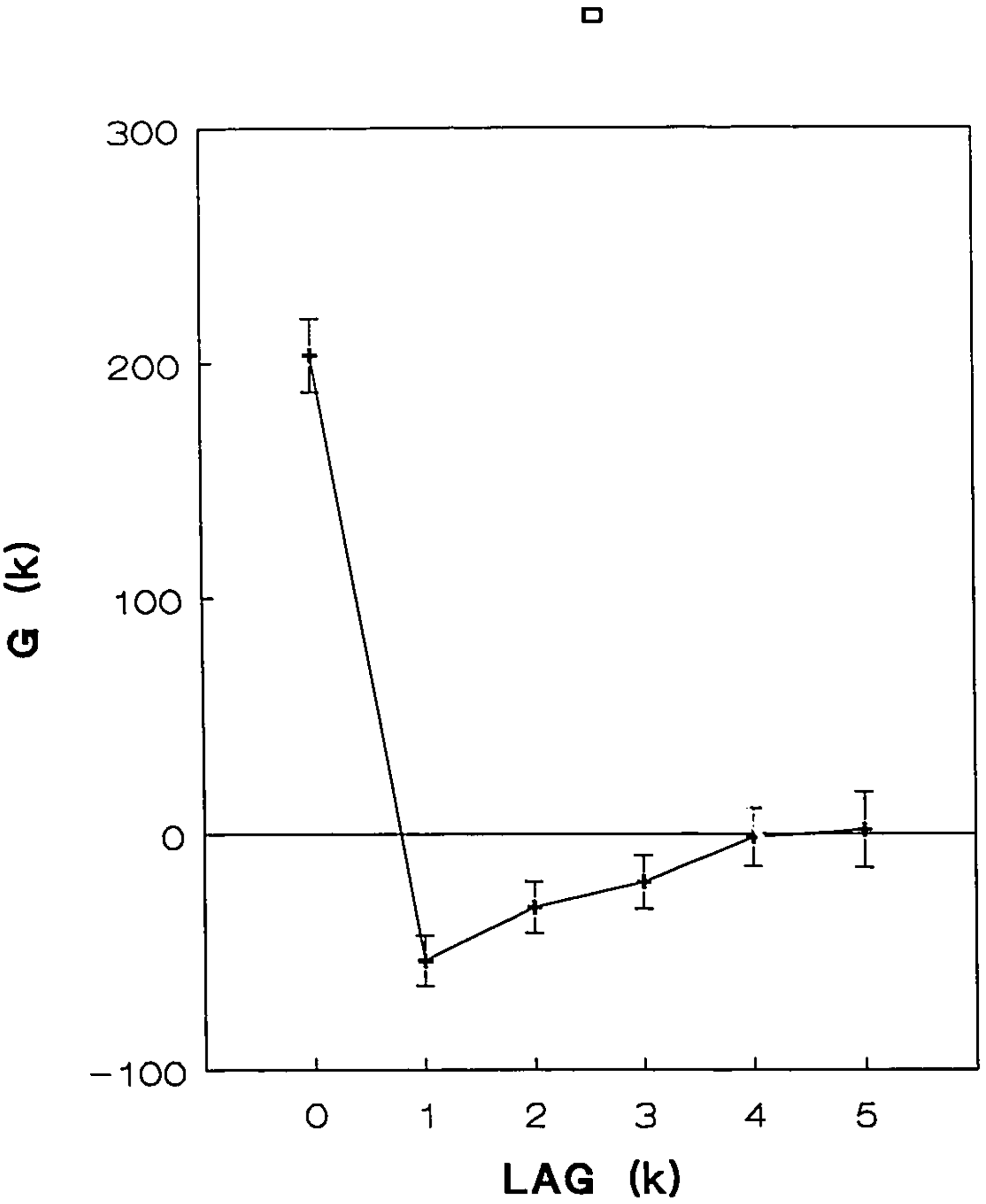
PANEL	SUBJECT	T (msec)
A	AK	233
B	AK	367
C	AK	466
D	AK	734
E	AK	932
F	AK	1468
G	LL	175
H	LL	233
I	LL	367
J	LL	466
K	LL	734
L	LL	932
M	LL	1468
N	GF	175
O	GF	233
P	GF	367
Q	GF	466
R	GF	734
S	GF	932
T	GF	1468

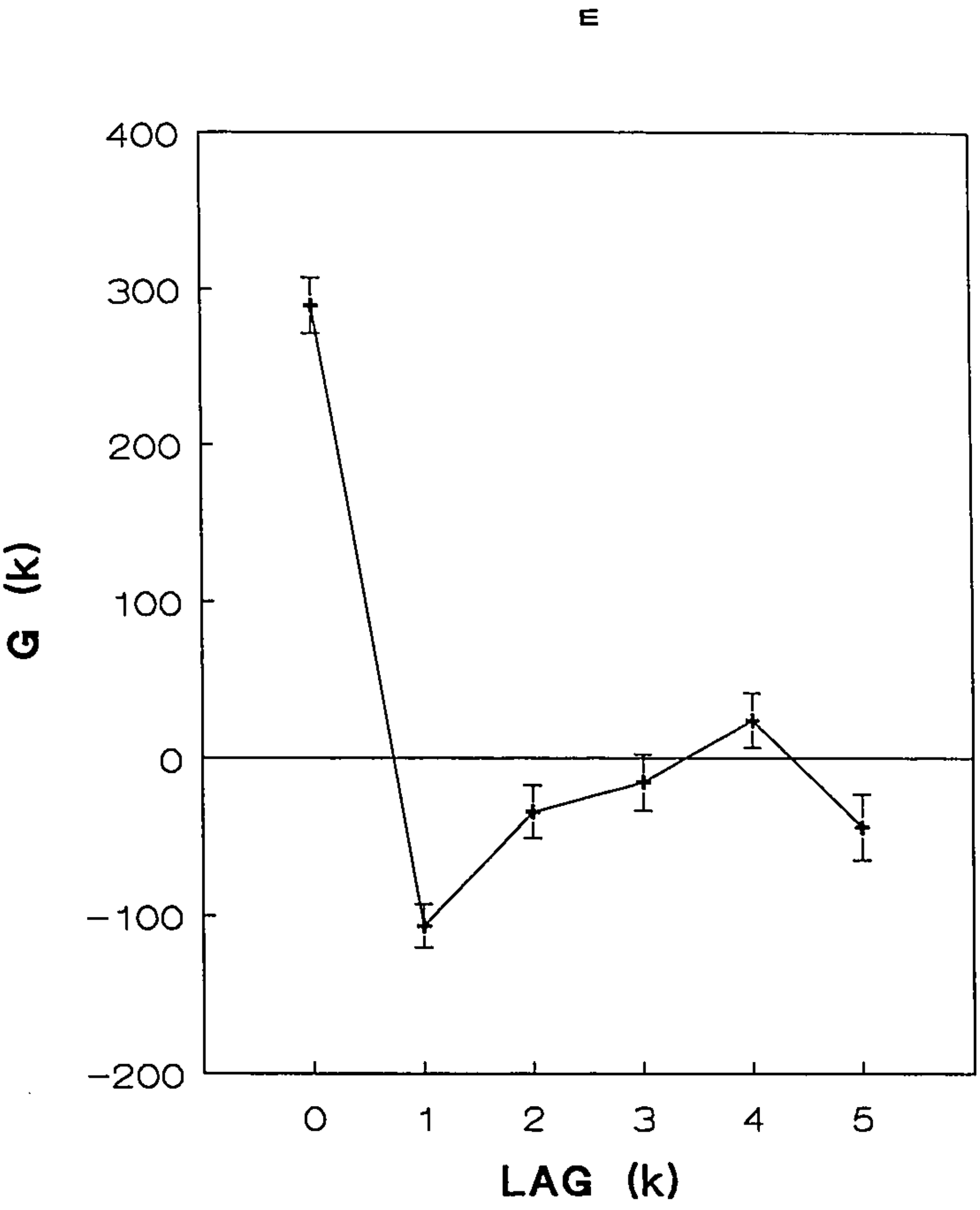
A



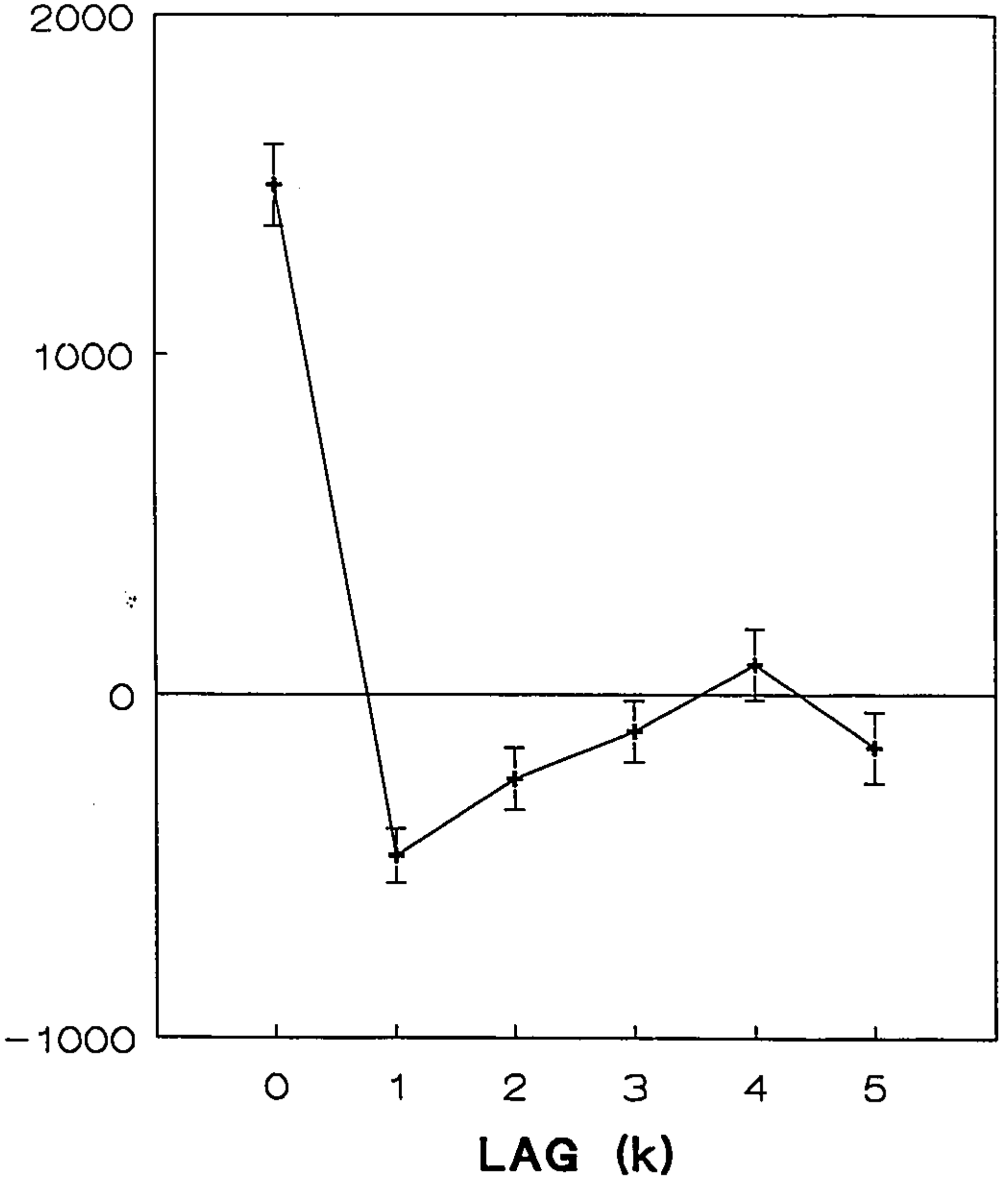

B
200
100
0
−100
G (k)
0
1
2
3
4
5
LAG (k)


c
200
100
0
−100
G (k)
0
1
2
3
4
5
LAG (k)

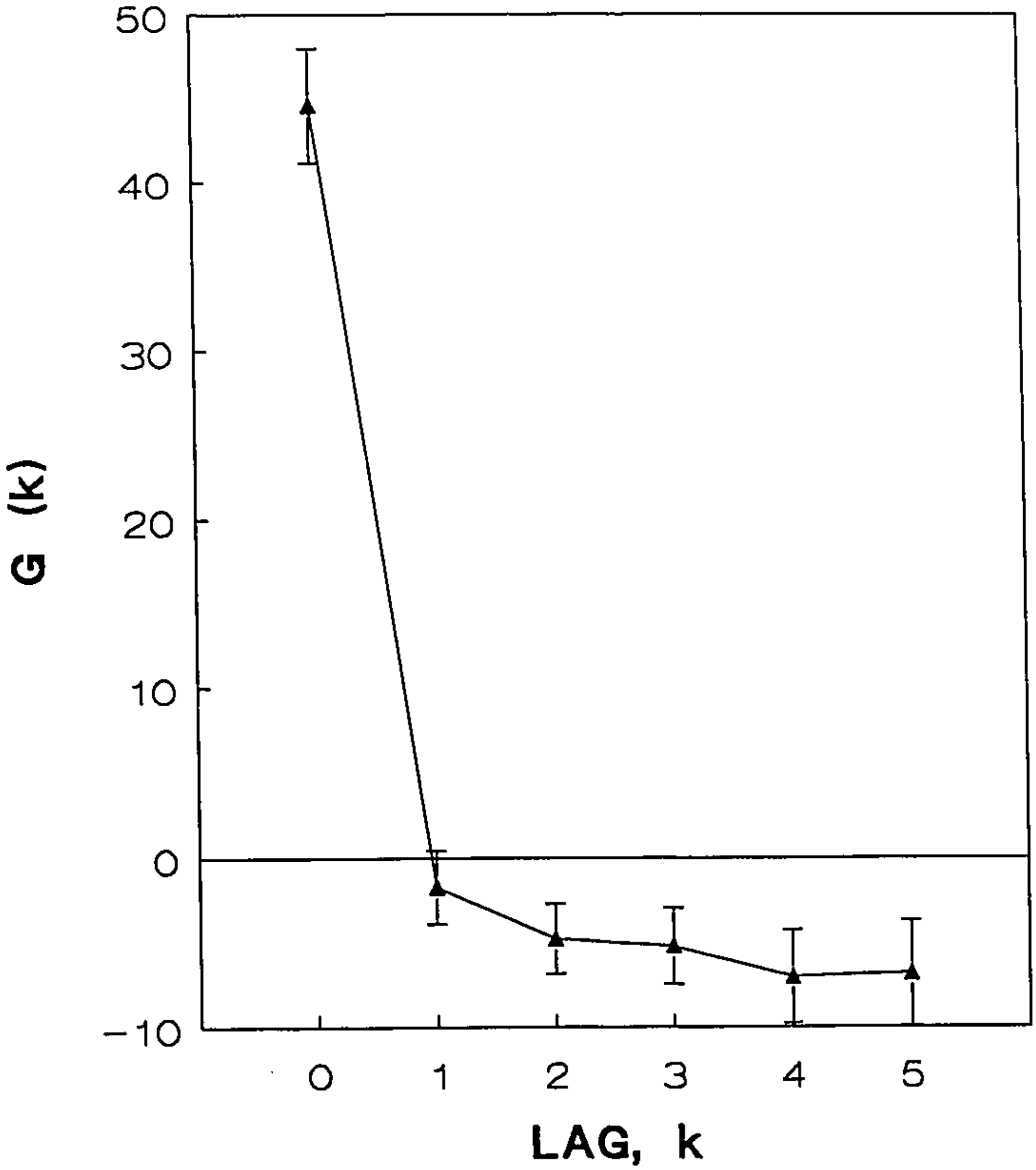

D
300
200
100
0
−100
G (k)
0
1
2
3
4
5
LAG (k)


E
G (k)
400
300
200
100
0
−100
−200
0
1
2
3
4
5
LAG (k)

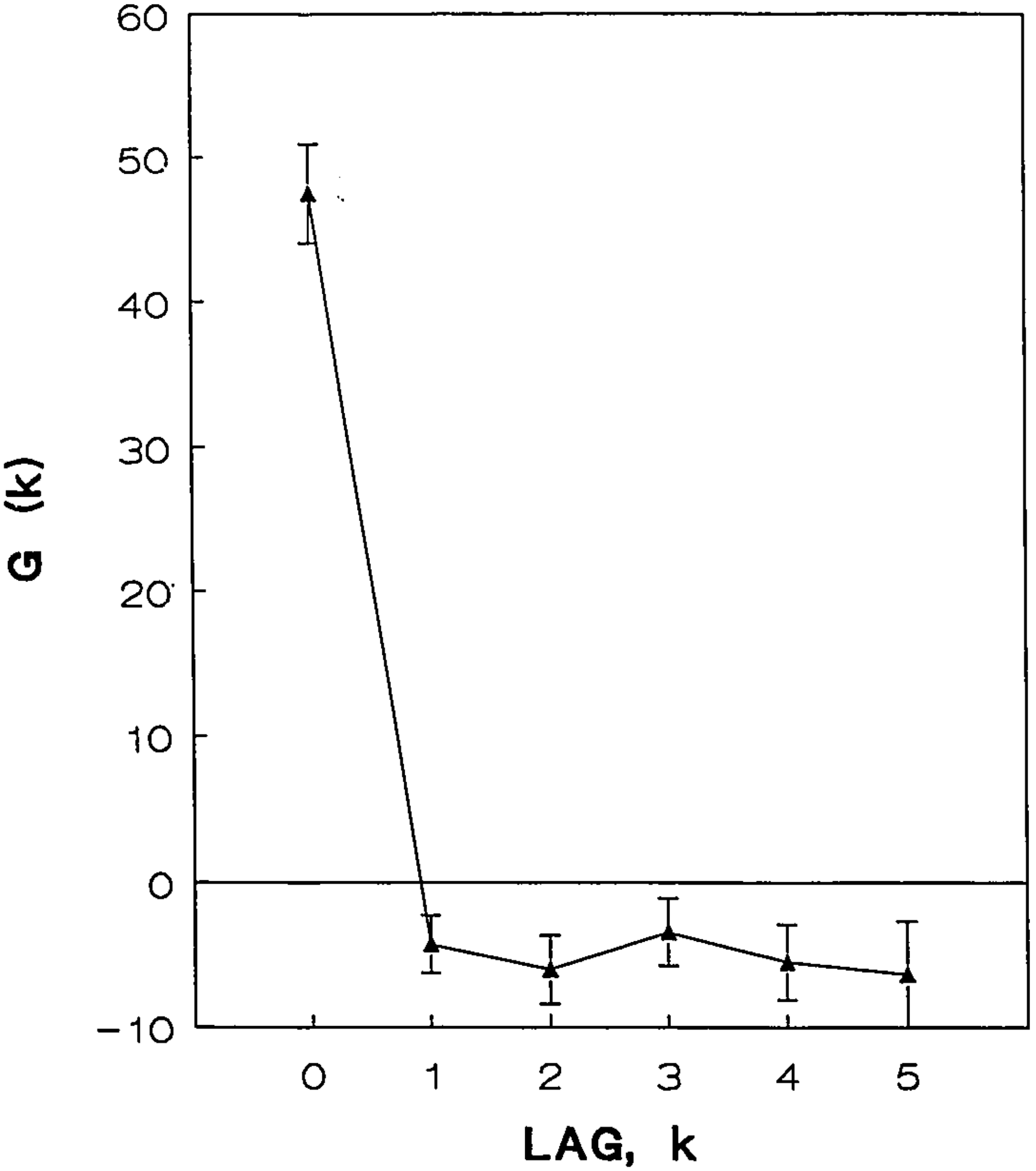
F

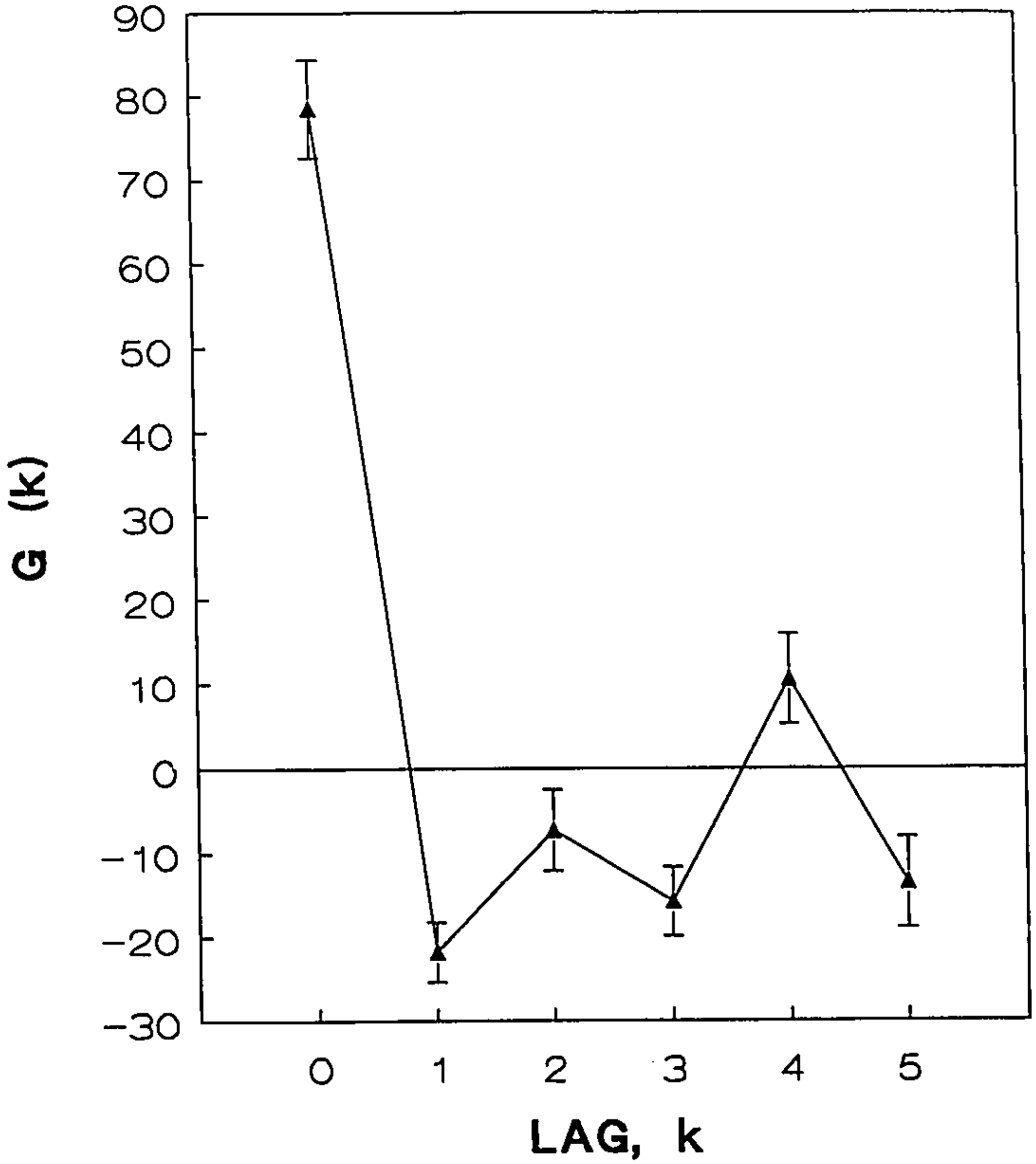


G

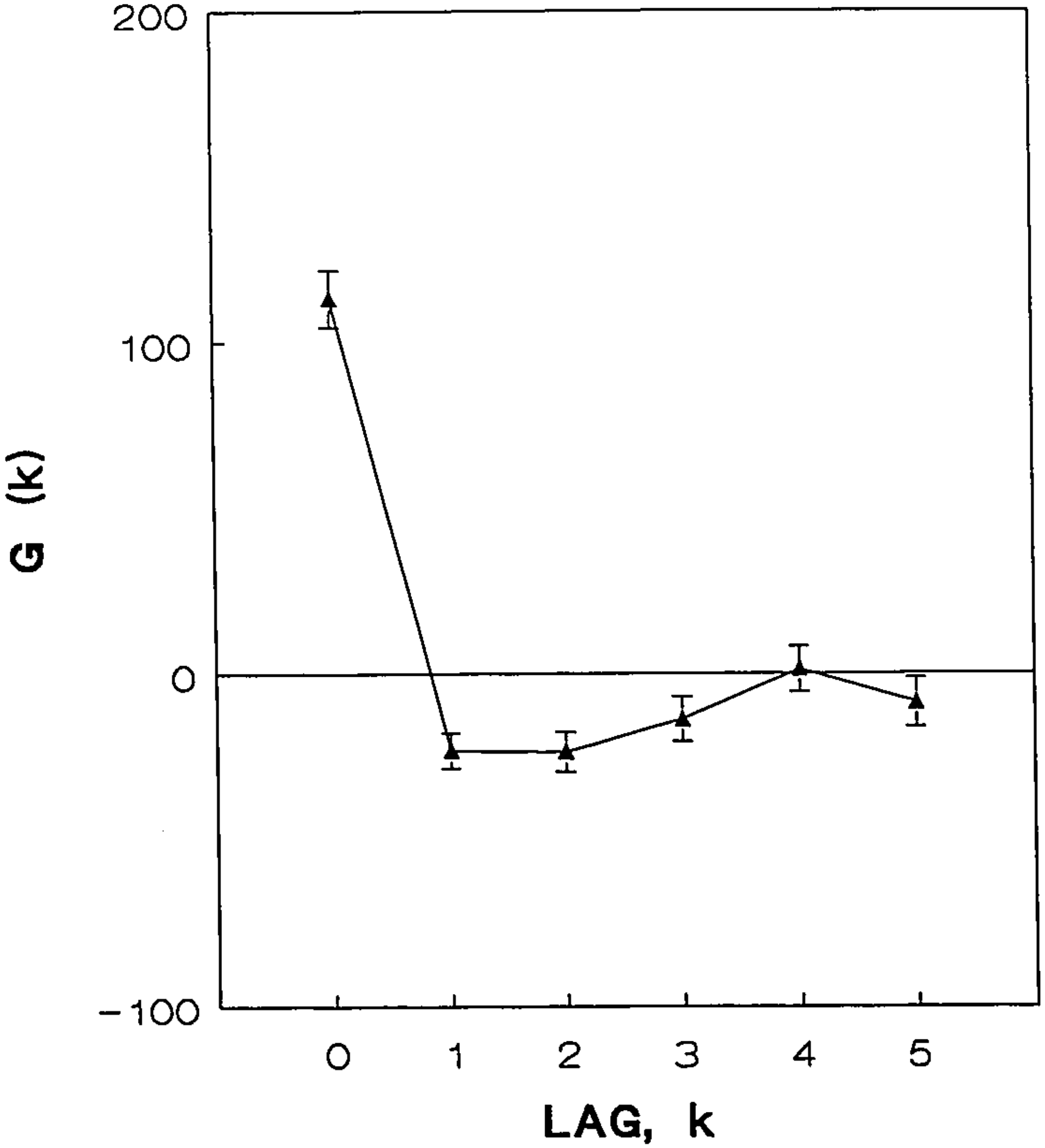


H

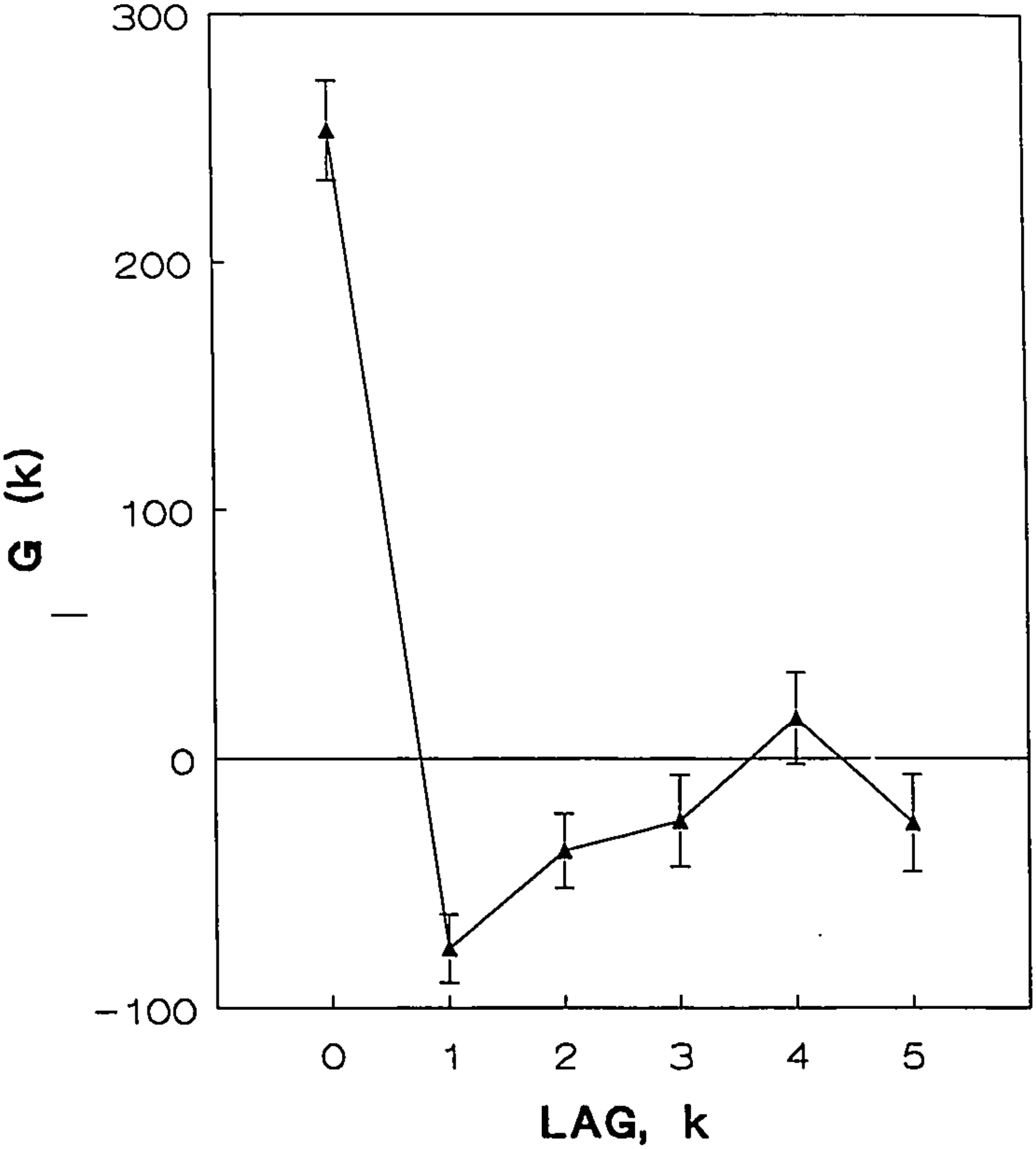



90
80
70
60
50
40
30
20
10
0
−10
−20
−30
G (k)
0
1
2
3
4
5
LAG, k

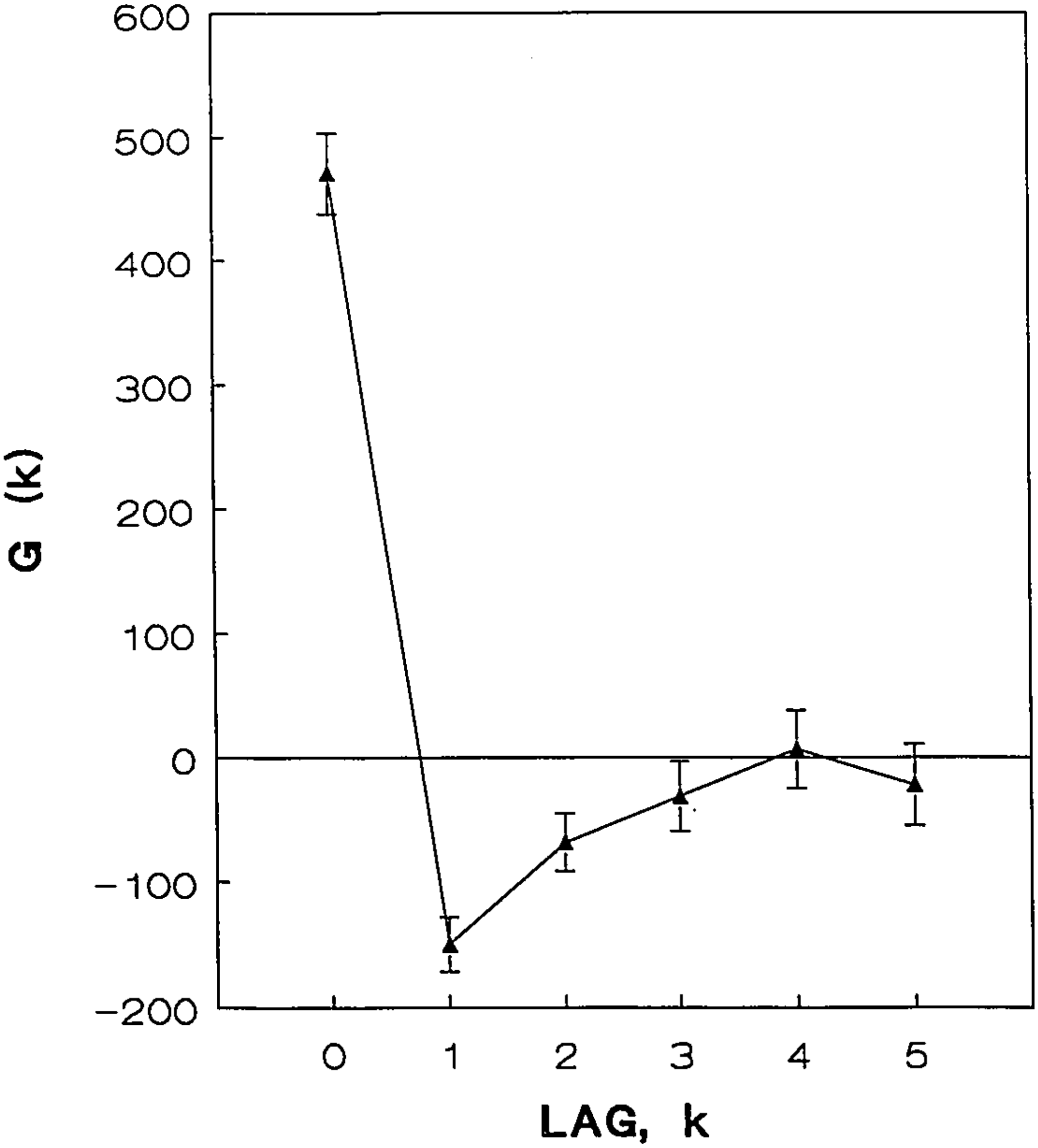
J



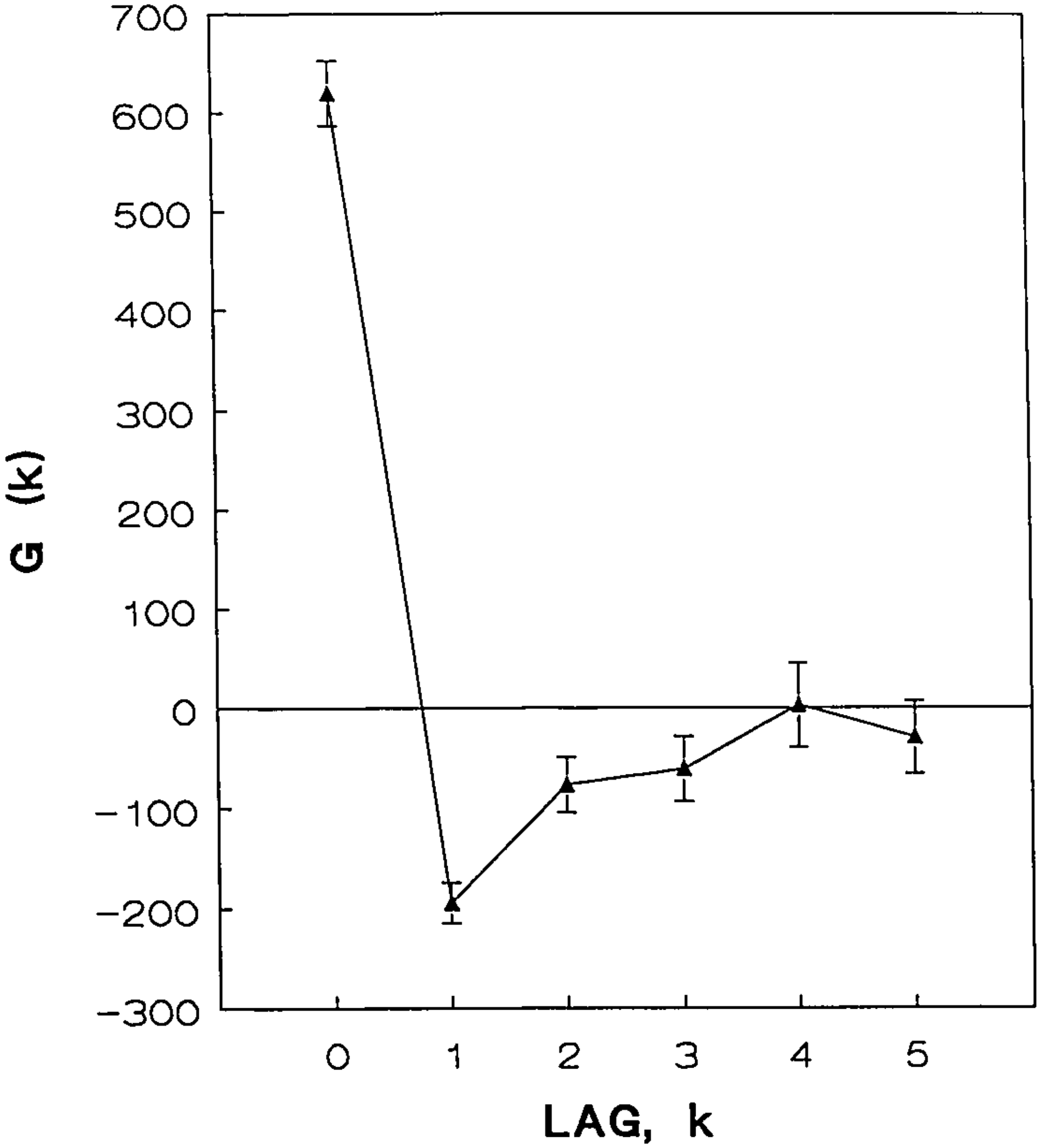
K



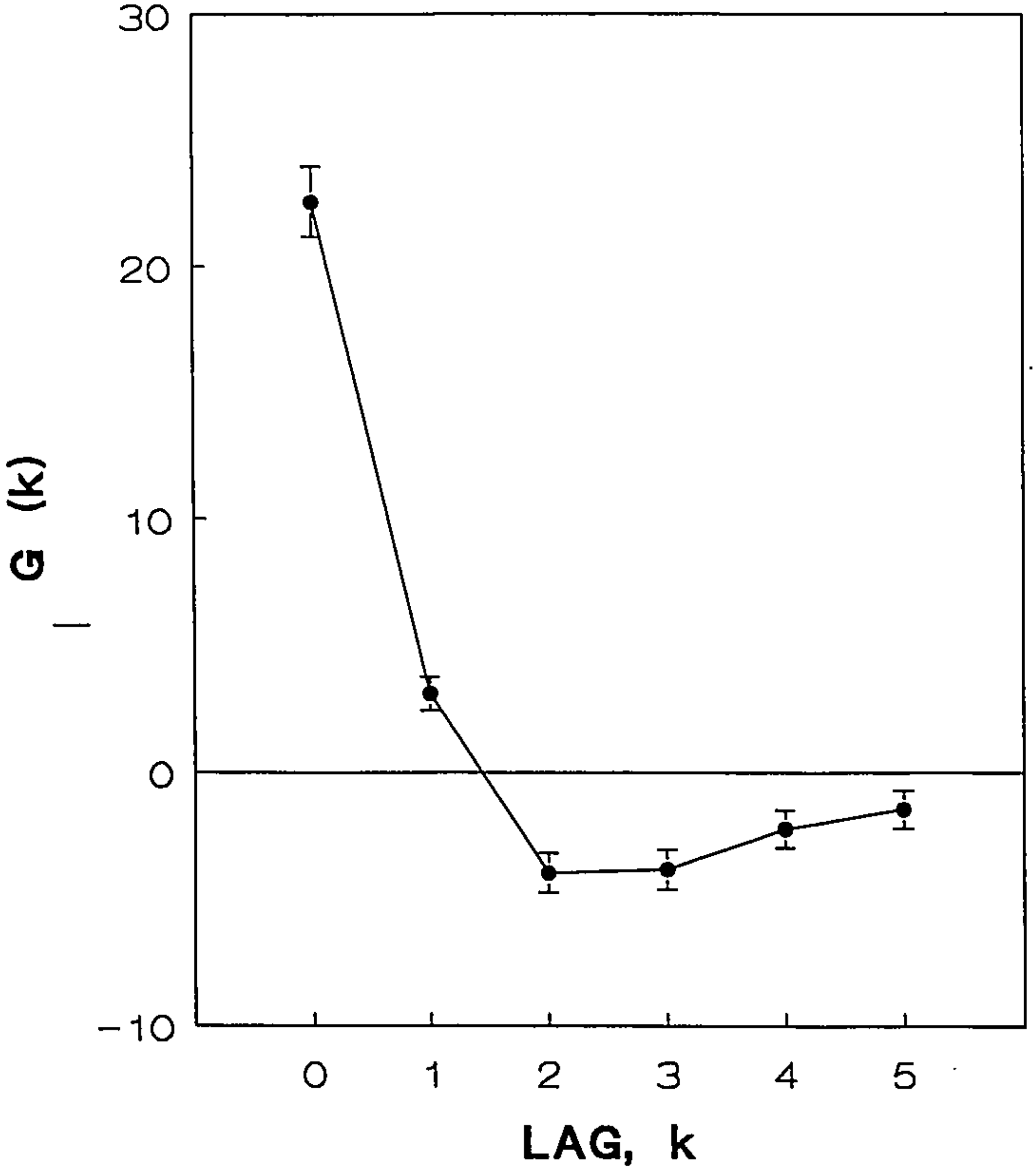
L

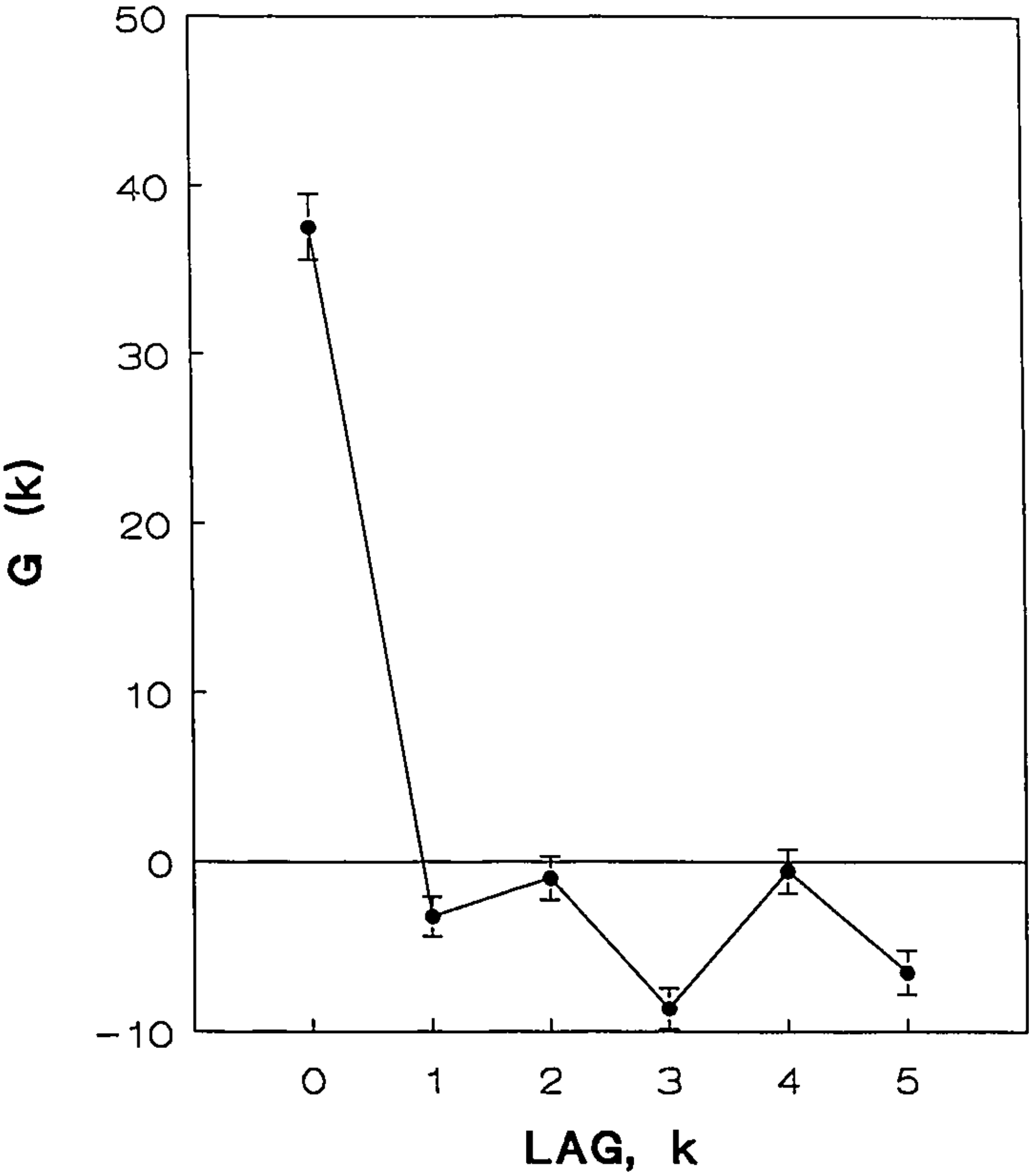


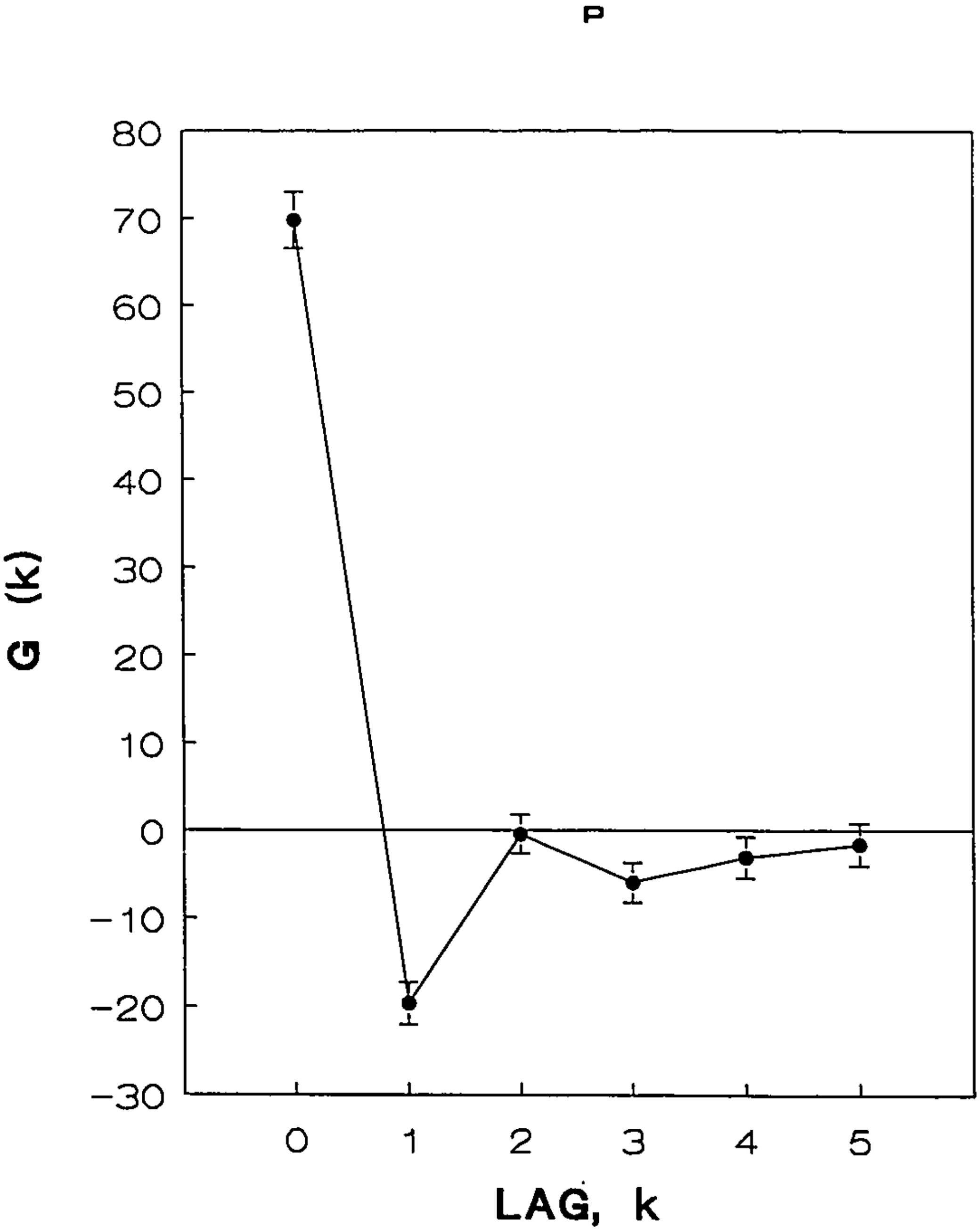
M

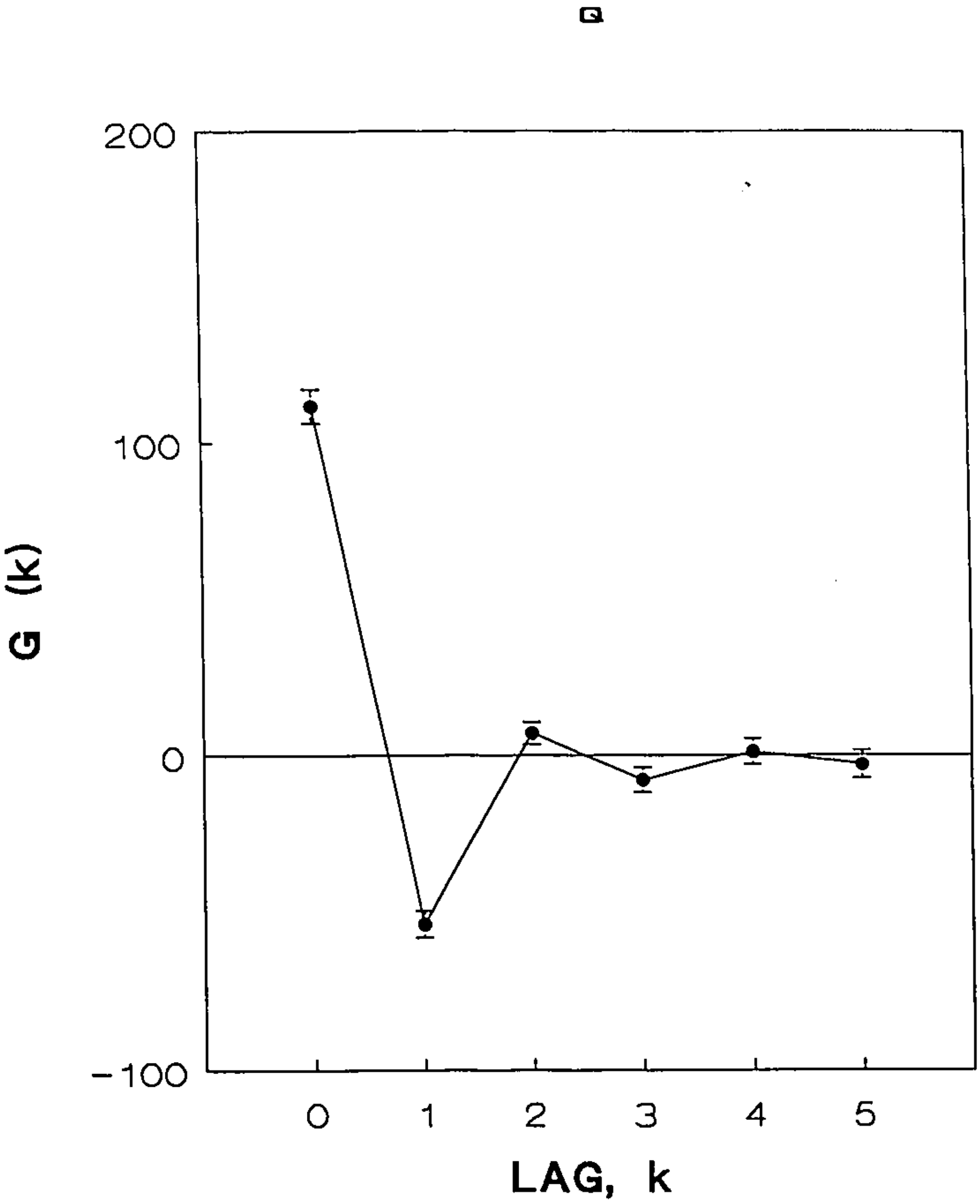


N

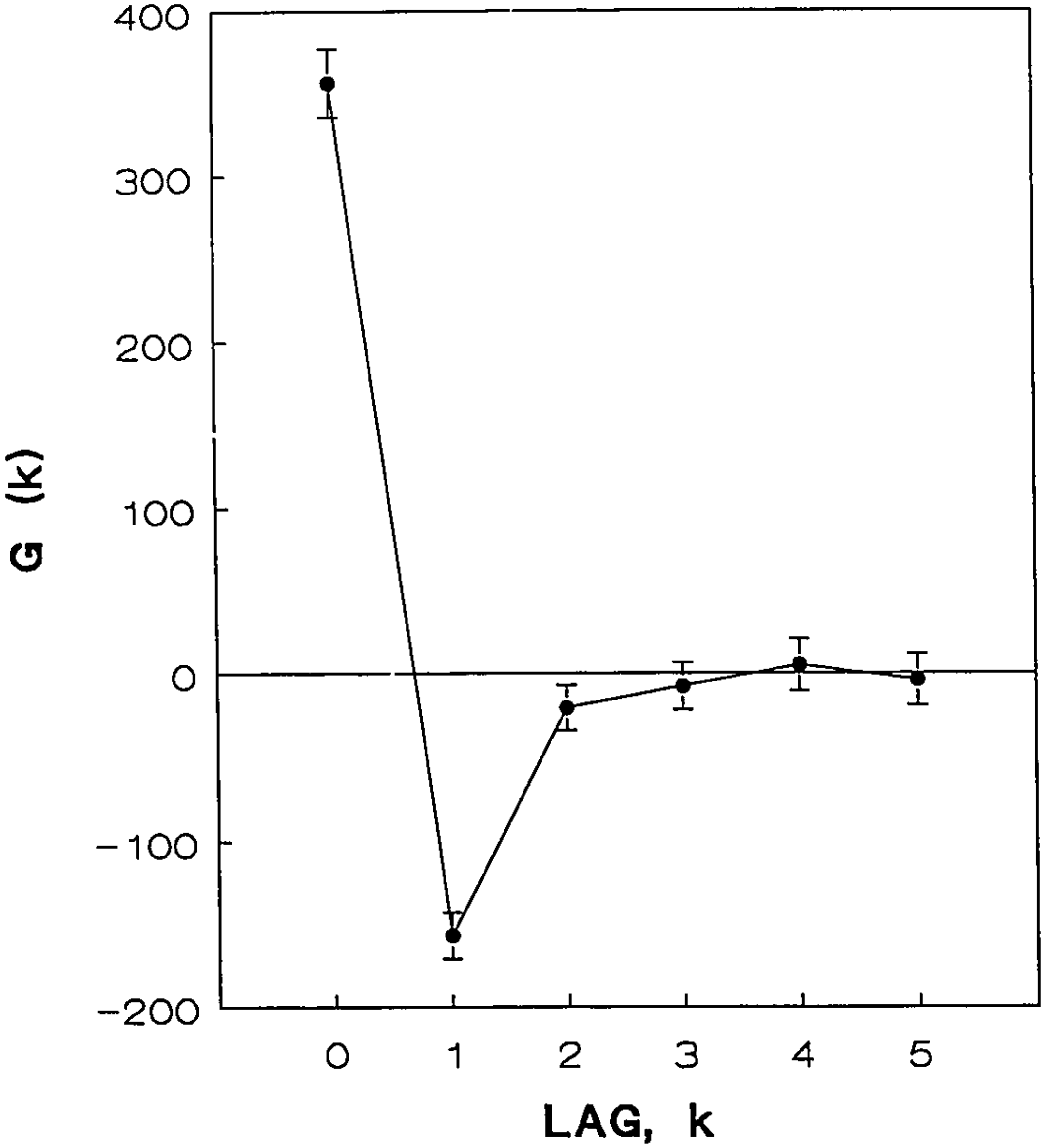


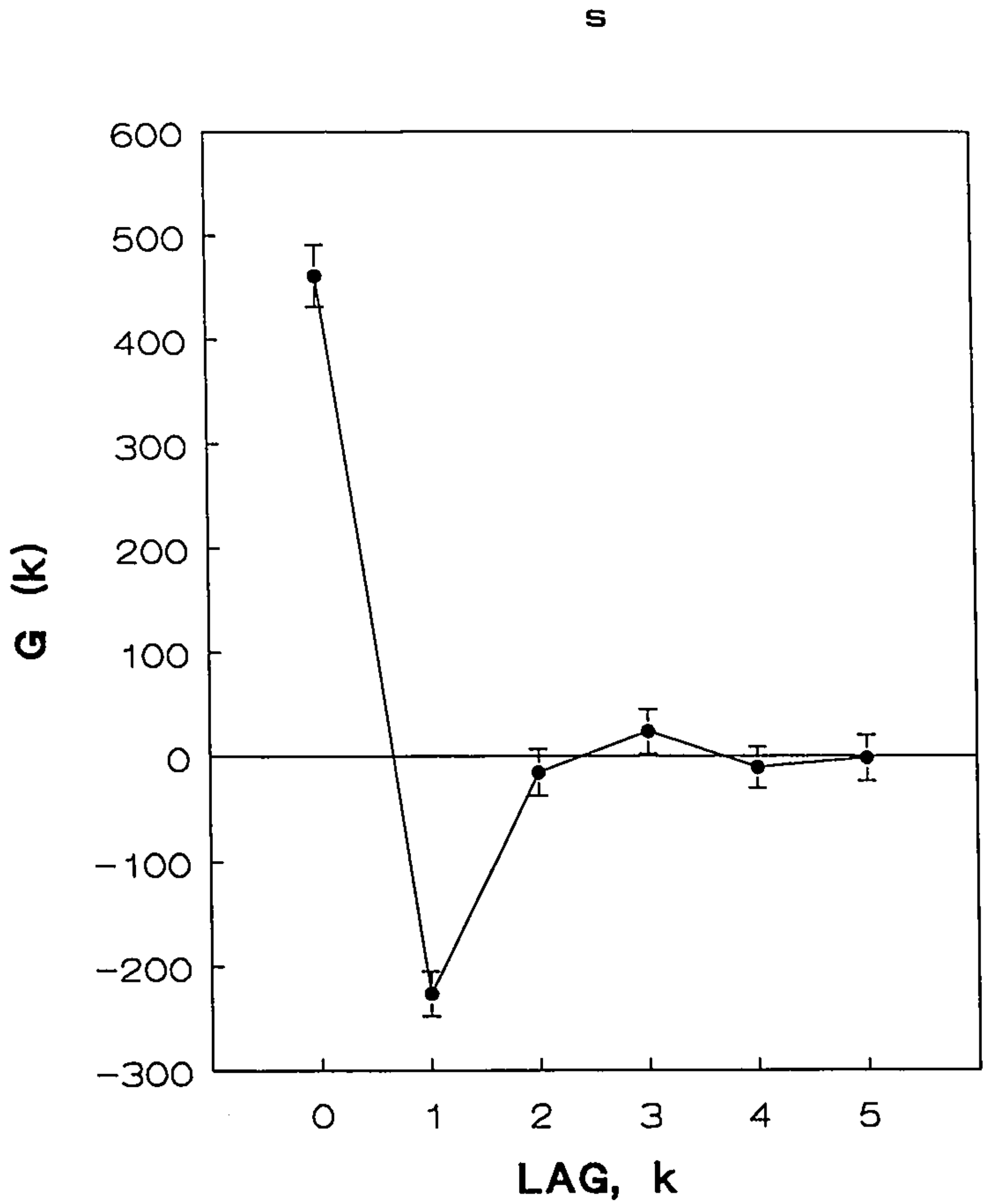

50
40
30
20
10
0
−10
G (k)
0
1
2
3
4
5
LAG, k

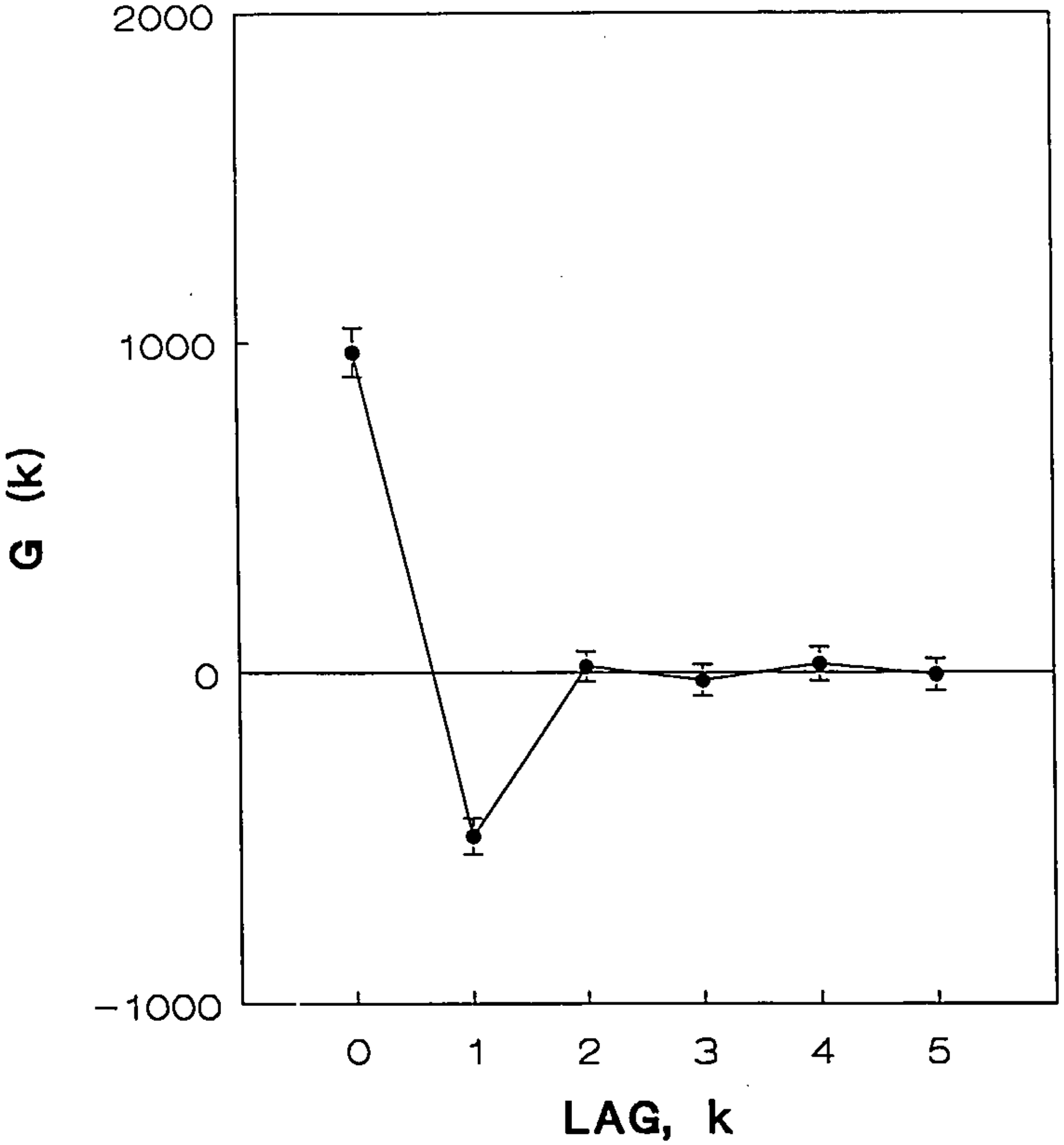

P
G (k)
80
70
60
50
40
30
20
10
0
−10
−20
−30
0
1
2
3
4
5
LAG, k


a
200
100
0
−100
G (k)
0
1
2
3
4
5
LAG, k

R




S
600
500
400
300
200
100
0
−100
−200
−300
G (k)
0
1
2
3
4
5
LAG, k


2000
1000
0
−1000
G (k)
0
1
2
3
4
5
LAG, k

description is adequate sometimes, generally it is inadequate. For the most part $\lambda_I(k)$ for $k>1$ deviate significantly from zero and $\lambda_I(1)$ is almost always less than $-0.5\ \lambda_I(0)$. The five instances when the model is fairly accurately reflected by the data occur for AK at T=466 msec. and for GF at T = 466, 734, 932, and 1468 msec.. Thus, while the model is not completely rejected the level of support for it is tenuous. Clearly, the model needs to be modified to account for the variety of observed autocovariance functions.

SUMMARY

In summary, it is accurate to say that responding in the SP is governed by a stationary process. Probably related to this high degree of stationarity is the precision and accuracy with which responses are made. SP IRI distributions are symmetrical and unimodal with the modal bin located almost directly over T. By comparison SP IRI distributions are less variable and more sharply peaked than their CP counterparts.

Practice is an important issue in SP responding as within session variance shows a downward trend with the number of sessions of experience at most base durations. Unfortunately an attempt to identify the functional properties of the processes associated with the practice effect was not fruitful. The only firm conclusion arising from that attempt is that the practice effect appears to be non-homogeneous. Such a conclusion points toward a multi-faceted integration of components, linked together into a complex structure that collectively operate on IRI responding.

We now know that combined bias corrected SP s_C^2 does not change systematically with T. s_D^2, on the other hand, is related to m_I - both linear and quadratic trend components are significant. Both of these results are consistent with the SCM. However, caution was expressed as individual analyses are in some cases contradictory. Finally, Weber's law models more accurately described the combined SP s_D vs m_I function. This means that the combined variability of all the subject related components (e.g., central clock and motor delay) are more consistent with the proportional standard deviation models than with Creelman's proportional variance model.

According to the SCM, s_C^2, or clock variance, estimates the variability of the interpulse intervals (note: remember that it is called "clock" because the model states that the auditory pulses serve as the Ss timekeeper). On the other hand, s_D^2 represents an estimate of the variability of the timing of all events occurring between the onset of a pulse and the synchronization response to the next pulse. Because of these differences, s_C^2 and s_D^2 represent very different theoretical entities in the context of the analysis of CP IRIs, in terms of the TPM, and in the context of the analysis of SP IRIs in terms of the SCM. As a result they are not directly comparable between models.

In this regard it is interesting to note that the analysis of the CP s_C^2 vs m_I functions bears a striking resemblance to the SP s_D^2 vs m_I function analysis. The comparison between SP and CP analyses becomes more interesting when CP s_D^2 vs m_I and SP s_C^2 vs m_I function analyses are considered - they too are remarkably similar. The absence of external pulses in the CP is associated with a reversal in the parameters of the TPM: CP s_C^2 is a quadratic function of m_I whereas SP s_C^2 is independent of m_I, and SP s_D^2 is a quadratic function of m_I whereas CP s_D^2 is independent of m_I.

Once again, it is difficult to infer anything on the basis of between model comparisons of s_C^2 and s_D^2 because they are measures of variability that refer to different entities for the TPM and the SCM. However, based on analyses of the IRIs, it is undoubtedly the case that there is a clear difference between timekeeping in the two phases. It is impossible to confirm the causes of these differences but they must in part be due to the existence of pulses in the SP and the absence of them in the CP. Perhaps fundamentally different timekeepers or strategies are being accessed as a result of the presence or absence of pulses. The present results illustrate the need to estimate central and motor component variabilities in the SP that are directly comparable to those obtained from the CP. With those estimates we would be in a position to make meaningful comparisons between timekeepers in the two phases.

OVERALL CONCLUSIONS

The purpose of using the continuation method was to have the auditory pulses of the SP start and set the CP clock which then continues to control IRI responding in the CP. However evidence from the present experiment indicates that there might be two timekeeper processes, one operating in the SP and one in the CP. This two clock hypothesis is damaging to the continuation method because it means that first the SP clock is set and then S is forced to switch to the CP clock after the pulses cease. Although tapping in the SP appears to facilitate timekeeping in the CP because the CP clock is set very well somehow, the switch from the SP to the CP probably unnecessarily complicates, and ultimately hinders timekeeping in the CP. Since the primary objective of the tapping experiment is to investigate motor timekeeping in the CP, a better understanding of the underlying mechanism(s) calls for the use of an alternative method to set the CP motor clock.

Clearly, a better alternative method must eliminate the SP but somehow still start and set the motor clock to run at an experimenter determined rate. The "tap to criterion" method, which is described below, should achieve that goal.

The tap to criterion method is similar to the continuation method in that there are two phases within each sequence. However, in the tap to criterion method the SP is substituted by the criterion phase. The criterion phase is used to set the target rate of tapping at the beginning of a sequence. During the criterion phase S starts tapping at a rate he estimates is close to the target rate. If, after several responses the mean IRI does not sufficiently approximate T, a computer monitoring ongoing IRI times would present visual feedback informing S of his mean tapping time. S would use this information to adjust his tapping rate to more closely approximate T (i.e., to increase the tapping rate if the mean rate of responding were greater than T, or decrease it if it were less than T). After the rate of tapping had reached a criterion level of acceptance, S would "continue" to tap for a prespecified number of intervals in the absence of additional feedback. This "continuation phase" ends when an audible computer generated signal is presented to the listener.

Feedback provided during an ongoing sequence might itself be highly disruptive to S. However, S should be able to learn to tap at a fixed rate so that the criterion phase would become very short or completely eliminated. The kind and amount of practice will probably be of great importance in such a procedure. If the same base T is used for all sequences within each session and over many consecutive sessions, there is a good chance that the criterion phase, if not completely eliminated, will be eliminated from a high proportion of sequences.

There are many ways in which the criterion could be defined. One method would involve a comparison between the running mean of the last n IRIs to the target T. For example, criterion would be reached when a prespecified number of sequential running means fall within m msec of T. This definition has the advantage that S would never know exactly when the criterion phase ends and the continuation phase begins. This is an advantage as it would motivate S to tap to the best of his ability throughout the entire sequence. However, it would be necessary to place an upper limit on the number of IRIs in the criterion phase because without such a limit, the sequence could go on indefinitely.

The "tapping to criterion" method circumvents the main problem associated with the original continuation method. Because the SP is replaced by the criterion phase no abrupt transitions take place within a sequence. However, one potential problem with the tapping to criterion method is that the number of IRIs in the criterion phase is not set at a specific number, so sequence lengths would vary. But this variability in sequence lengths is due to variability in the number of IRIs in the criterion phase; the number of

IRIs in the CP would be fixed. This is a potential problem because the extent of variability in sequence lengths is an empirical matter which must be investigated experimentally.

Finally, the tapping to criterion method serves as a motor analog to the implicit standard MF DD method used by Kristofferson (1980) - the standard is never explicitly presented. From the information available at present, it appears that when an explicit standard is presented, whether it is in a perception or motor timing setting, the Weber function is smooth (i.e., it does not increase in a stepwise manner), and when it increases, it does so in accordance with Weber's law. A method employing an implicit standard has been investigated in the context of DD (Kristofferson, 1980) and from that study we know that the step function emerged following extensive and specific practice. What remains to be determined is the form of the Weber function using a repetitive tapping procedure in which the standard is implicit and extensive and specific practice is afforded. The tapping to criterion method allows one to investigate the effects of an implicit standard in the context of motor timing.

GENERAL DISCUSSION

The idea that a single internal clock, or timekeeper, mediates the temporal control of all behaviour is certainly incorrect. Nevertheless it is possible that a variety of behaviours either share a common timekeeper or are mediated by functionally similar timekeepers. If that is the case it should be possible to integrate results generated by a variety of experimental paradigms within the general context of timekeeping.

At a very basic level, we know that the results from a variety of experimental procedures probing the timekeeping abilities of human beings have features in common. For example, above a critical duration and over a wide range of durations, variability increases as T increases. This feature can be seen in the PTDD, MFDD, R-SS, and CP functions. However, it is important to emphasize that over small ranges local features vary considerably (e.g., Kristofferson, 1980 for MFDD; Kristofferson, 1976 for R-SS; Wing & Kristofferson, 1973 for tapping). In other words, the specific nature of the relationship between variability and temporal interval is not consistent across tasks.

How can these similarities and differences be interpreted in terms of underlying temporal mechanisms? The approach that is adopted generates estimates of central, and in some cases efferent, variance from statistics obtained by modeling the various functions. If different comparisons yield similar estimates for each of these variables, and they are consistent with others found in the literature, then an integrated and coherent understanding of the underlying mechanism(s) could emerge.

The main comparisons that will be used are of the shapes and locations of the variability versus mean functions. Theoretically these functions do not consist of the same components so extreme care must be taken when comparisons are made. For example, theoretically the PTDD s_C^2 vs m_I function incorporates only central variability whereas the s_R^2 vs m_R function obtained in R-SS incorporates both central and efferent variability. Afferent variance does not enter into consideration in either of these functions because previous research has shown that it is inconsequentially small relative to the other components.

Because substantial intersubject differences are obtained in the present experimental results, generalizations between paradigms will be based upon within S comparisons when possible. Similarly, since level of practice has an effect on performance it too will be considered when comparisons are made.

Table 4.1 provides a summary of statistics based on the analyses of the functions for several Ss from several experimental paradigms. With the exception of MFDD, Kristofferson's (1976) model provides the best fit to the functions. Because of the excellent fit of Kristofferson's model to the data, comparisons between functions will be made on the basis of the statistics generated by that model.

It is very fortunate that AK has participated in and has a high degree of practice with all four experimental procedures. A high level of practice with all four procedures will facilitate comparisons. Comparisons are also facilitated because very similar empty auditory stimuli were employed in all of these experiments. Response demands differed in these experiments, but it is those differences that allow one to obtain independent estimates of efferent and central variability. Unfortunately neither LL nor GF have experience with MFDD or R-SS, so within subject comparisons of their data sets is limited to PTDD and tapping.

COMPARISONS AMONG SEVERAL PSYCHOPHYSICAL PROCEDURES

If certain assumptions about the underlying temporal mechanisms are made, comparisons between any two of the four functions should reveal information about those mechanisms. For example, estimates of minimum central timekeeper variance, and the

TABLE 4.1

Summary of Kristofferson's generalized Weber's law model fitted to the functions obtained from PTDD, CP tapping, and R-SS. K, L, and V_0 are parameter estimates of the model. Also shown are the estimates of the parameter K for the original Weber's law model for MFDD. AK, LL, and GF are the three subjects who participated in the current research programme.

PTDD: s_C^2 vs m_I FUNCTION, KRISTOFFERSON'S MODEL

AK K = 0.031, L = 301, Vo = 18.
LL K = 0.031, L = 361, Vo = 15.
GF K = 0.049, L = 510, Vo = 26.

TAPPING: BIAS CORRECTED s_C^2 vs m_I, KRISTOFFERSON'S MODEL

AK K = 0.031, L = 151, Vo = 120.
LL K = 0.020, L = 0, Vo = 13.
GF K = 0.026, L = 32, Vo = 0.

MFDD: s_C^2 vs m_I FUNCTION, WEBER'S LAW MODEL

AK K = 0.051, line through origin before practice
K = 0.026, step function after practice

R-SS: s_R^2 vs m_R FUNCTION, KRISTOFFERSON'S MODEL

AK K = 0.034, L = 550, Vo = 142.

manner in which central timekeeper variance changes with temporal duration, should be possible as a result of a comparison among these functions. In addition, new estimates of efferent delay variance and the duration of any deterministic intervals should be possible.

In order to compare results among procedures it is assumed that processing involves at least three distinct stages or components; afferent, central, and efferent. Unless otherwise stated it is further assumed that each of these stages operates independently of the others. Thus the total variance for a given procedure is equal to the sum of the variances of the contributing stages. On the basis of evidence presented earlier, variability in the afferent system is negligible. For present purposes afferent latencies are assumed to be non-variable. If that assumption is valid, the points on the PTDD and MFDD functions are interpreted to be direct measures of central variance. Similarly, each point on the R-SS function is interpreted to be a combined measure of central and efferent variances. The CP IRI tapping function is composed of central variance plus two times efferent variance since each IRI is defined by two responses. Further comparisons between the CP tapping functions and the functions of the other procedures are possible because IRI functions can be decomposed into separate central and efferent functions via the TPM (Wing and Kristofferson, 1973). The equations below show the variance ($V_{component}$, where component is c for clock, a for afferent, and e for efferent) of the contributing components for each point on each of the four functions under consideration.

MFDD: $V_c + V_a = V_c$ if $V_a = 0$

PTDD: $V_c + V_a = V_c$ if $V_a = 0$

R-SS: $V_c + V_a + V_e = V_c + V_e$ if $V_a = 0$

CP TAPPING: $V_c + V_e + V_e$

PTDD AND MFDD FUNCTIONS

When AK's PTDD function is compared to his MFDD function a distinction of theoretical importance emerges. Early in practice the MFDD function (Kristofferson, 1980) is well described by the strict form of Weber's law in which s_C is proportional to m_I over the full range of base durations. The zero intercept function has a constant of proportionality equal to 0.053, which is, as Kristofferson (1980) points out, in good agreement with Getty's (1975) K of between 0.05 and 0.06. In PTDD K equals 0.056 for AK early in practice. These similar values of K suggest that the pre-practice Weber constant, K, is the same for PTDD and MFDD.

It is important to realize that the pre-practice PTDD function has a deterministic component in it that is not reflected in K. The PTDD function is flat at the lower end and it rises in accord with Weber's law for differences in means above L, which in this case equals 398 msec. Thus, while the value of K is nearly identical for the two DD paradigms, the functions differ considerably. As practice continues this difference manifests itself more dramatically.

Following extensive and specific practice both PTDD and MFDD functions change. The MFDD function changes both in shape and location; the simple proportional relationship transforms into the step function (Kristofferson, 1980) which was, for the most part, lower in location. The PTDD function lowers in position but it maintains its basic shape - a PTDD step function does not emerge even though extensive and specific practice is given at each base duration.

What causes these very different functions to emerge? Kristofferson (1980) proposed that a quantal counting mechanism might be responsible for the emergence of the MFDD step function. Each step defines a unique quantum value and the slope of the step indicates that the error in the quantal counter increases with the number of quanta counted. The gradual flattening of the steps with practice was interpreted to be the consequence of the reduction in quantal counting error.

It is not obvious how a quantal counting mechanism can explain the PTDD function but if one supposes that error in quantal counting does not change with practice under certain circumstances (e.g., with the use of an explicit standard) then such an hypothesis could preserve the straight line segment that describes the PTDD functions for durations greater than L. But this hypothesis must be rejected because while K decreases with practice, the linear shape of the function does not change.

To complicate matters further, K actually increases for two Ss (LL & GF). According to the hypothesis outlined above, an increase in K should indicate an increase in counting error with practice. Although possible, that does not seem to be a very plausible explanation.

In summary, many pieces of evidence suggest that the temporal process underlying PTDD probably is not an imperfect quantal counter. Rather the PTDD data support the idea that it is a stochastic process for increments in duration in excess of a lower limit L. For durations below L the data indicate that a different process is in effect, one in which variance does not change as a function of base duration.

PTDD and MFDD have many methodological similarities but there is one significant difference between them that may be related to the type of timekeeping process that is available to S. That difference is that the standard is implicit in MFDD and explicit in PTDD.

Kristofferson (1987, 1990) proposed that the method by which the internal criterion is established may be a critical factor in determining the shape and location of the resulting function. He proposed that because the standard interval is implicit in MFDD, I (the internal interval in the RTCT model) must be fixed indirectly. That in turn could lead to a memory controlled criterion. In contrast, a procedure that uses an explicit standard (e.g., PTDD) could lead to a stimulus driven criterion.

Jezdic (1986) tested the implicit/explicit standard idea and concluded that the criterion is also memory controlled in PTDD. But, Kristofferson (1990) notes that it is possible that memorial representations of temporal intervals differ depending on how the memory is encoded. Particular experimental conditions, such as explicit and implicit standards, may lead to different memory representation and retrieval processes. From the available evidence to date it appears that encoding the memory representation of the PTDD explicit standard does not lead to a quantal retrieval process. However, encoding the memory representation of the MFDD implicit standard appears to lead to a retrieval process involving a quantal mechanism.

We now know that the memory representation generated by an explicit standard can be transferred and used when the standard is switched and becomes implicit (Jezdic, 1986). But we do not know if the reverse holds - that is, whether the memory representation for a standard generated by an implicit standard can be transferred and used when the standard is switched and becomes an explicit one. Performing the appropriate experiment to determine whether that would be the case is important because it might provide insight into the encoding processes involved with both types of standards.

From the foregoing discussion it appears that there is a connection between the way the internal criterion is established (i.e., via implicit or explicit standards) and the nature of the timing mechanism (i.e., quantal or stochastic). For example, it also appears that a criterion established by an implicit standard is linked to a quantal timer and one that is established via an explicit standard is linked to a non-quantal timer that incorporates deterministic and stochastic processes.

This connection between the type of criterion and timing mechanism could hold for other psychophysical procedures as well. In R-SS an explicit standard is potentially available - on every trial the subject must attempt to synchronize his response to a stimulus that explicitly defines the end of the synchronization interval. Thus the standard presented on a given trial is not used for the trial on which it is presented but standards presented on previous trials could be used on subsequent trials. We do not know if standards presented on previous trials are used in this fashion but it is interesting that the R-SS function qualitatively is more similar to the PTDD function than it is to the MFDD function. This information does not prove that subjects use prior trials to encode their memory representations of the standard and that that standard is then used on later trials, but it is consistent with that idea.

It would be informative to alter the basic R-SS paradigm and incorporate an explicit standard on the trial in which it is to be used. This could be accomplished by presenting a fixed number of isochronous pulses prior to the R-SS pulse pair in order to define the explicit standard on each trial. The task would require an attempt to synchronize a response to the final pulse in the pulse train. This experiment would be similar to the PTDD paradigm except that rather than making a discrimination judgment to a temporally displaced final pulse, S would make a synchronization response to the final non-displaced pulse of the pulse train. If the altered R-SS function is qualitatively similar to the original R-SS function then that would further support the hypothesis that Ss are using an explicit standard in the original R-SS paradigm.

One more example in which the standard is explicit and the results conform to the above expectations is the continuation paradigm (Wing, 1973). The standard is explicit because it is repeatedly presented during the SP. The CP function was found to be monotonically increasing by Wing (1973) and in the present research.

There are remarkably few procedures that make use of an implicit standard. The MFDD procedure is one example (Allan & Kristofferson, 1974) and certain time estimation procedures may qualify as others. While other procedures could provide implicit standards it is not just the type of stimulus that is important for the step function to emerge. High levels of specific practice are also required, presumably to create the right conditions to reduce quantal counting error. In this respect I know of no implicit standard experiment in which Ss are given the degree and kind of practice that Kristofferson's Ss received. It would be very informative to conduct an implicit standard experiment, using a procedure other than MFDD (and with sufficient levels of practice), to determine if the type of criterion/timing mechanism connection is maintained.

One procedure that could be used to accomplish that goal might be called implicit standard pulse train duration discrimination. On each trial of this procedure a short and a long reference stimulus would be presented, one following the other. The midpoint (e.g., the arithmetic or geometric mean) of these two reference stimuli would define the standard. The standard would be implicit because no stimulus equal in duration to it would ever be presented to S. A short time following the end of the second reference stimulus the test stimulus would be presented and S would be asked to judge whether the test stimulus was shorter or longer than the standard. Feedback as to the correctness of the judgment would be provided at the end of each trial in order to experimentally categorize responses according to how the standard is defined.

Another set of procedures which derives from Gibbon's (1977) Scalar Timing Theory (STT) could be used to further probe the type of criterion/timing mechanism relationship. If PTDD and implicit standard PTDD are carried out without any feedback given following responses, they would be converted to explicit and implicit standard pulse train bisection discrimination experiments respectively. STT could then be applied to the data in order to evaluate the criterion/timing mechanism relationship.

The implicit standard pulse train duration discrimination procedure borrows the pulse train characteristic from PTDD and bears a strong resemblance to MFDD (Allan, 1979; Kristofferson, 1980) and the human bisection discrimination experiment (Allan & Gibbon, 1991). It is similar to the MFDD and bisection procedures in that the standard is implicit. The feedback characteristic is typical of both PTDD and MFDD and it is the primary difference between DD and bisection discrimination procedures. Another feature that distinguishes the proposed procedure from MFDD and bisection discrimination is that both reference points would be presented on every trial. In Allan and Gibbon's (1991) bisection discrimination experiment the short and long reference points each were presented on only 14 of a total of 91 trials and feedback was given on half of those. In contrast, a reference stimulus was never presented in Kristofferson's (1980) MFDD experiment and only one test stimulus was presented on a trial.

PTDD AND R-SS FUNCTIONS

The similarities between the PTDD and R-SS functions are most striking. Both functions have a flat, or deterministic region, over the lower range of base durations and an increasing Weber's law region, with similar slopes, over the higher ranges.

Although these two functions are very similar, important differences between two of the statistics generated by the fitting procedure deserve comment. The difference between estimates of V_0 from AK's R-SS and PTDD functions equals 124 msec^2 (142 - 18; but 142 probably is an overestimate because later Hopkins and Kristofferson (1980) obtained much smaller S-R latency variance estimates with modified procedures. Their estimate was on the order of 50 msec^2. But because AK was not a subject in those experiments the estimates from Kristofferson (1976) will be used for present purposes). Likewise the difference between estimates of L equals 249 msec (550 - 301).

What might these differences tell us about underlying temporal processes? Let us assume that Kristofferson's (1977) Real Time Criterion Model accurately models the temporal processes governing behaviour in R-SS and PTDD. That model states that for both procedures there is an afferent latency interval that has a small amount of variability associated with it, and a centrally timed interval that terminates at the criterion. The time of occurrence of the criterion is variable and the isosceles triangle distribution is used to represent its variability.

In PTDD a judgment is made on the basis of a race between the criterion and the internal event corresponding to the end of the interval being judged. Hence, the only potential sources of variability are the afferent and central systems. In R-SS, however, the criterion acts as a trigger to activate the efferent system, a third source of variability that is not present in PTDD. Because the overt response in R-SS is meant to occur at the same time as the end of the test stimulus, the internally timed interval (I) terminating at the criterion is longer in PTDD than it is in R-SS when the base temporal interval is the same in both procedures. On average this difference should be equivalent to the sum of afferent and efferent latencies.

If one assumes that afferent and efferent variability do not change as a function of temporal interval then all changes in the R-SS function should be due to changes in central variability. Because PTDD does not include an efferent component, the 124 msec^2 difference between V_o estimates in the flat region of the two functions may be interpreted as an estimate of efferent variability for AK. Similarly, the 249 msec difference between estimates of L represents the mean sum of afferent and efferent latencies in R-SS, most of which should represent efferent latency.

The present estimates of efferent latency and variability are higher than those published in the literature. From the CP of Wing and Kristofferson's (1973) finger tapping experiment, estimates of efferent variance ranged between 10 and 50 msec^2. An independent estimate of efferent variance obtained by Hopkins (1984), through a simulation of R-SS data, was about 15 msec^2. Thus the present estimate of 124 msec^2

seems high when compared to these other estimates, especially Hopkins' (1984) result. The difference between the present estimate and Hopkins' (1984) is most likely due to the substantial modifications in procedure that Hopkins (1984) incorporated into the R-SS paradigm.

One may be tempted to use simple reaction time variance as an estimate of efferent variability. Kristofferson (1976, 1977) and Saslow (1974) report simple reaction time variance to be approximately 350 to 400 msec^2 which is substantially higher than either the present estimate or any of the other estimates discussed. This large difference suggests that simple reaction time variance is not simply equivalent to efferent variance.

Kristofferson (1976) noticed that simple reaction time variance is typically higher than R-SS variance. This is interesting because R-SS intervals are longer than the simple reaction time limit and presumably they include an additional, centrally timed interval with its own source of variance. Kristofferson (1976) suggested that one possible cause of this difference is trigger interference. The internal trigger for a simple reaction response may add temporal variability as a result of being temporally coincident with the internal registration of the external stimulus. Separate the trigger from the sensory event, as in R-SS, and response variance drops significantly (from roughly 375 to a low of about 142 msec^2; V_0, Kristofferson, 1976). The difference between these two estimates of variance could reflect the maximum amount of variance due to trigger interference. That difference equals 233 msec^2.

If trigger interference accounts for 233 msec^2 of the total variance then the remaining 142 msec^2 (375 - 233) presumably is the sum of central and efferent variances. Of that 142 msec^2 we have estimated that 124 msec^2 derives from efferent sources. Interestingly, this leaves only 18 msec^2 (142 msec^2 - 124 msec^2) that must represent the sum of the variances of the afferent and central components. Thus if the afferent system is variance free, then the central component of the R-SS chain of events has a variance of only 18 $msec^2$ associated with it.

Estimates of efferent latency also differ from previously published estimates. Kristofferson (1976), for example, reports minimum simple reaction time latency to be about 160 msec. This figure closely matches that published by Saslow (1974) and now is accepted as the established minimum simple auditory reaction time latency. The mean minimum simple reaction time latency obtained from the three subjects in Kristofferson's (1977) speeded response MFDD paradigm is 174 msec, slightly higher than 160 msec. This estimate is higher because two of the three subjects had not yet reached their asymptotic level of responding. The one subject that did reach the optimal level of responding had a simple response latency of 168 msec.

The present efferent latency estimate of about 249 msec is 89 msec higher than the established minimum simple reaction time latency. What might account for this difference? Kristofferson's (1976) idea that a non-variable delay of up to 400 msec may be inserted into the temporal chain of events will, for the most part, account for the difference. Along this line of thinking let us suppose that a delay of up to 300 msec may be inserted into the centrally timed interval when the task does not involve the efferent system (e.g., non-speeded MFDD or PTDD). Evidence for this delay can be seen as the flat portion on AK's PTDD function. Similarly, let us suppose that when the efferent system is involved (e.g., R-SS) that a delay of up to 400 msec can be inserted into the central interval. Kristofferson (1976) provides evidence supporting a delay of this magnitude (L - simple reaction time limit). I can offer no conclusive reason why the inclusion of a response might extend the duration of the deterministic delay in the central component. At a speculative level it is possible that the transfer of information from the central to the efferent systems takes a period of time (100 msec) and that this transfer involves a negligible amount of variability. Such a transfer would not exist in PTDD or MFDD thus giving rise to the shorter deterministic interval.

The two conditions that give rise to the two centrally located deterministic delays, together with trigger interference, can explain the differences between the PTDD and R-SS functions and also integrate simple response time data into a logical framework. For a simple reaction time response three conditions will give rise to the observed response latency and variance. They are 1) maximum trigger interference, 2) zero central variability and zero deterministic interval inserted into the central interval, and 3) efferent variability. As the R-SS interval increases above the simple reaction time limit, continuously adjustable deterministic delays are inserted into the central component and a residual amount (e.g., 18 msec^2) of central variability is introduced. The small delay inserted into the central mechanism serves to separate the response trigger from the internal sensory event thereby quickly reducing response variance due to trigger interference. Evidence of such a reduction can be seen in Fig. 5 (Kristofferson, 1976) in which there is a rapid decrease in variance from the simple reaction time limit to approximately 280 msec, the upper limit of Region I (Kristofferson, 1976). According to this interpretation trigger interference is no longer a factor for intervals in excess of 280 msec. Variance remains stable throughout Region II, suggesting the insertion of additional non-variable delays.

For an R-SS interval of 550 msec the deterministic delay of the centrally timed interval is approximately 400 msec. Total variance reflects simple response time variance, with variance due to trigger interference reduced to zero, plus a small amount of residual central variance (i.e., 18 msec^2). Timing of increments above the 550 msec point is accomplished via a stochastic mechanism in the central system that obeys Weber's Law. That timer is activated only after the deterministic delay is fully in place.

It appears to be the same for both PTDD and R-SS because of highly comparable values of K (0.034 and 0.030 respectively for AK).

If this line of thinking is correct then we have a starting point toward an integrated understanding of the differences between the PTDD and R-SS functions. The present proposal ties together several features of simple reaction time, PTDD, and R-SS functions. It incorporates deterministic delays in the central timing mechanism as per Kristofferson (1976) but it differs from Kristofferson's (1976) proposal in that the delay has a maximum of 300 msec under some conditions and 400 msec under others.

PTDD, CP TAPPING, AND R-SS FUNCTIONS

Estimates of efferent and central variability also can be obtained when the CP tapping function is compared to the PTDD and R-SS functions. For example when V_o is calculated from AK's CP IRI function it is substantially higher than when it is based on either his R-SS or PTDD function. But that is exactly as it should be because each IRI, according to Wing and Kristofferson's (1973) TPM, has three sources of variance associated with it - the central component and two efferent delay components. If all components are mutually independent then the sum of the associated variances should equal the IRI response variance.

To obtain an estimate of efferent variance from the CP function, an estimate of central variance first must be subtracted from V_o and the remainder divided by two. If an estimate of minimum central variance is taken from AK's PTDD function (V_o equals 18 msec^2) efferent variance equals 108 msec^2 [(233 - 18)/2]. That value is very close to the 124 msec^2 estimate which was obtained via a comparison between the R-SS and PTDD functions. However, if an estimate of central variance is taken to be equal to V_o from AK's CP s_C^2 vs $\bar{m}_I$ function (120 msec^2) then efferent variance is reduced to 56.5 msec^2 [(233 - 120)/2]. The first estimate corroborates well with other estimates in the present set of experiments but the latter is more consistent with estimates of efferent variance cited in the literature (e.g., Wing & Kristofferson, 1973).

Another estimate of efferent variance may be obtained by subtracting V_o based on the R-SS function (142 $msec^2$) from V_o of the CP IRI function (233 $msec^2$). This procedure yields an estimate equal to 89 $msec^2$. These estimates must be considered as slight overestimates because adjacent response delays are not independent (Wing, 1980). A model based on first-order autoregressive response delays should provide estimates of efferent variance that are slightly lower than those which are based on independent response delays. In any case, the present results suggest that efferent variance ranges between a lower limit of about 50 $msec^2$ and an upper limit of 120 $msec^2$.

Estimates of the central deterministic interval also can be derived from a comparison between functions. For example, from modeling AK's bias corrected s_c^2 functions, L equals 151 msec. This is exactly half of that based on his PTDD function. These dissimilar values suggest that the deterministic interval is available in very diverse conditions and more importantly that it is adjustable.

At this stage two important points should be be emphasized. First, in keeping with Kristofferson's (1976) idea that the central deterministic delay is adjustable it appears that adjustments in the deterministic interval can take place. The value of L based on the bias corrected s_c^2 function is exactly half of L obtained from the PTDD function. This could be coincidence but it could indicate that the deterministic interval has a halving/doubling characteristic similar to Kristofferson's (1980) quantal step function in which both the quantum size and the deterministic delays (the tread widths on the function) increase in a doubles set. Second, although Kristofferson's (1976) model fitted AK's CP bias corrected s_c^2 function the best among the models evaluated that function also could be well represented by a two tread step function for T up to and including 734 msec, and a Weber law component for T greater than 734 msec. With a couple of important differences that were described earlier, such a description is very similar to the MFDD quantal step function obtained by Kristofferson (1980).

The emergence of similar step functions from MFDD and tapping goes contrary to the hypothesis linking the type of standard to the timing mechanism. In MFDD the type of standard is implicit while in tapping the standard is explicit, yet in both procedures very similar step functions emerged. Such a finding means that the link between the type of standard and the timing mechanism does not always hold, but that needs to be confirmed. However, on a much more fundamental issue, the emergence of similar step functions from two vastly different experimental paradigms implies the possibility of common timing mechanisms for both tasks.

Properties of quantal timing have rarely been cited in the tapping literature and when they have been there are no cases when those same properties have been forthcoming on the same subject in a perception task such as duration discrimination. This is the first such report and it suggests that there might be common ground between the timekeepers mediating DD and tapping. It emphasizes the necessity to further investigate the relationship between timekeeping in perception and motor movement. Several key requirements of undertaking an investigation of this nature are now becoming clear: The same subjects must be included in both experiments and, at least initially, within subject comparisons of results are of paramount importance because subjects differ so much in their experimental results. Extensive levels of practice must be afforded at each base temporal interval studied before moving on to the next interval.

In the present investigation, the within subject approach of comparing results obtained from diverse tasks such as tapping and PTDD has obvious limitations. Up to this point estimates of the various components (e.g., efferent variance) have been based on the results of one subject, AK. Similar comparisons using simple reaction time or R-SS functions cannot be made for LL or GF because data for them are not available on either of those tasks. But their results do provide some relevant information with respect to the present analysis. For example, the maximum delay that may be inserted into the centrally timed interval is 360 msec for LL and 500 msec for GF. Similarly, the residual central level of variability is 17 $msec^2$ and 27 $msec^2$ for them respectively. But neither efferent latency nor variability can be calculated using this approach since estimates of these quantities can only be made on the basis of a comparison between the R-SS and PTDD functions. Finally, based on the PTDD function, variability above the deterministic region is predicted to obey Weber's law and have values of K equal to approximately 0.03 for LL and 0.05 for GF.

Comparisons between bias corrected s_C^2 vs m_I functions and PTDD functions for LL and GF do not follow the same pattern as they do for AK. Their tapping functions are difficult to interpret in the same manner as AK's functions because L equals zero for LL and V_o equals zero for GF.

When L equals zero (which was the case for the CP tapping function for LL), presumably the duration of the deterministic delay equals zero and no such delay is introduced into the timing chain of events. Although the deterministic delay differs between the two tasks (L = 361 msec for PTDD) for LL it is interesting that the estimates of the minimum variance associated with the central process (V_o) are very similar (13 and 15 $msec^2$). This is interesting because it implies that while minimum central variance remains constant, the duration of the deterministic delay is not fixed.

The values of K differ between LL's PTDD and CP bias corrected s_C^2 functions. This difference could represent a real change in the stochastic process or it may be simply a mathematical result of the reduction in L. If it represents a real change in the stochastic process then we have reason to believe that the processes are different in the two tasks. However, if it represents a change due to the absence of a deterministic interval being inserted into the chain of events then we are not forced to conclude that the stochastic timing processes involved in PTDD are different from those involved in tapping.

The comparison of GF's functions indicates that the deterministic interval is much longer in PTDD (510 msec) than it is in CP tapping (32 msec). It turns out that this is a common feature among all three subjects; L is smaller in CP than it is in PTDD. Again, these results indicate that the deterministic interval is not fixed because the values obtained from the two procedures are different. Finally, for GF, both V_0 and K are smaller in magnitude in CP tapping than in PTDD.

In summary, the comparisons between PTDD and CP bias corrected s_C^2 functions illustrate that there are significant differences in the timing processes involved in the two tasks, differences that were commented on in detail above. More importantly however, they also show that there are substantial similarities between the timing processes involved. For example, for short temporal intervals Ss can insert a non-variable temporal delay into the chain of events. That delay is adjustable, a fact that makes the entire process dynamic and flexible in both procedures.

The timing of intervals above the upper limit of the deterministic interval involves a different process, one that obeys Weber's law. The operation of such a stochastic process is evident in both PTDD and CP tapping. Although the values of the estimated parameters often vary a great deal within and between Ss, both principles of timing are present in the results of each procedure.

Kristofferson (1990) recently outlined three principles of timing; the quantal principle, the deterministic principle, and the stochastic principle. All three principles are manifested by the quantal step function first presented by Kristofferson (1980). Data consistent with the operation of all three principles have once again been identified in the present set of experiments. The fact that these three principles have been identified in such a diverse set of procedures indicates the general functional similarities of the mechanisms that give rise to them. However, the existence of common principles of operation does not rule out the possibility that entirely separate timekeeping mechanisms, be they dedicated or non-dedicated mechanisms, service timekeeping in perception and motor timing. The idea that there are many timekeeping mechanisms to serve a large number of categories of behaviour is not a particularly appealing one because such a system would be a highly inefficient distribution of resources.

The application of STT (Gibbon, 1977) and the connectionist approach (e.g., Church & Broadbent, 1990) is sure to provide new questions and hence answers to the delicate relationship between human timekeeping in perception and motor movement. Coupled together with the already established principles of timing (e.g., quantal, stochastic, deterministic) new results are now emerging in the domain of rhythm perception. Desain (1992) for example, outlines an expectancy theory based on connectionist principles that he calls the "Connectionist Quantizer". It is this type of theoretical integration that eventually should lead to new discoveries and answers to long-standing questions. Unfortunately experimental procedures to test new theoretical developments often take considerable time to develop and implement. Fortunately, this new inter-disciplinary era of theorizing and experimentation has begun. It is just a matter of time before these theories are applied to classical psychophysical paradigms in order to further our knowledge of human timing mechanisms.

SUMMARY AND CONCLUSIONS

Some of the goals outlined in the Introduction are specific to the PTDD experiment while others concern only the tapping experiment. In addition, there are others that pertain to the relationship between these two experiments. This chapter summarizes the main results and comments on the implications those results hold for the stated goals.

THE PTDD EXPERIMENT

The main reason for choosing the PTDD method was to assess the significance of using an explicit standard in the context of duration discrimination. In this regard the principle goal of the PTDD experiment was to determine the empirical characteristics of the PTDD function. Those characteristics should reveal certain implications about the underlying temporal process. A secondary goal, and one which is related to the principle goal, is to identify the role that practice plays in PTDD.

In general, the PTDD function is flat over short base durations and it rises in accord with Weber's law over longer base durations. Thus, the proposition that variance increases linearly with mean is rejected in favour of a modified proportional standard deviation model. These results are consistent with previous work (e.g., Jezdic, 1986; Schulze, 1989; Halpern & Darwin, 1982). The above description applies to PTDD data both early in training and following concentrated practice. The only apparent difference due to concentrated practice is that the function drops to a lower location. A step function similar to the quantal step function (Kristofferson, 1980) does not emerge. This difference implies that quantal timing, similar in nature to that identified in MFDD, is not involved in explicit standard PTDD.

Of several contemporary mathematical models that were evaluated, Kristofferson's (1976) model proved to fit the PTDD function the best. As Kristofferson (1976) hypothesized in the context of R-SS, the flat segment of the PTDD function is also here interpreted to mean that a deterministic interval is inserted into the temporal chain of events. For durations above the upper limit of the flat segment, evidence suggests that timekeeping is governed by a timekeeper that obeys Weber's law.

The differences between the shapes of the PTDD and MFDD functions led Kristofferson (1990) to suggest that access to the memory representation of the standard stimulus might depend on how the stimulus is encoded. He suggested that the process involved in encoding the representation of an explicit standard may lead to access of that representation only by non-quantal mechanisms. Similarly, the process for encoding the representation of an implicit standard may lead to access of that representation only by a quantal timekeeper. This suggestion forms a logical link between theory and data and it is one that needs to be thoroughly examined, especially since PTDD results are consistent with such a link.

THE TAPPING EXPERIMENT

In common with the PTDD experiment, the main goal of the tapping experiment was to determine the empirical characteristics of the CP s_C^2 vs m_I function. The range of base SOAs that was used was considerably wider than previous investigations in order to determine whether the tapping function was better described as being linear in clock standard deviation or variance.

The main conclusion emerging from the tapping investigation is that a proportional standard deviation model, and not a proportional variance model, better describes the form of the relationship between clock variability and mean IRI. This was interpreted as support for the existence of a Weber's law timekeeper.

For LL and GF the smooth shape of the tapping s_C^2 vs m_I function indicates that if quantal timing is present in tapping, it does not manifest itself in a quantal step function similar to the one described by Kristofferson (1980). The variability versus mean functions change with practice but a stepwise function does not emerge. Because no evidence of quantal timing was found in the tapping data for these two subjects it was concluded that motor timekeeping probably does not involve a quantal process.

Significantly, AK's CP bias corrected s_C^2 vs m_I function does increase in a stepwise manner at least over part of the temporal range. This is an important result because it is consistent with the quantal motor timekeeper hypothesis. However, since only one subject showed this pattern one cannot state that, in general, the motor timekeeper is quantal in nature. This result suggests that AK's motor timekeeper probably is different than that of the other two subjects. On the other hand, AK's CP bias corrected s_C^2 vs m_I function is remarkably similar to his MFDD implicit standard duration discrimination function. The resemblance between these two functions implies that the operating characteristics of the timekeepers are similar for the two tasks. This does not mean that there is only one timekeeper for both tasks but the data are not inconsistent with that idea. Unfortunately such a comparison cannot be made for the other subjects because MFDD data are not available for either of them.

The second objective of the tapping experiment was to determine the limits of applicability of the TPM. Concerning this goal, the TPM was successfully applied to most base SOAs under 1000 msec. Some difficulties (i.e., negative delay variance estimates especially for LL and GF) were encountered when the model was applied to data generated at the two highest base SOAs. At a speculative level, several possibilities come to mind as to why these inconsistencies arose. If the TPM is valid for intervals over the entire temporal range studied then the model might fail for timekeeping at the higher intervals because of increasing role played by higher level cognitive processes.

On the other hand, the TPM might only be valid for shorter temporal intervals which suggests that at least two timekeeping mechanism are available. A third possibility is that the TPM does not represent the true underlying mechanism at any interval and only appears to do so at the shorter intervals. Of these three possibilities the first is most preferred because other than the few points for which negative delay variances were reported, the TPM accounts for the data extremely well.

An objective of secondary importance was to describe the process(es) underlying the effects of concentrated practice in tapping. The most notable empirical feature related to practice is that the reduction in IRI variance is gradual and steady. That is, a large number of sessions must be afforded at each base SOA before IRI variance reaches an asymptotic low level. Once at that low level, IRI variance stays low although small between session fluctuations occur.

An attempt to model the practice effect by identifying which of several standard functions best described the practice curves was only marginally successful. Clearly some of the functions did not describe the practice curves well and they could be eliminated as viable alternatives. However, no single function consistently described the practice curves better than the others. Thus the nature of the process underlying practice appears to be heterogeneous with many variables coming into play.

GENERAL CONCLUSIONS

The idea that a single internal timekeeper underlies PTDD and tapping would be supported if the PTDD and tapping functions have the same shape and are similarly located. However, if the functions were of different shape (e.g., straight line versus step function) and/or they were significantly displaced then the hypothesis of different timekeepers or timekeeping principles (e.g., deterministic or quantal) would gain support.

Evidence of similarities between motor and perceptual timekeeping exist in the present research. Both PTDD and CP tapping functions are better described by proportional standard deviation models than by proportional variance models. The two timekeeping systems appear to obey Weber's Law for intermediate temporal intervals, although estimates of K, the Weber parameter, differ slightly. Thus, the statistical principle of timing appears in both perceptual and motor timing data and in both cases it is the proportional standard deviation variety.

Only the statistical principle was found to be common to both experimental procedures used in the present investigation. However, the comparisons among AK's MFDD, PTDD, and CP tapping functions are particularly interesting because they show similarities between motor and implicit standard duration discrimination timekeepers and similarities and dissimilarities between implicit and explicit standard duration discrimination timekeepers.

AK's tapping function increases in stepwise increments and is very similar to his MFDD step function. This shows that sometimes all three timing principles appear to operate within the domains of perceptual and motor timekeeping. However, AK's PTDD function does not follow the same pattern. The conclusion that one reaches when comparing these three functions is that motor timing is similar to implicit standard duration discrimination and that implicit and explicit standard duration discrimination differ greatly. These comparisons suggest that it may be unreasonable to hypothesize artificially distinct temporal domains (e.g., perceptual vs. motor) of timekeeping each with its own timekeeping mechanism(s) and principles of timing. Rather they suggest that there might be a pool of resources available to the subject and that many endogenous and/or exogenous factors contribute to the deployment, or inhibition, of these resources.

Using the ideas of deterministic and statistical timing, a comparison between the PTDD and R-SS functions led to new estimates of minimum efferent latency (249 msec) and variance (124 msec^2) for AK that were higher than established norms. This comparison also led to a new and shorter estimate of the maximum deterministic delay that could be inserted into the centrally timed interval (300 msec) when the efferent delay was not involved, and to the idea that a similar but longer (up to 400 msec) deterministic interval could be inserted into the centrally timed interval when the efferent delay was involved. Finally, a new estimate of minimum central variance (18 msec^2) also was obtained.

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Appendix 1

Due to either equipment malfunctioning (e.g., obstruction of electrical contact of response key) or improper responding (e.g., lack of sufficient pressure to establish electrical contact), an unacceptable response might be made in the course of responding. In the event of such a response, at the end of the sequence S is informed that a problem occurred and that the sequence will be repeated. In order to detect problems of these kinds an accuracy time-window was imposed in both phases of every sequence of a session following the first two sequences which serve to orient S to the task. It is included in the SP in an attempt to force S to remain attentive to the task throughout the session. In the SP the time-window is in effect after the fourth response and it is defined as T/4 msec around the time of onset of the pulse. One is included in the CP primarily to detect responses for which the electrical contacts of the telegraph key do not meet. It is twice as wide as that in the SP and it is centered around a reference point in time defined by T msec beyond the onset of the preceding response. A response is considered to be unacceptable if it occurs outside the accuracy time window.

Another problem that is known to exist with the use of a Morse response key is key bounce. Sometimes a single response will result in numerous electrical contacts being made and detected. To avoid detecting bounces as separate responses, a debounce delay was programmed into the timing routine. It operates such that, following an electrical contact, the next response is scanned for only after a contact-free period of 64 msec had elapsed.