THE TIMING OF INTERRESPONSE INTERVALS

THE TIMING OF INTERRESPONSE INTERVALS
BY HUMAN SUBJECTS.

By

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SCOPE AND CONTENTS:

Accounts of the psychophysics of duration have attributed variance on the temporal decision axis either to variability in a psychological timekeeper or to variability in afferent delays between the times of stimulus presentation and registration at the timekeeper. A similar distinction could be made when accounting for variance in the timing of discrete responses either in terms of timekeeper variability or in terms of variability in efferent delays in responding. Thus in each case, an ambiguity exists for the identification of variance estimates based on behavioural data and strong assumptions have been made about the variance in one process when attempting to characterise the variance attributable to the other. It is demonstrated in this thesis that this need not be the case in tasks where subjects are required to maintain some interval (T) between sequences of identical discrete responses. Two classes of model are recognized as possible accounts of performance in such tasks.

In the tandem process model it is assumed that a timekeeper initiates responses at intervals with mean approximating T but that there is variable time lag in observing each overt response as a result of efferent delays. In the associative element chaining model it is assumed

that no timekeeping as such takes place but that a reflex chain of events triggered by one overt response produces, as the last element in the chain, the next overt response. A Morse telegraph key tapping task with T in the range 170 through 350 msec reveals estimates of interresponse interval (I) lag one serial correlation to be consistently negative. This finding rejects the associative element chaining model but confirms predictions of the tandem process model.

Under the tandem process model the variances of the timekeeper intervals and the response delays can be separately determined using estimates of the variance and lag one serial covariance of I. In two experiments which employ different Ss and response equipment it is found that, whereas response delay variance changes little with I, timekeeper interval variance is a linear increasing function of I. The last mentioned finding is consistent with a set of stochastic models of the timekeeper. These postulate that intervals are generated by the time taken to attain a given count of events where interevent times are independently and identically distributed. If it is assumed that the events originate in a Poisson source, estimates of the rate parameter are of the order of 10^3 events per second and well within the range of estimates obtained from psychophysical procedures. Implications of findings of non-zero response delay variance for studies of reaction time are also considered. Some of the response delay variance is shown to depend on the type of movement used in making the response. Further analysis of the data of Experiment 2 suggests that successive response delays are negatively correlated. However conclusions with respect to either of the process variances are little changed.

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Throughout my work I have received the support and participation of my wife, Joyce: she knows how much that means to me.

This thesis is dedicated to the memory of my father, Herbert D. Wing.

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Introduction

Paradigms and models in the study of human temporal abilities.

Provided the difference in duration of two otherwise identical stimuli is not too small, it is a relatively simple task for a human subject (S) to discriminate between the stimuli. Such decisions about stimulus differences need not necessarily make use of duration information, (for example, an alternative cue might be the total energy in the stimulus), but it can be shown in some situations that duration information is sufficient for discrimination, (Carbotte and Kristofferson, 1973).

Creelman (1962) assumed that the basis for subjective estimates of time lies in a large pool of neural elements which fire at random times. The expected number of such events occurring per unit time (λ) is assumed to be constant. During the presentation of a stimulus of duration T it is assumed that S maintains a cumulative count of the number of events that have occurred. For fixed T, the value of n will be a Poisson-distributed random variable with mean and variance equal to λT, (Feller, 1968). Suppose S is required on each trial to discriminate between two successive stimuli, one of duration T the other of duration $T + \Delta T$. According to the theory there is a distribution of counts associated with each stimulus, such that the differences between counts are distributed with mean $\lambda \Delta T$ and variance $\lambda (2T + \Delta T)$. On any given trial it is assumed that S makes his decision, for example, as to which stimulus is the longer, by comparing the difference in counts with a criterion difference. In the ideal case the criterion is zero provided the two alternative orders of presentation are equiprobable.

Thus, the inherent variability of the process leading to the count is translated into variance on the decision axis for temporal discrimination. The latter variance is a linear increasing function of T, so that a fundamental prediction of this counter model is that performance, (say, probability of a correct discrimination), should be inversely related to T.

Such a model was tested by Creelman* (1962) using a two alternative forced-choice (2AFC) procedure. This presents two auditory noise bursts on each trial in random order and S's task is to state whether the longer duration stimulus was in first or second position on that trial. Theoretical functions relating performance to T and ΔT provided a reasonable fit for values of T in the range 40 through 1500 msec. Values of λ inferred from the data ranged, over Ss, from 2.7×10^3 through 10.0×10^3 events per second.

Abel (1972a) also ran experiments on the duration discrimination of clearly audible noise bursts using a 2AFC procedure. She found further support for a Poisson event counter model in the one parameter form in terms of the relation between ΔT and T for a given level of performance. Her analyses showed that λ is fairly constant over T values in the range 0.16 through 80 msec with averaged estimates of λ falling in the range 0.5×10^3 through 1.0×10^3 events per second. As T was increased from 80 through 500 msec, it was found that estimates of λ decreased to about 0.1×10^3 events per second.

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*In fact Creelman gives a three parameter formulation of the model. One of the extra parameters handles situations in which the signals are not fully detectable. The other is intended to allow for possible interference with the stored representation of the first stimulus during the processing of the second stimulus.

For the discrimination of noise bursts, Abel (1972a) found that estimates of λ were unaffected by changes in signal parameters, supporting Creelman's (1962) assumption that the event rate is a constant independent of the particular stimulus energy. With filled intervals replaced by temporal gaps between brief clearly-audible markers, Abel (1972b) found performance as a function of T also supported the counter model. But, although estimates of λ were approximately constant in a range 0.1×10^3 through 0.5×10^3 events per second for values of T between 10 and 160 msec, they depended on the parameters of the marker stimuli defining the intervals.

The psychophysical approach is somewhat indirect as a method for assessing variance attributable to a basic time unit, since it is necessary to make auxiliary assumptions about the decision procedures used by Ss. If response timing and duration discrimination reflect the operation of one and the same underlying mechanism, one might instead make use of the variance of Ss' response timing abilities as direct estimates. In essence, this approach was one adopted by Treisman (1963) using two variants of an interval reproduction paradigm. On each trial a standard stimulus of duration T is presented to S who is then required to attempt to reproduce T, either by terminating with a response a stimulus initiated by the experimenter, or, by both initiating and terminating the interval with his responses. For estimates based on interval reproductions over all trials at a particular value of T, Treisman found a straight line relation between mean and standard deviation for T in the range 250 through 3000 msec. That is, the variance of intervals generated by the timekeeper would appear to increase more rapidly than the mean. Although psychophysical findings suggest that the variance of the subjective measure of stimulus time increases linearly with the interval, it is not necessary to conclude that two different processes are involved. Instead it is suggested here that the variance estimates used by Treisman do not provide pure estimates of the variance of interval generation by the timekeeper.

Assume that timekeeping is based on a Poisson source of events with rate parameter λ. In duration perception the subjective measure of T units of elapsed time is taken to be the count n which has expected value λT. Suppose that the timing of a response to generate some interval is achieved by a corresponding wait process. If S withholds his response until n' events from a Poisson source with rate parameter λ' have occurred, then an interval T' with expected value n'/λ' would result. It can be shown, (for example see McGill, 1963), that T' will be gamma-distributed with variance n'/λ'^2 so that the variance of the response intervals will be directly proportional to the mean, with constant of proportionality given by $1/\lambda'$. If S makes repeated attempts at reproducing T by waiting for the same number of counts n' on each trial, a linear increasing relation between mean and variance would thus be predicted. In the reproduction paradigms used by Treisman (1963), the standard interval was presented before each reproduction so that the value of n' would probably be determined anew from n every trial. In that case, the variance of waiting times would be compounded with the variance of n for a particular value of T with the result that the variance of reproductions should increase more rapidly than the mean. To permit estimation of the true relation an experimental procedure should be used in which response timing variance estimates are taken from reproductions all based on the same perceived standard, or preset count, n'.

So far, discussion has focused on models of timekeeping with stochastic properties. Another formulation might assume the timekeeper to be deterministic and not a source of variance for the temporal decision axis. For example, an account of duration discrimination by Allan, Kristofferson and Wiens (1971) assumes that the timekeeper is variance-free. Errors are taken to be a result of variability in afferent delays in the registration of the signals representing stimulus onset and offset at the place in the central nervous system where duration is judged. Assuming such arrival latencies can be described by a random variable (A) with mean and variance which are not a function of T, the "internal" interval evaluated at the timekeeper will have twice the variance of A. Data were collected in a single-stimulus recognition task using light flash stimuli of base duration T equal to 50 and 100 msec. With values of ΔT equal to 10, 20, 30 or 40 msec, performance was not a function of T, in agreement with the model and contrary to the predictions of a Poisson event counter model.

The distinction between central and peripheral accounts of the limitations on duration discrimination performance has a direct parallel in the related area of temporal order judgment. There, paradigms are used in which each trial presents two stimuli in succession and S is required to indicate which came first. In this case one may ask what determines the sensitivity of temporal order judgments to changes in the interstimulus interval? Or, equivalently, what determines the slope of the psychometric function?

A systematic difference is found between the objective simultaneity of two stimuli and the point of subjective simultaneity as estimated from the psychometric function. This difference is usually attributed to differences between the times taken by the signals representing the two stimuli to arrive at the place in the central nervous system where their order is judged. Such arrival latencies, might include delays in signal registration as well as nervous transmission delays. If they are variable, order discrimination errors would result to the extent that the variability introduces some reversals in signal ordering at the point in the nervous system where temporal order is judged. The greater the variability, the shallower will be the slope of the psychometric function. On the other hand, it could be that the precision of temporal order judgements is limited chiefly by the resolving power of the central timing mechanism. At small interstimulus intervals, for which some threshold for temporal order is not exceeded, the S's response probabilities would remain at chance level. When the threshold is exceeded, discrimination would be perfect. In this view, precision is determined by the magnitude of the threshold for the resolution of incoming sensory events.

A complete review of models of both classes may be found in Sternberg and Knoll (1973). Clearly a major problem in this area in common with that in duration discrimination studies is the determination of the relative contributions of central and peripheral factors in determining performance. Or, put another way, until we can estimate the extent of peripheral factors, measures based on the psychophysical function may not give a true picture of the operation of the central timing mechanism, or timekeeper.

We have seen that arrival latency variance may provide an alternative to timekeeper variance in accounting for duration discrimination errors. In analogous fashion, response timing variance might be due to variance in the time taken to produce an observable response after completion of each timekeeper interval rather than being due to variability in the actual timekeeper itself. Such response delays might occur in, (1) the selection and organisation of the response, (2) the transmission of neural signals to the musculature, (3) the completion of the physical movement which results in an overt response. For example, McGill (1962) has developed a model in which random fluctuations in the rate of a steady stream of responses in biological systems are attributed to variability in the delays, subsequent to periodic triggers from some timekeeper, before the corresponding responses are observed.

In the case of response timing by human Ss, suppose there is a variable response delay (D) following each trigger from a deterministic clock. The observed interresponse interval variance may simply be the combined variance of the delays in the initiating and terminating responses, that is, twice the variance of D. Or, where the reproductions are defined by the response termination of an interval initiated by the experimenter, the observed variance could be the combined variance of arrival latency and response delay, that is, the variance of A plus the variance of D. If it is assumed that the variance of A and of D are not a function of I, one prediction of this model would be that the interresponse interval variance is constant over I. Bartlett and Bartlett (1959) required Ss to attend a sequence of Ts defined by a train of brief auditory clicks. When satisfied they were "following the rhythm" they were to strike a response key to coincide with the next click, in effect terminating an interval initiated by the experimenter. For two highly-trained Ss, the variance of response timing was found to be constant over three values of T in the range 250 through 350 msec.

A tandem process model for the timing of discrete responses.

The following two-stage model is intended to characterise the distinction between timekeeper and peripheral response delay processes that are possibly involved in response timing. It is shown that, given nothing more than information about the times of occurrence of successive responses it is possible to infer the variance of each of these processes.

In Figure 1 trigger pulses from some timekeeper give rise to a series of overt responses which define a sequence of interresponse intervals. It is assumed that intervals between immediately successive trigger pulses are the result of some stochastic timekeeper and may be described by the independent random variable C with mean μ_C and variance σ_C^2. Further, it is assumed that the delay between the times of occurrence of each trigger pulse and the overt response conditional on that trigger pulse may be described by the independent random variable D with mean μ_D and variance σ_D^2. Since it is intended that the theoretical results derived should not be restricted to any specific probability distributions for the random variables, it is simply assumed that the respective distributions exist.

If the subscript j is used to index the trigger pulse interval C_j and response delay D_j which culminate in the j^{th} overt response, the interresponse interval bounded by the overt responses subject to the delays D_{j-1} and D_j is given by:

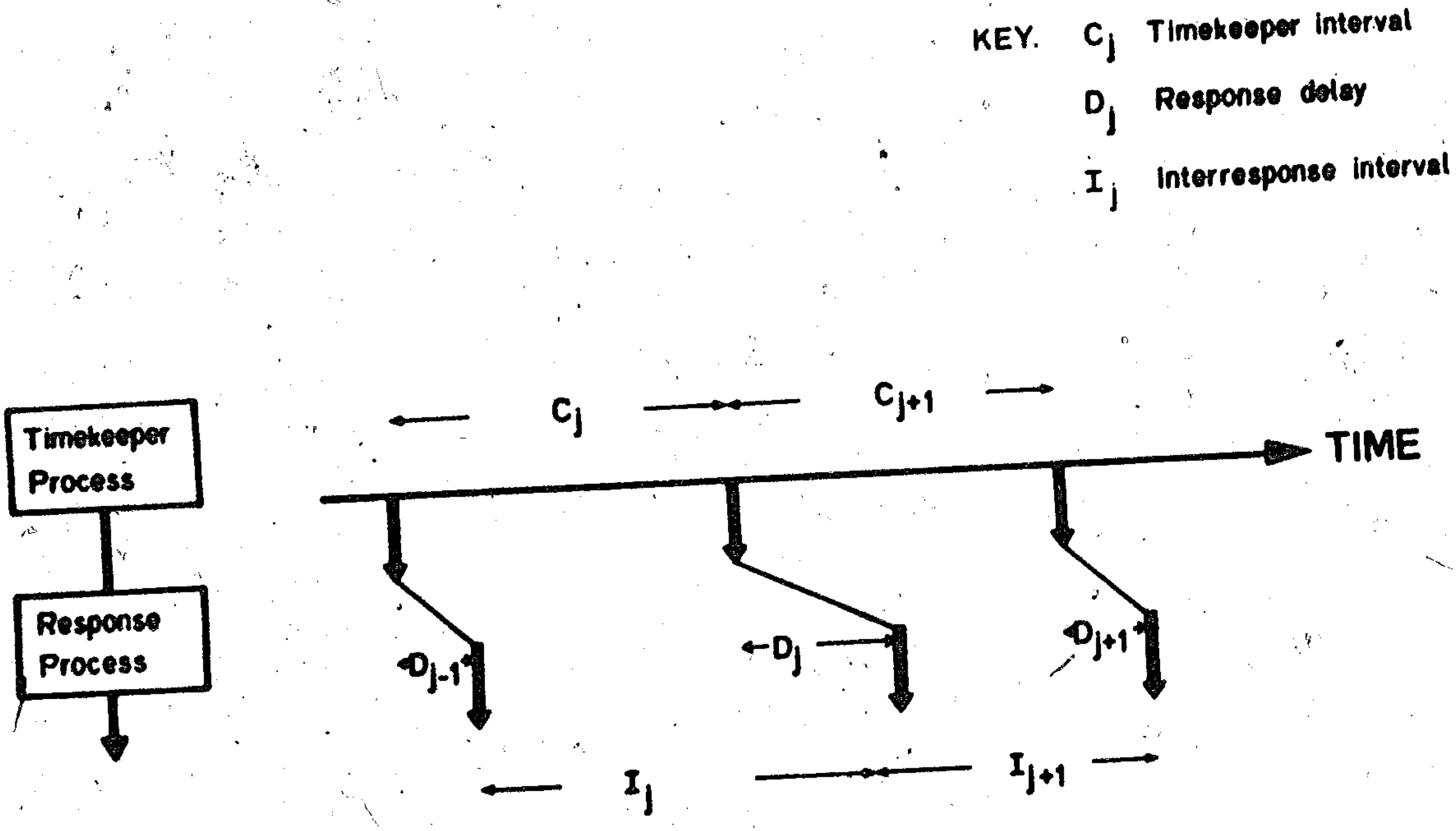

Figure 1: Tandem process model for the timing of repetitive discrete responses.

$$I_j = C_j - D_{j-1} + D_j \tag{1}$$

with variance, σ_I^2, and mean, $\mu_I = \mu_C$.

The lag one serial covariance of I*, $\gamma_I(1)$, is defined as the expectation of the product of the deviations about the mean of one interresponse interval and the immediately preceding interval:

$$\begin{aligned}\gamma_I(1) &= E\ \{(I_j - \mu_I)(I_{j-1} - \mu_I)\} \qquad ,j= \ldots, -1, 0, 1, \ldots \\ &= E\ \{[(C_j - \mu_C) - (D_{j-1} - \mu_D) + (D_j - \mu_D)]\ (I_{j-1} - \mu_I)\} \\ &= -\ E\ \{(D_{j-1} - \mu_D)(D_{j-1} - \mu_D)\} \\ &= -\ \gamma_D(0) \\ &= -\ \sigma_D^2 \end{aligned} \tag{2}$$

since, for C and D independent, all other expectations are zero. The lag zero serial covariance, which is equivalent to the variance, is defined:

$$\begin{aligned}\gamma_I(0) &= E\ \{(I_j - \mu_I)(I_j - \mu_I)\} = \sigma_I^2 \\ &= E\ \{[(C_j - \mu_C) - (D_{j-1} - \mu_D) + (D_j - \mu_D)]\ (I_j - \mu_I)\} \\ &= \sigma_C^2 + 2\sigma_D^2 \end{aligned} \tag{3}$$

Since overt responses are indistinguishable under the model, these relations hold only if the ordering of the trigger pulses is maintained in the overt response ordering: that is, if $I_j > 0$, for all j. Suppose $I_j < 0$

---

*The term autocovariance is often used as a synonym for serial covariance. The terminology adopted here follows Perkel, Gerstein and Moore (1967), who reserve the term "autocovariance" for the renewal density, defined over continuous time as the probability of encountering some event as a function of time lag after a given event has occurred.

were possible, then the j^{th} observed interval between successive responses need not be the I_j bounded by D_{j-1} and D_j as assumed above. In the model, such jumbling of overt responses would occur if, for example, μ_C were decreased while all other parameters were left unchanged. Nelsen and Williams (1970) have treated a queueing system with this property and show that lag one dependence decreases as μ_C becomes small with respect to σ_D^2, (see also Govier and Lewis, 1967).

From Equations 2 and 3 the following result may be obtained:

$$\sigma_D^2 = -\gamma_I(1) \quad \text{and} \quad \sigma_C^2 = \gamma_I(0) + 2\,\gamma_I(1) \tag{4}$$

These equations provide a basis for the estimation of the variances due to response delays and to the timekeeper, given we can estimate the lag zero and lag one serial covariance of the interresponse intervals. The tandem process model leads to a prediction on the bounds of the lag one serial correlation of $0 \geq \rho_I(1) \geq -1/2$, since:

$$\rho_I(1) = \frac{\gamma_I(1)}{\gamma_I(0)} = -\frac{1}{2 + \dfrac{\sigma_C^2}{\sigma_D^2}} \tag{5}$$

Equation 5 is formally equivalent to a result derived by Ten Hoopen and Reuver (1967). The bounds on $\rho_I(1)$ are associated with the special cases of the tandem process model for which response delay variance is zero, ($\rho_I(1) = 0$), and timekeeper variance is zero, ($\rho_I(1) = -1/2$). Thus, to the extent that response delay variance is very small compared to the variance of the timekeeper, the lag one serial correlation will tend to zero and the observed interresponse interval variance provides an appropriate estimates of timekeeper variance. However, if the lag one serial correlation of the interresponse intervals were much less than zero, we would have to infer that response delay variance is not negligible in relation to timekeeper variance. It would then be necessary to make the appropriate correction to the observed interresponse interval variance when estimating the timekeeper variance.

For a sequence of interresponse intervals[*] I_j; $j = 1,2 .. N$, an estimate of $\rho_I(1)$ is given by, (see Jenkins and Watts, 1968):

$$\rho_I(1) = \frac{G_I(1)}{G_I(0)} \tag{6}$$

with

$$G_I(1) = \frac{\sum_{j=2}^{N}(I_j - \bar{I})(I_{j-1} - \bar{I})}{N - 1} \tag{7}$$

and

$$G_I(0) = \frac{\sum_{j=1}^{N}(I_j - \bar{I})^2}{N} \tag{8}$$

---

[*] It is assumed that the time series in I, indexed by j is stationary with j. If there were, for example, a large trend in the mean with increase in j, positive serial correlation could result, even if the process was really one with a deterministic increasing mean value function and random error about that function.

where

$$\bar{I} = \frac{\sum_{j=1}^{N} I_j}{N} \qquad (9)$$

Estimates for σ_C^2 and σ_D^2 are given by:

$$S_D^2 = -G_I(1) \quad \text{and} \quad S_C^2 = G_I(0) + 2G_I(1) \qquad (10)$$

Interresponse interval regulation in a sequential responding paradigm.

In the previous section equations were set out which would permit the estimation of the variance of timekeeper intervals and response delays, provided stationary sequences of interresponse intervals are available on which estimates of the lags zero and one serial covariance may be based. The following procedure might be expected to accomplish this, and at the same time affords some experimental control over the response rate adopted by S, beyond that afforded by verbal instruction. After a warning signal, (see Figure 2), a train of very brief auditory pulses, spaced apart by the standard interval, T, is presented to S who is instructed to respond in synchrony with each pulse. Following the last pulse in the synchronization phase, S is required to continue responding at the established rate until a second warning signal indicates that he should stop. With practice, and provided sequences are not so long as to induce fatigue, it would be expected that such a procedure would generate relatively stable data, (for example, see the data of Stevens, 1886).

Since the tandem process model does not provide an explicit account of temporal synchronization, it is not intended to make use of the synchronization data from this paradigm. To do so it would first be necessary

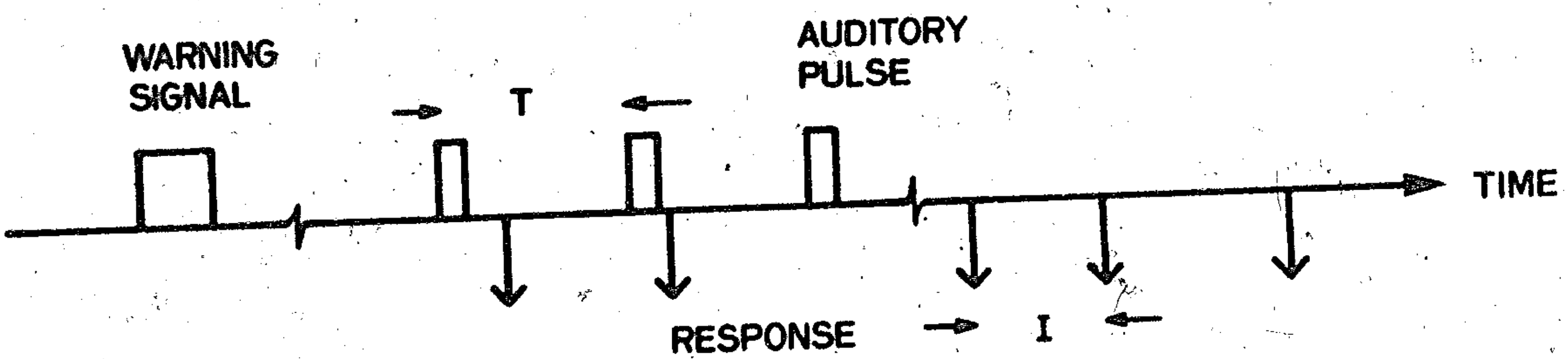

Figure 2: The sequential response paradigm event sequence.

to establish whether Ss actually make use of the perceived time intervals between successive pulses in the train in adjusting the intervals between their responses, or whether they simply use the synchronization error of each response to correct the subsequent delay before the next response. Studies of synchronization by Voillaume, (Fraisse and Voillaume, 1971; Voillaume, 1971), suggest that within a sequence Ss will do both. Compared to the difficulty of analysing mixed strategies of this nature, characterizing temporal mechanism variability through the use of the continuation data in conjunction with the tandem process model appears relatively straightforward.

In discussing temporal integration of behaviour, Lashley (1951) suggests that the serial ordering of units of speech in language might be achieved by a central activating mechanism driving the response system. That is the information needed to give the proper temporal relations in the motor output might be entirely central in the nervous system. This he contrasts with associative element chaining models derived from Sherrington reflexology. These propose that coordinated output is built up from small, discrete units of movement, linked together by chain reflexes with sensory feedback eliciting each subsequent unit.

A similar distinction has recently been made by DeLong (1970) in asking the question: How does the nervous system produce temporally patterned motor output? He points out that, while the selection of appropriate muscles will be met by specific neural pathways that convey impulses to appropriate motoneurons, one can distinguish two theoretical positions concerning the way in which the proper temporal relationships between participating muscles might be fulfilled. According to peripheral control theory, the timing requirements are accounted for by varied afferent activity routed in feedback loops to control discrete phases of the movement with time lag determined by the loops. On the other hand, a central mechanism might contain all information necessary to specify the temporal aspects of the movement.

In the context of the timing of a repeated response there is no a priori reason why timing could not be based on the reflex chaining of associative elements instead of involving a central timekeeping or activating mechanism as is assumed in the tandem process model, (see Figure 3). Subsequent to each response and after a delay, A_j, an afferent signal could elicit the next response which is subject to delay, D_j. Provided, A and D are mutually independent random variables, the distribution of I is given by the convolution of A and D, and I will be stochastically independent. To lengthen the interresponse interval while using the same response S could make the movement preceding each response have a longer trajectory resulting in a larger D if performed at the same velocity. If longer trajectory movements are associated with greater temporal variability, an increasing relation between the mean and variance of I would be predicted. Another possible mechanism by which S might increase the mean of I would be to cause the afferent signal to initiate some internally generated delay before eliciting the response. In that case the relation between the mean and the variance of I would reflect the variance of the generated interval, provided the characteristics of A and D do not change. The basis for discrimination between tandem process and reflex chaining models rests on the presence of dependence in successive values of I. If it can be shown that estimates of $\rho_I(1)$ are significantly different from zero in the sequential responding task, it would be possible to reject the reflex chaining model.

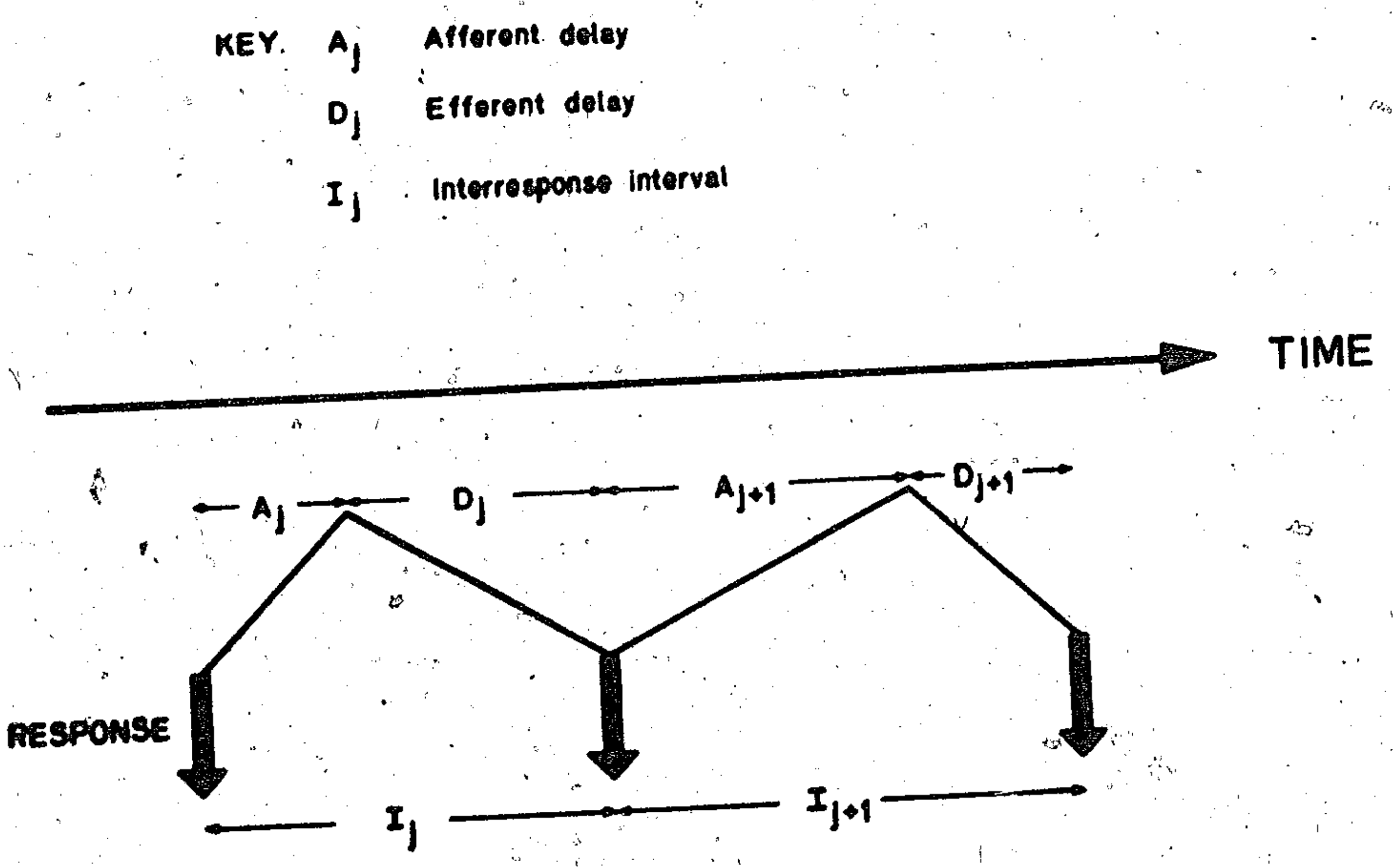

Figure 3: Associative element chaining model.

If the estimates should be negative and have a lower bound of - 1/2, this would be taken as support for the tandem process model. Note that, if independence were not rejected, the special case of the tandem process model for which response delay variance is zero could still apply. In the first experiment estimates of $\rho_I(1)$ are based on many short sequences run under the same value of T using a Morse telegraph key response. In this way it is possible to set up empirical confidence regions about the point estimates when testing for non-zero $\rho_I(1)$.

The chief characteristic of the tandem process model is the presence of response delays conditional on pulses from a timekeeper process. The consequences of variance in these delays are important, not only for the understanding of response timing, but also in the study of simple reaction time (RT). The object of RT experiments is to obtain an index of the processing of a sensory signal by Ss, in order to test theories of the signal detection process. For example, Green and Luce (1971) have formulated a model for the signal detection process which leads to specific predictions for the distribution of latencies associated with it. Since it is likely that other processing stages are involved in making a response to a stimulus, the overall RT distribution will not provide a pure measure of signal detection processing. A stage which might be expected to be present would be one involved in the generation of a response subsequent to the detection of a signal. Kornblum (1973), for example, explicitly recognises the possibility of delays due to response generation in an account of anticipatory responses based on time estimations which can occur in RT experiments. However, he assumes there is no variance in the response delays.

If estimates of σ_D^2 are non-zero two further questions will be examined in the context of sequential responding in the following experiments. The first is whether the estimates change with the interval between responses. The method of analysis afforded by the tandem process model does not permit estimation of σ_D^2 in a discrete trial situation. However, if estimates of σ_D^2 are relatively unaffected by change in I, extrapolation of the estimates could be taken to provide an indication of σ_D^2 in RT studies. Another factor which might affect σ_D^2 estimates is the type of movement which S is required to use in responding. That is, since σ_D^2 is identified with delays in generating responses an experimental manipulation of the level of σ_D^2 might be possible through the choice of response movement.

Of more direct interest to the study of psychological timekeeping will be the estimates of σ_C^2 and their relation to the mean interresponse interval, (equivalent to μ_C). In the following experiments the value of T for response synchronisation is varied over a range approximating the psychophysical studies reviewed. The shortest interval is restricted to rates somewhat slower than the physiological limit since, at a very rapid response rates, fatigue is likely to result in the introduction of non-stationarities in the interresponse interval data. Earlier, an account of the timing of a response was formulated, based on a Poisson source of events. A linear relation was predicted between the mean and variance of intervals generated in that way. If the timekeeper interval were equivalent to T', the waiting time to attain a count of n' events, a zero intercept straight-line relation would be predicted between timekeeper interval mean and variance. Suppose the intercept were non-zero. This could imply that C is not equivalent to T', but that it is the sum of T' and another quantity:

$$C = R + T'$$

If R is an independent random variable with mean μ_R and variance σ_R^2, then:

$$\sigma_C^2 = \sigma_R^2 + \sigma_{T'}^2$$

Provided μ_R and σ_R^2 are not a function of T', a linear relation between σ_C^2 and μ_C would still hold, but the intercept would be determined by both μ_R and σ_R^2. That is, an interpretation of a non-zero intercept straight-line mean-variance relation would be that there is a stage in processing in the timekeeper with a delay which may be described by the random variable R having mean and variance unaffected by the interval to be generated.

In the following, three experiments are described which test the tandem process model and examine the variances of each process as a function of I. Then a theoretical section contrasts the predictions of two different generalisations of the tandem process model and the results of further analysis of the data from the second experiment are reported.

Experiment 1: Morse telegraph key tapping.

Method.

The task required of S was a combination of paced and unpaced tapping of a Morse telegraph key, (see Figure 2). Following a warning signal, a sequence of 10-msec duration, 2000-Hz auditory pulses, separated by intervals of (T - 10) msec, was presented binaurally. The pulses were clearly audible, (sound level, 62 dB re 38dB background), over headphones worn by S.

The instructions to S required him to depress the key periodically so that contact would be made in synchrony with the pulses; if a response led or lagged any given pulse by more than 35 msec, visual feedback was immediately given to indicate the direction of error. With practice, Ss had little difficulty in staying within this time window. If S skipped a response after the first four in a sequence, the sequence automatically aborted and restarted. Following the last pulse of the train of 24 pulses in the synchronization phase, S was required to continue tapping at the established rate for an additional 31 responses. The warning signal was sounded after the last response in this continuation phase to indicate to S that he should stop. An interval of approximately 13 sec preceded the next warning signal and ensuing sequence.

The telegraph key, which was clamped in a fixed position relative to S's chair, required a weight of 120 gm to make contact for recording purposes, and the vertical movement in the key was less than 0.3 cm, (see Figure 4). The S's arm was not constrained, but he was encouraged to adopt an habitual mode of responding. In another room a PDP-8

Figure 4: Morse telegraph key used in Experiment 1.

computer was used to control stimulus event times and to record Is with an accuracy to the nearest 1 msec.

After several preliminary practice sessions, nine conditions were run with values of T of 170^2, 180, 200, 220, 220^2, 250, 270^2, 300, and 350 msec, those marked with the superscript being run at a slightly later date. In each set, the order of assignment of T was pseudo-random and different for each S. The actual value of T used was held fixed over several practice sessions before data for analysis was collected on four successive sessions. In the case of JW, the number of practice sessions was four throughout, as it was for the other three Ss in the three conditions marked with superscripts. However, these other Ss received six practice sessions in the set of six conditions run first.

Sessions lasted approximately 35 min and comprised five blocks of 11 sequences each. Three paid Ss and the author took part. All were right handed.

Results.

The results reported are for the 30 Is recorded in the continuation phase of each sequence. Due to poor responses approximately five percent of sequences could not be used in the analysis. These responses originated in equipment malfunctions of two kinds. Sometimes the electrical contact necessary for recording purposes did not occur with S's response and this would result in interresponse intervals which were approximately some multiple of the required standard. The other problem encountered with the apparatus was that following a response and before S actually released the key, electrical contact would sometimes be broken and remade within a period of a few milliseconds to produce a double response with a very short interresponse interval. Unless otherwise detailed, the estimates used are based on the averages of the statistics defined in Equations 6 through 10 over all sequences at a given T, that is, 220 less the number of rejected sequences, (details of the actual number of sequences involved may be found in Appendix A).

As a measure of consistent monotonic increasing or decreasing trends, for every sequence, estimates of the mean of the first 15 and of the last 15 Is were calculated and the latter subtracted from the former. The means and twice the standard error of these differences over all sequences at a given T are given in full for individual Ss in Appendix A. In about half the cases the 95% confidence intervals* about the changes in mean do not include zero and the assumption of stationarity of the mean should be rejected in these cases. However, detrending is not really warranted by virtue of the relative smallness of such trends, in all cases being of the order of one percent of the mean or less. That is, although the effects are significant, their magnitude is negligible. The changes in mean for each S, averaged over all T, are shown in Table 1.

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*The 95% confidence interval on the mean is defined $\overline{\Delta I} - y < \mu_{\Delta I} < \overline{\Delta I} + y$ where $y = (S_{\Delta I}^2/n)^{1/2} t(\alpha/2, N-1)$ and $\alpha = .05$. For N moderately large, y is given by twice the standard error of ΔI.

Table 1

Average change in mean interresponse interval ($\overline{\Delta I}$) for each S, (msec units).

	Subject			
	AW	JW	IT	MF
$\overline{\Delta I}$	-0.7	-1.4	-0.4	-0.8

Interresponse interval variance (S_I^2) is plotted as a function of $\bar{I}$ for each S in the upper sections of Figures 5 through 8, (data points for all the plots may be found in Appendix B). The filled points indicate the three conditions run at the later date; it will be noted that there is good agreement between the pairs of estimates at T = 220 msec. The high degree of experimental control over the "free" responding in the continuation phase is evidenced by the closeness of each $\bar{I}$ to the corresponding values of T, (indicated on the I - axis in the figures).

It is found that above 250 msec S_I^2 increases steadily with $\bar{I}$. Below that value there is little change in S_I^2 with $\bar{I}$, though for two Ss, (AW and JW), S_I^2 at the smallest T is as large as that at T = 350 msec. At the time of the experiment these two Ss reported increased difficulty in responding at the fastest rate, which approached the upper limit on the rate of Morse telegraph key tapping of seven responses per second, as determined by Vince (1949).

In the lower halves of Figures 5 through 8 are shown estimates of the corresponding $P_I(1)$. Intervals equal to twice the standard error of estimate are shown to either side of each $P_I(1)$. Only in one case, (MF at T = 170 msec), does such an interval include zero, and none of the

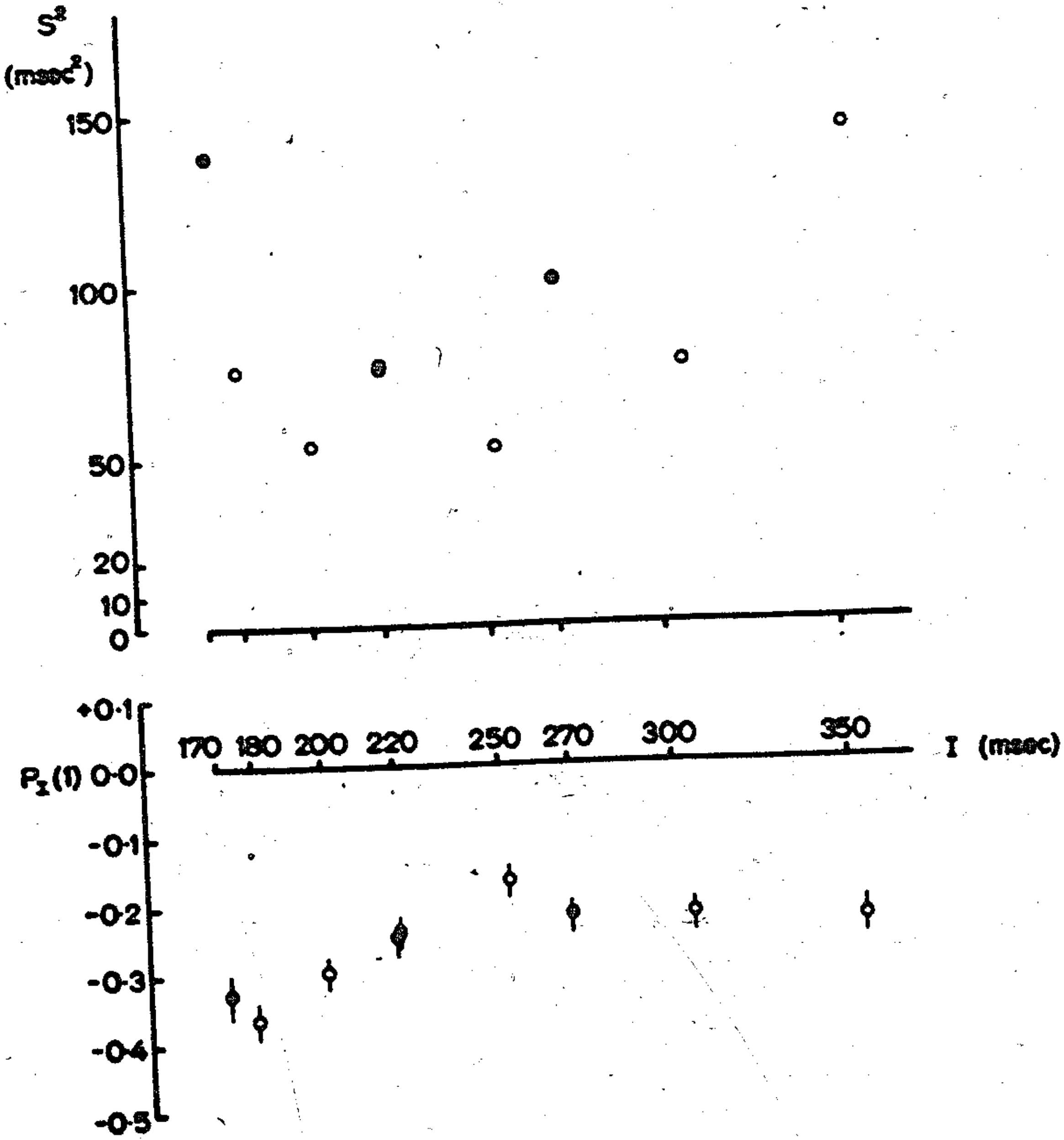

Figure 5: Estimates of interresponse interval variance (S_I^2) and lag one serial correlation ($P_I(1)$) as a function of mean interresponse interval ($\bar{I}$) for AW. The vertical bars indicate two standard errors about the estimates, $P_I(1)$.

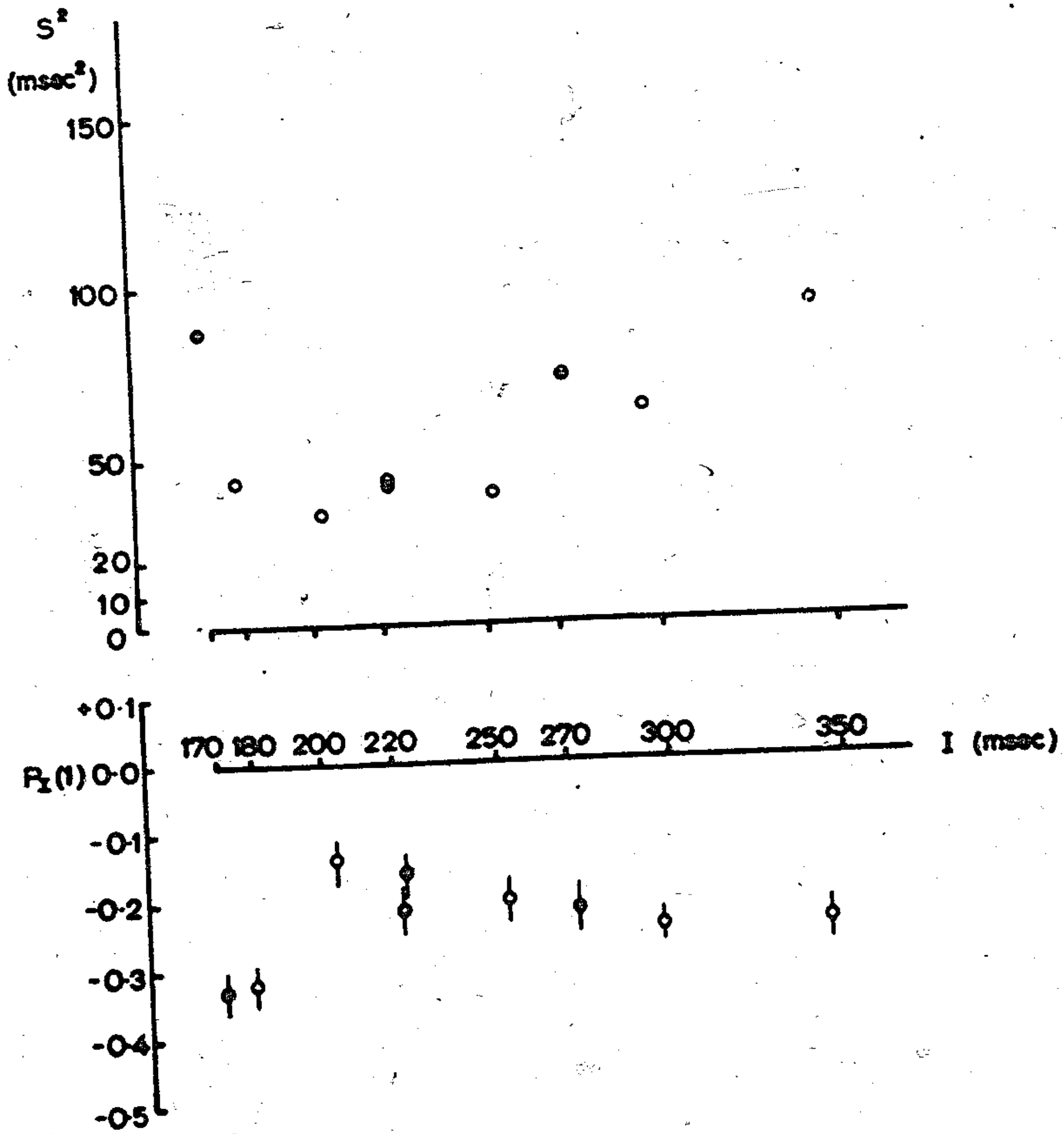

Figure 6: S_I^2 and $P_I(1)$ versus $\bar{I}$ for JW.

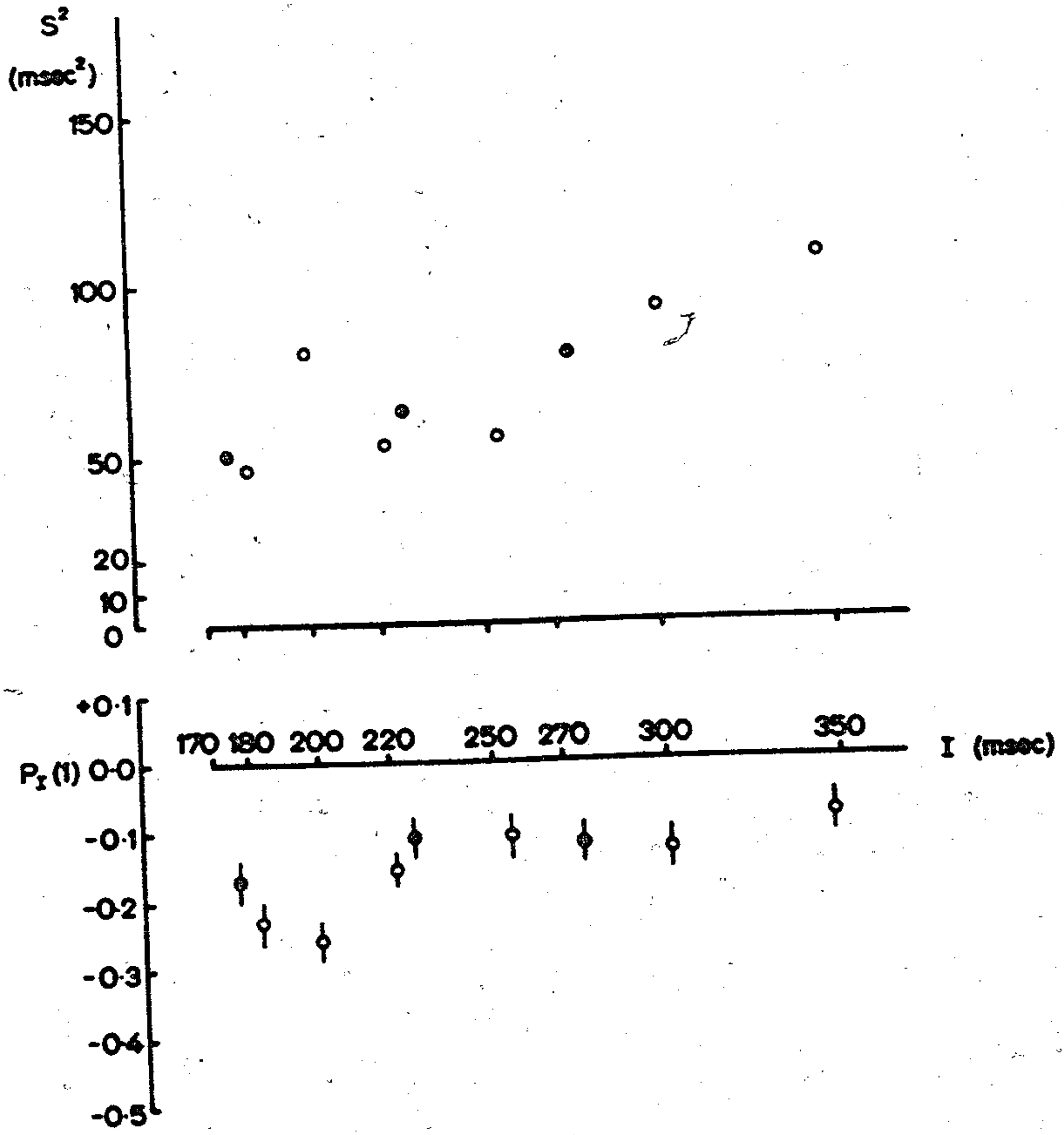

Figure 7: S_I^2 and $P_I(1)$ versus $\bar{I}$ for IT.

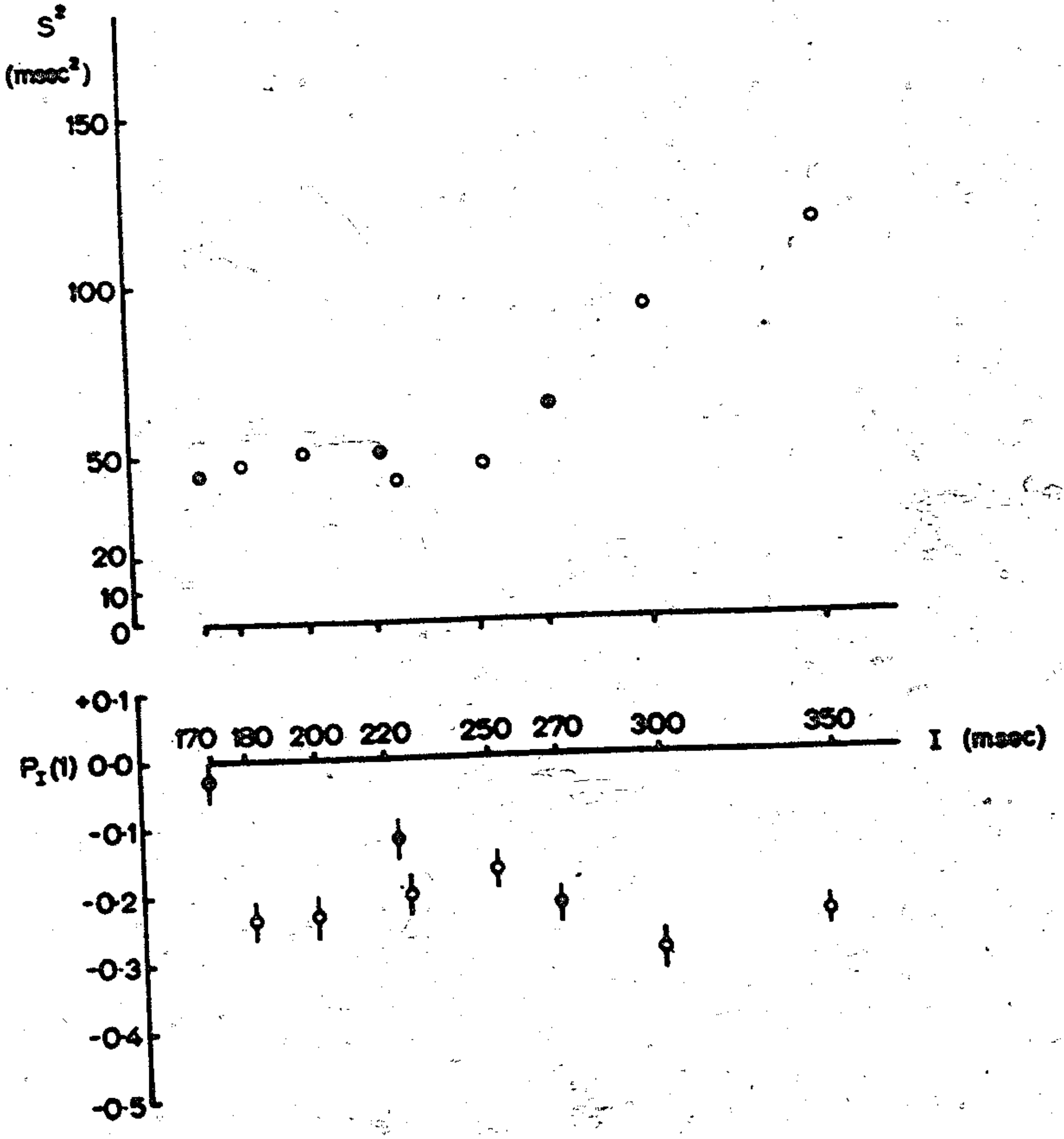

Figure 8: S_I^2 and $P_I(1)$ versus $\bar{I}$ for MF.

intervals includes -1/2. While distributions associated with large correlations are skewed toward zero, the relatively small values under consideration here make it a reasonable approximation to treat these regions as 95% confidence intervals on the means. Thus models for which predictions of $\rho_I(1) = 0$ or $\rho_I(1) = -1/2$ obtain may be rejected.

Estimates of σ_C^2 and σ_D^2 are plotted as a function of $\bar{I}$ for each S in Figures 9 through 12. Best fit straight lines of the form, $S_C^2 = \alpha\ (\bar{I} - \beta)$, determined by least squares are indicated by the continuous lines. The adequacy of the linear form in describing the functional relation may be demonstrated by showing that, whereas the coefficient of the linear term in the least squares best fit linear polynomial is significantly different from zero, the quadratic coefficient in the best fit quadratic polynomial is not, (Graybill, 1961). This is achieved by comparing the error accounted for by the linear term with the residual error about the linear polynomial and the error accounted for by the quadratic term with the residual error about the quadratic polynomial. The results of such ANOVAs for linear and quadratic polynomial models for each S are given in Table 2. For all Ss, except MF, it is concluded that the linear function is adequate. For these three Ss values of β are in the range 19 through 106 msec.

The points in Figure 13 show the averages of the estimates, S_C^2 and S_D^2 over Ss as a function of overall mean interresponse interval. ANOVA for linear and quadratic polynomials supports the indicated linear relation between S_C^2 and $\bar{I}$, (linear term, $F(1,7) = 17.08$, mean square error $= 64{,}68$, $p<.05$; quadratic term, $F(1,6) = 3.5$, mean square error $= 47.80$, $p >.05$). Although each S shows some decrease in S_D^2 at intermediate values

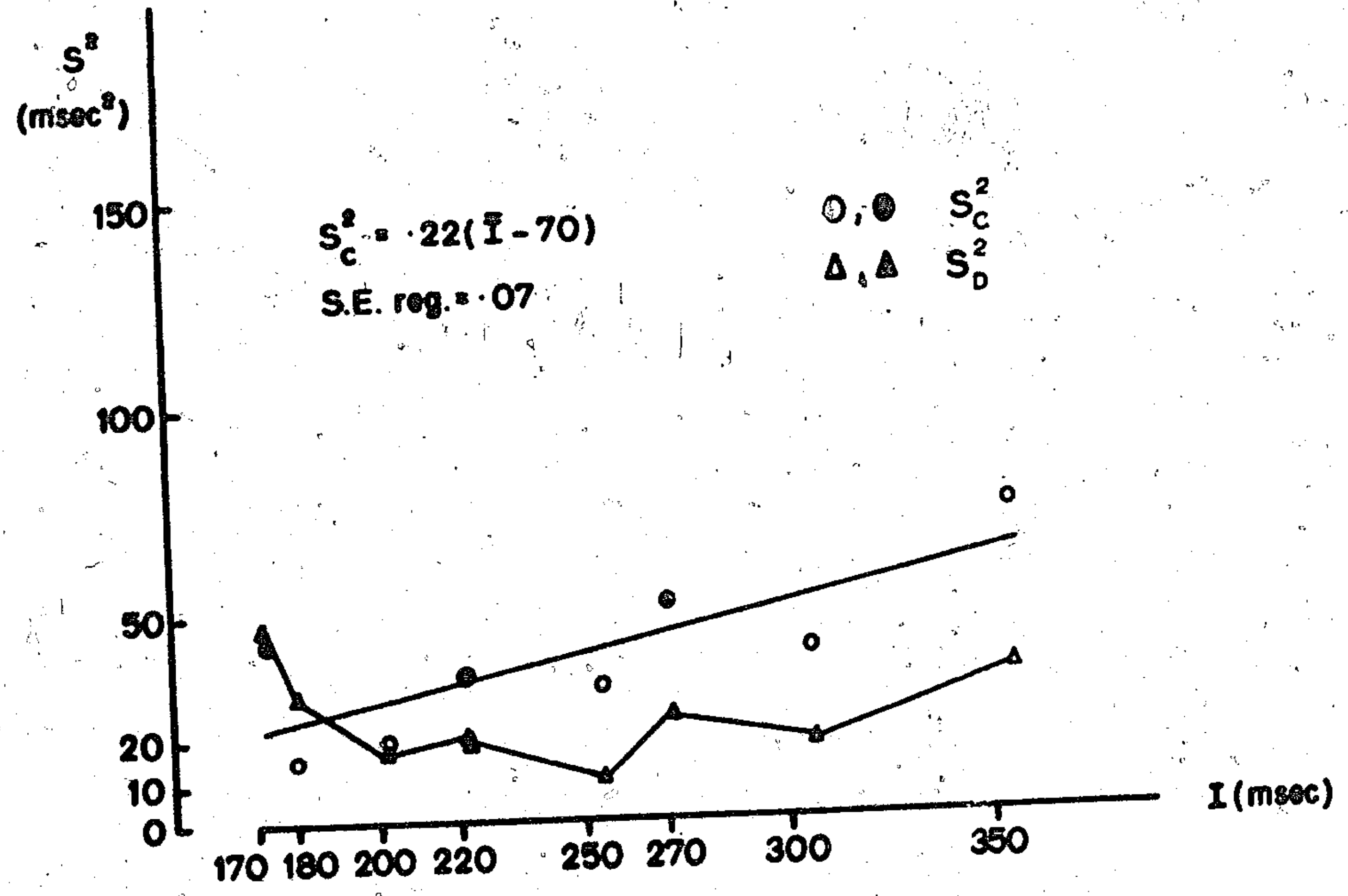

Figure 9: Estimates of timekeeper variance (S_C^2) and response delay variance (S_D^2) as a function of $\bar{I}$ for AW.

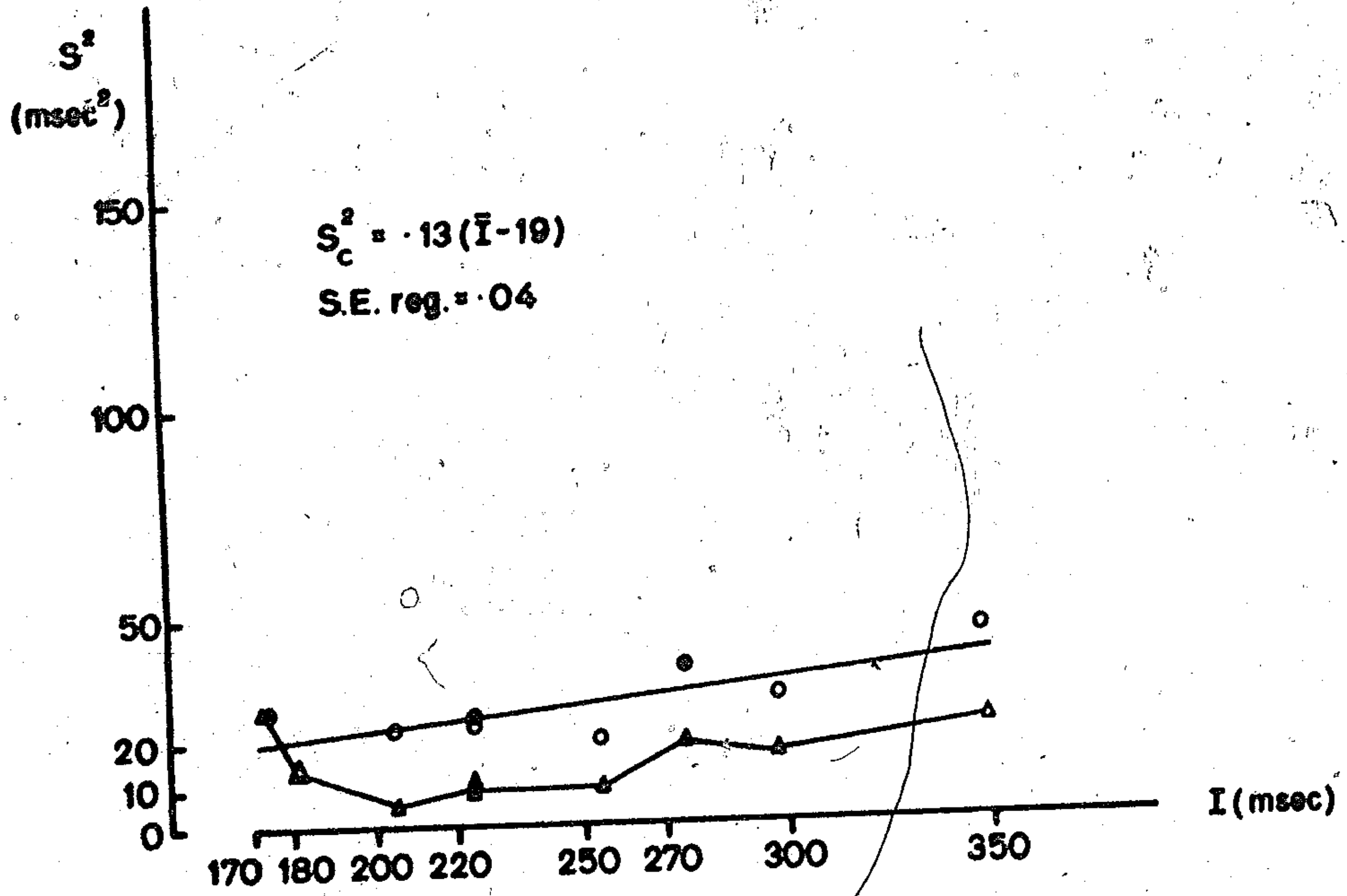

Figure 10: S_C^2 and S_D^2 versus $\bar{I}$ for JW.

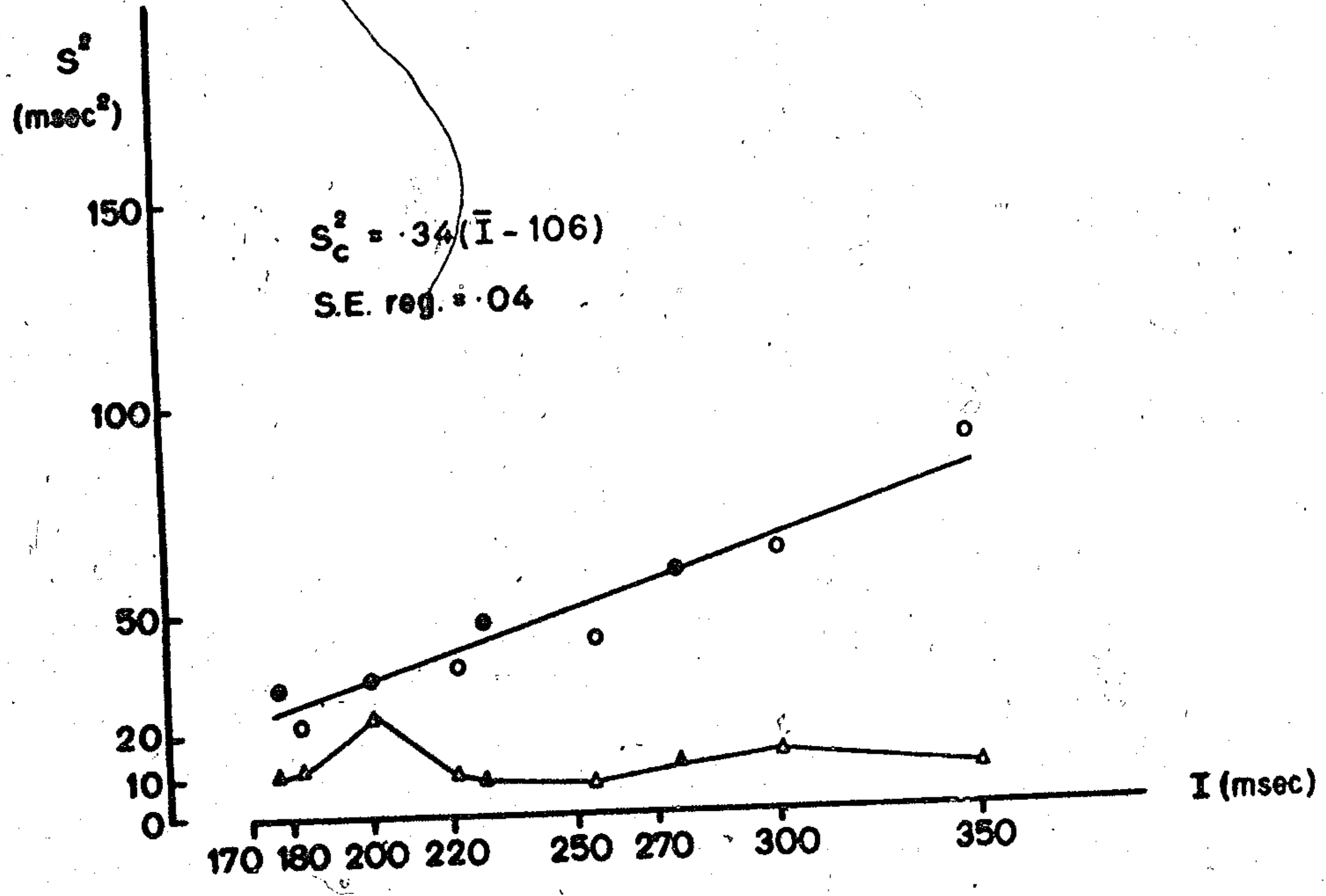

Figure 11: S_C^2 and S_D^2 versus $\bar{I}$ for IT.

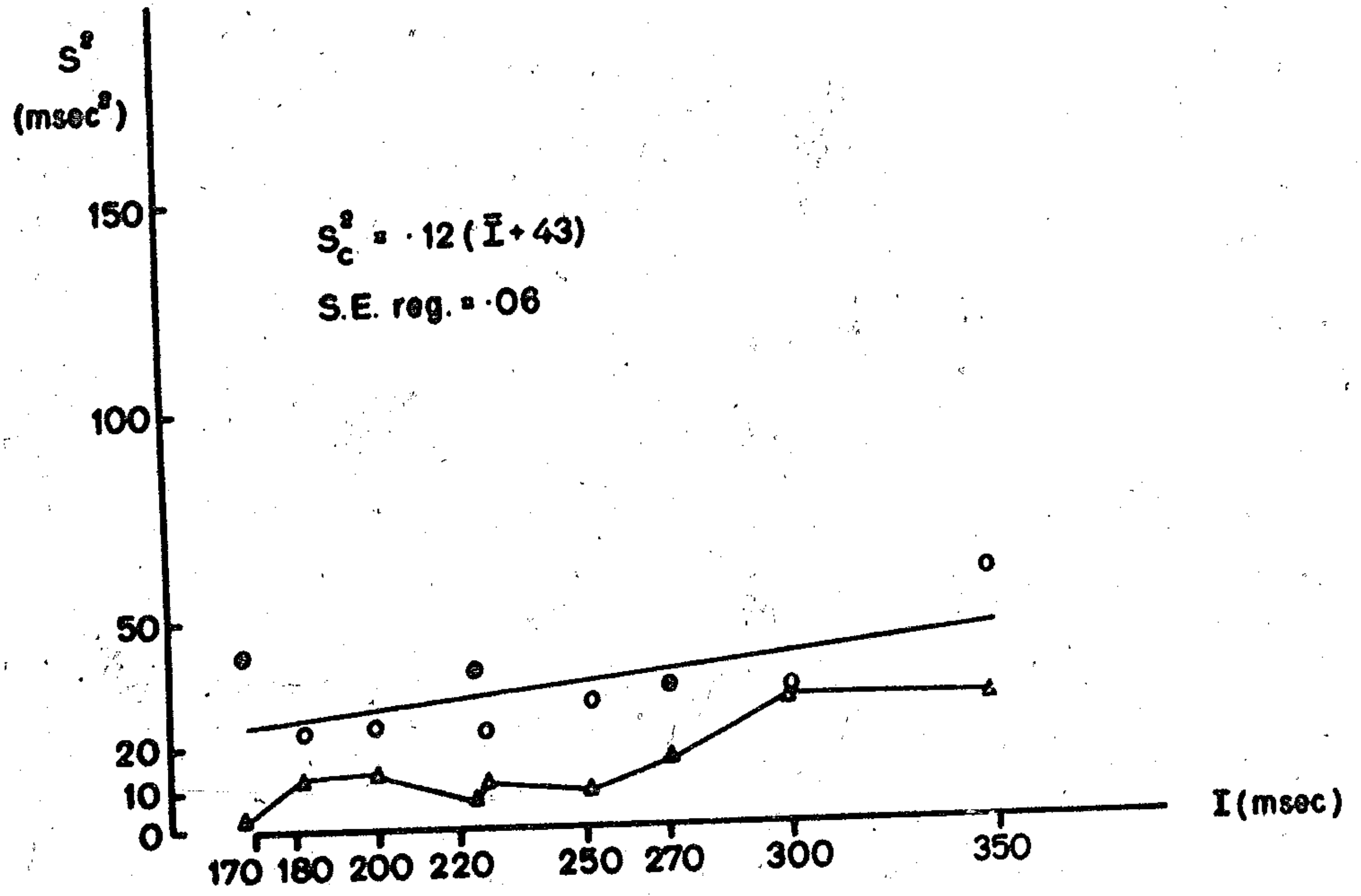

Figure 12: S_C^2 and S_D^2 versus $\bar{I}$ for MF.

Table 2

Summary of ANOVA for linear and quadratic polynomials for the relation between S_C^2 and $\bar{I}$. Significance of the F-ratio at the .05 level indicated by an asterisk.

Subject	Linear term		Quadratic term	
	Mean square error	F(1,7)	Mean square error	F(1,6)
AW	148.85	9.66*	136.56	1.63
JW	41.11	9.83*	36.66	1.85
IT	35.08	87.48*	28.86	2.51
MF	96.88	3.84	49.42	7.72*

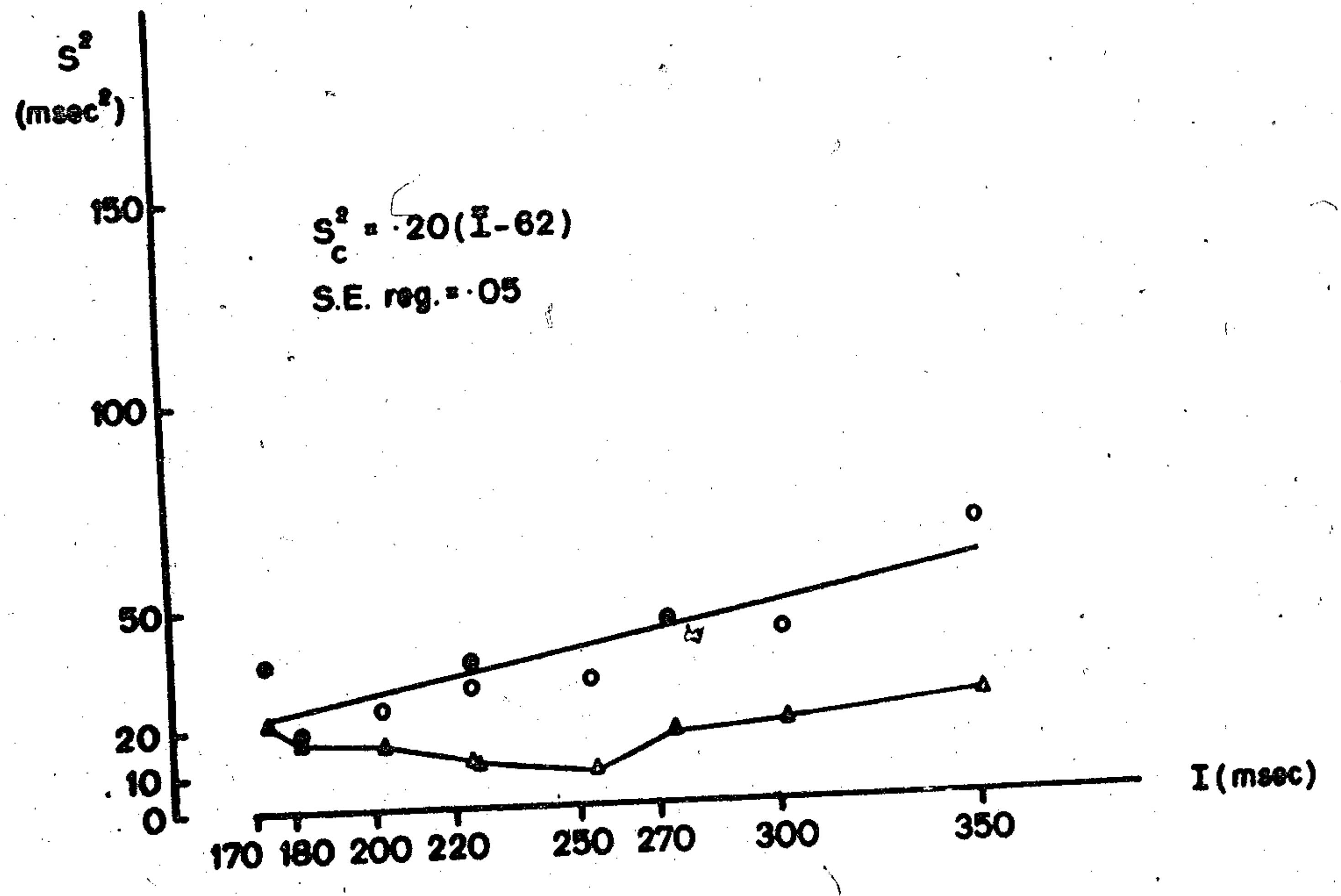

Figure 13: S_C^2 and S_D^2 versus $\bar{I}$; averaged data, Experiment 1.

of T, the effects of T over Ss is not significant, (F(8,24) = 1.67, mean square error = 65.44, $p > .05$).

Discussion

The low levels of S_I^2, reflect good performance on the part of Ss in this experiment. Michon (1967) has reported continuation data from a paradigm similar to the one used in this experiment with T in the range 333 through 3333 msec. The averaged estimate of the interresponse interval variance for response rates of about three per sec was five times more than that found in the present experiment. Most of the difference probably reflects the lack of practice given to Michon's Ss. Michon gave the actual form of the relation between the standard deviation (S_I) and $\bar{I}$ in terms of a power function:

$$S_I = k\bar{I}^{1.5} + a$$

where the constant k was of the order 0.04. Thus he had to conclude that a simple stochastic process would not account for the data, since the variance increased at a rate greater than that of the mean. The constant a he suggested, "may be visualised as the intrinsic noise level of the motor system." Unfortunately, the values of a are not reported.

Of the 36 separate estimates of the lag one serial correlation in the present experiment, only in one case was the hypothesis $P_I(1) = 0$ not rejected. Thus interpretations of response timing involving simply the chaining of associative elements may be excluded. Moreover, the finding that $P_I(1)$ was bounded by zero and minus one half provides strong support for the general case of the tandem process model. That is, both the timekeeper intervals and the response delays contribute to the observed interresponse interval variance.

Theoretical discussion in the Introduction regarding the nature of the timekeeper focused almost exclusively on its variability. But, a striking feature of the data collected in this experiment is the accuracy with which Ss are able to adjust $\bar{I}$ to within a few milliseconds of the standard. If such response timing is based on the waiting time to achieve a given count of neural events, the density of events on the time scale must be quite high to achieve this resolution. Theories with time units of the order of 50 msec (Kristofferson, 1967) would not be able to encompass the observed precision.

The averaged estimates of the timekeeper variance were found to be linear increasing with $\bar{I}$ and this is consistent with the prediction of simple stochastic wait formulations for the timekeeper, such as one based on a Poisson process. If a Poisson process is assumed, the estimate of λ' given by the reciprocal of the slope of the averaged data is 5.0×10^3 events per sec. With this density of events on the time scale, a resolution of 1/5000 sec or $\pm$ 0.1 msec is theoretically possible which is well within the observed precision of $\bar{I}$. Although the linear increasing mean-variance relation is consistent with the Poisson counter model, the finding of positive β , (the intercept for $S_C^2 = 0$), implies that the timekeeper interval is not identical to the waiting time, T', based on the Poisson source. In the Introduction an interpretation of a non-zero intercept was given in which some part of the timekeeper interval was due to a delay R with mean and variance not a function of T'. However, without further assumptions, an estimate of the extent of that delay cannot be made since the intercept is a function of both the mean and variance of R.

The procedure of giving Ss considerable experience with one value of T before moving on to another was intended to reduce experimental "noise" in the results. However this is not an ideal procedure for estimation of the relation between σ_C^2 or σ_D^2, and T for a given S, since it is prone to possible day-to-day effects. This could differentially affect estimates in particular sessions and, therefore, at a particular T value. To remove the possibility of this confound, averaged data from Ss run under different orders of conditions may be used. However, if the effects of T on the estimates within a S are of interest, a better procedure would be for each S to receive all values of T in random order in the course of each block. Results for the two procedures are compared in the next experiment, in which the range of T was extended to one half of one second.

In the present experiment it was found that S_D^2 was greater than zero with some suggestion that, for individual Ss, it might be related to $\bar{I}$. The randomized order of presentation of T used in the next experiment will be particularly appropriate to an analysis of the relation between S_D^2 and $\bar{I}$. Since S_D^2 may depend to some extent on the response apparatus used, it would be of interest to use equipment which approximates that found in RT studies, though the response required should still be one that is easily produced and repeated. In the next experiment equipment is used with which S simply had to touch a fixed response plate with his index finger to make electrical contact. This bears a greater resemblance to the microswitches usually used in RT experiments than does the telegraph key.

Experiment 2: Finger responding.

Method.

The event sequence was the same as for Experiment 1, but in the synchronization phase no feedback was given when responses led or lagged pulse onsets by more than 35 msec. Instead, immediately after the end of every session, Ss were informed of the mean and variance of the session's Is.

The response plate was clamped to the arm of the chair in which S was seated so that the right hand rested naturally on it in a cupped-downward, relaxed position with the index finger free to move in a vertical plane over the pointed contact button, (see Figure 14). Ss were instructed to make small amplitude responses, moving just the index finger through about 1 cm and leaving the finger actually resting on the contact for as short a time as possible after each response.

Ten values of T were used in the range 220 through 490 msec under two different conditions of presentation. In the Fixed Condition the same value of T was used throughout each of two successive sessions and the first session was treated by the experimenter for practice purposes only. For half of the Ss the order of assignment of T was 220, 280, 340, 400, 460 msec then 490, 430, 370, 310, 250 msec while the others received T in the order 490, 430 .. msec, etc. A session comprised five blocks of ten sequences each. Under the Random Condition, each block presented all ten values of T drawn at random without replacement. Twenty sessions of five blocks each were run in this condition, the first ten sessions being treated for practice purposes only.

Figure 14: Response touch plate used in Experiments 2 and 3.

Four paid Ss took part. After a number of preliminary practice sessions, Ss were run under both conditions, two (EL, SC) in the Fixed Condition first, two (BB, JS) in the Random Condition first.

Results.

The averaged statistics for the 30 Is in the continuation phases are taken from the second 50 sequences run at each T. Because sequences with missed or bounced finger responses in either synchronization or continuation phases were rerun immediately, each condition contains the same number of sequences.

Over all Ss the largest change from the mean of the first 15 to that of the last 15 Is averaged over all sequences at a given T was only of the order of two percent of the mean, and so the assumption of stationarity was retained as a reasonable approximation. Average changes for each S are given in Table 3, (details for this table may be found in Appendix A).

Table 3

$\Delta\bar{I}$ for each S, (msec units).

	Subject			
	EL	SC	BB	JS
$\overline{\Delta I}$ Fixed	-1.2	-0.7	-1.0	-0.2
Random	-1.3	-0.9	-1.3	-1.2

In Figures 15 through 18 the estimates S_C^2, S_D^2 under both conditions are shown for each S as a function of $\bar{I}$, (note the scale change in Figure 16). Only for BB is the quadratic coefficient in the least squares best fit quadratic polynomial significantly different from zero. Summaries of the ANOVAs for linear and quadratic polynomials are given in Tables 4 and 5. The best fit linear functions are shown in the figures with continuous lines in the case of the Fixed Condition and by dashed lines for the Random Condition. Tests performed to determine whether the slope estimates are significantly different gave a positive result only in the case of SC, ($t(16) = 2.92$, $p < .05$). Estimates of the intercept fall in the range 80 through 192 msec.

Visual inspection of Figures 15 through 18 suggests that in the Fixed Condition there are more peaks and dips in S_D^2 with changes in T. Individual ANOVAs summarised in Tables 6 and 7 reveal significant effects except in the case of EL in the Random Condition. However, while several significant differences between pairs of means were established on the basis of 95% simultaneous confidence intervals, (Scheffé, 1959), in the Fixed Condition, the only significant pairwise difference in the Randomised Condition was in the case of SC, (S_D^2 at T = 280 msec versus S_D^2 at T = 430 msec).

A summary of the results for this experiment is provided in Figure 19, in which each data point is an average based on estimates for all four Ss. A summary of the ANOVAs for linear and quadratic polynomials is provided in Table 8 and the linear form relating S_C^2 and $\bar{I}$ may be seen to provide a good description, the difference in slopes not being significant.

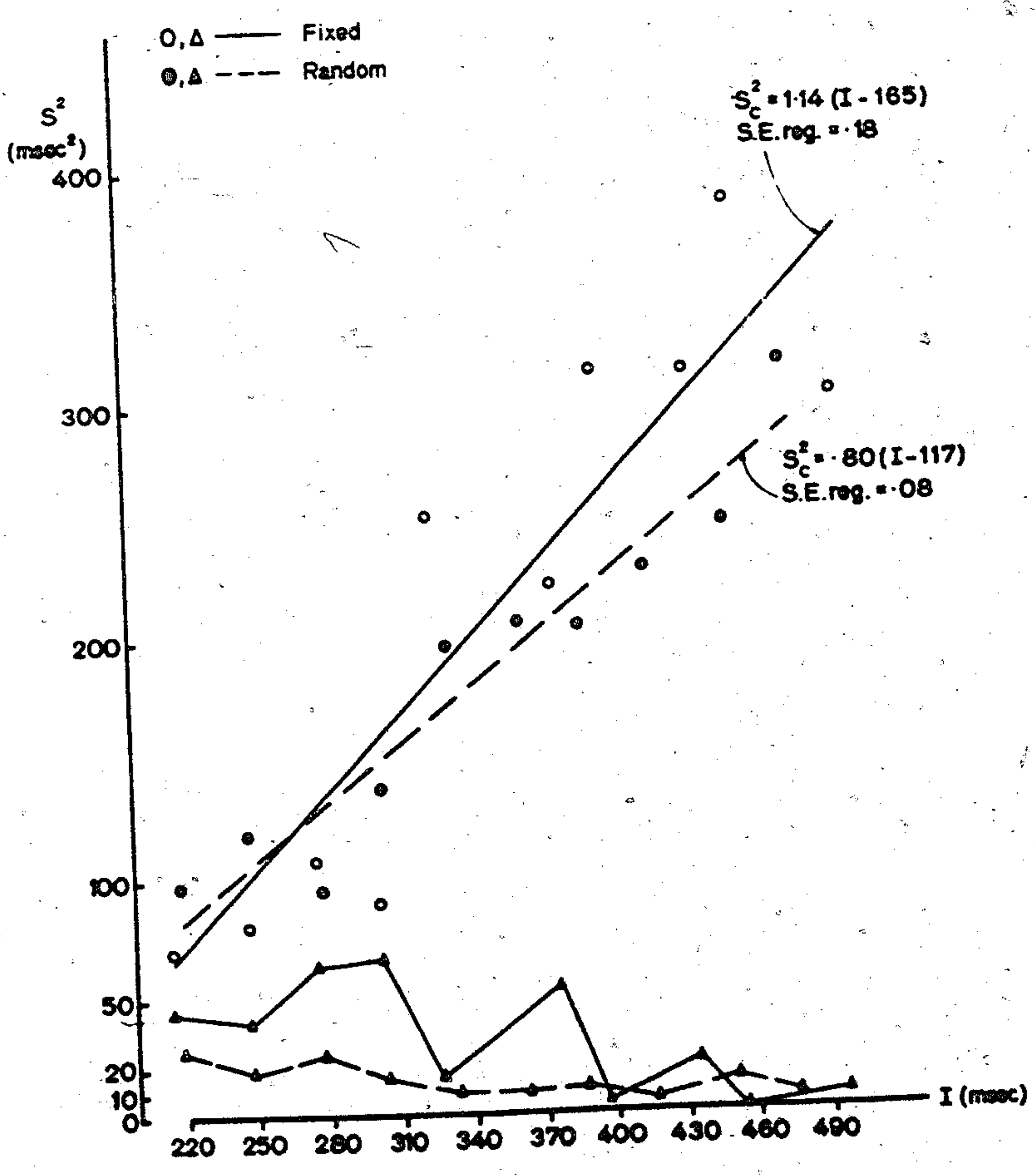

Figure 15: S_C^2 and S_D^2 versus $\bar{I}$ for EL.

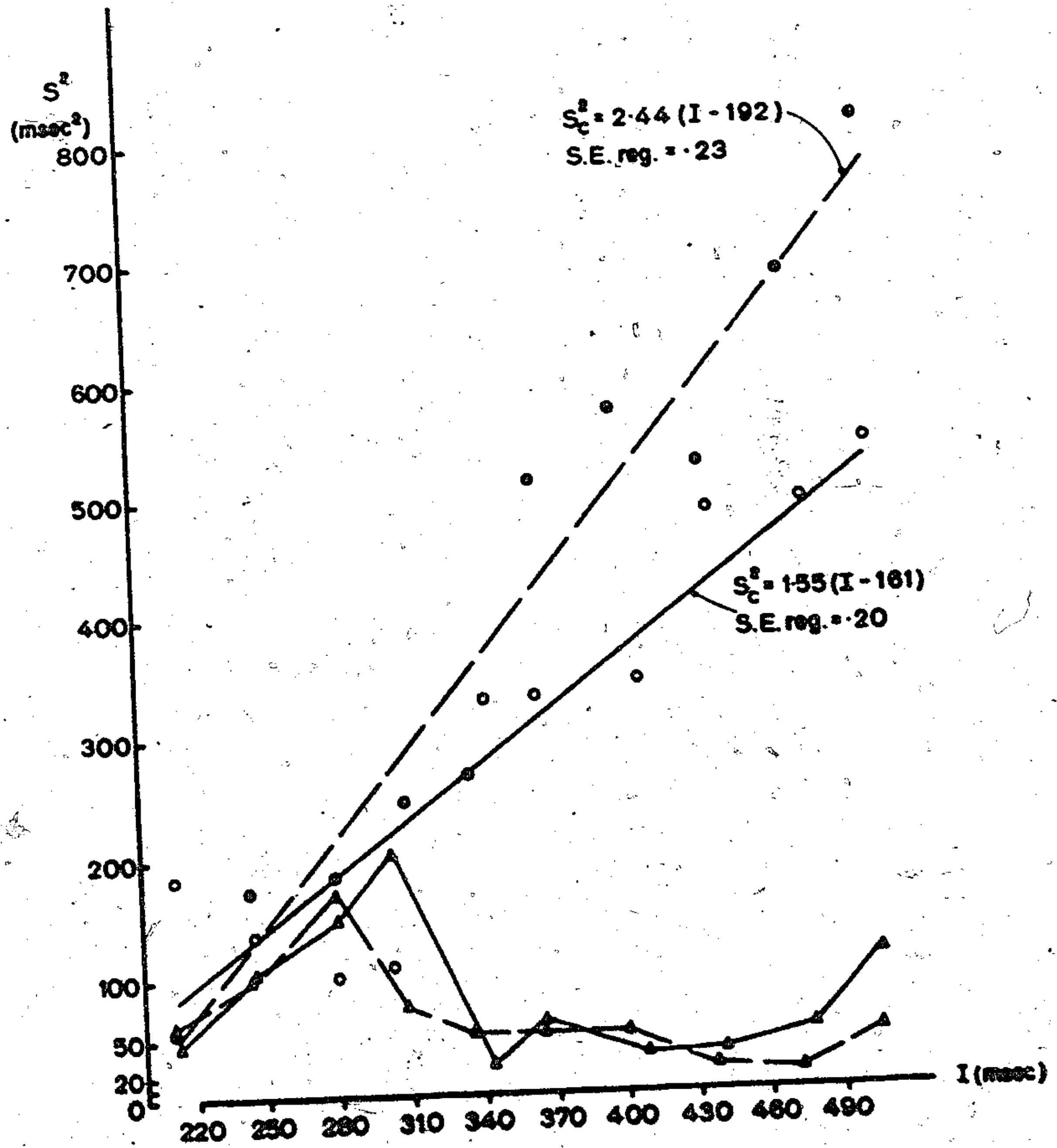

Figure 16: S_C^2 and S_D^2 versus $\bar{I}$ for SC.

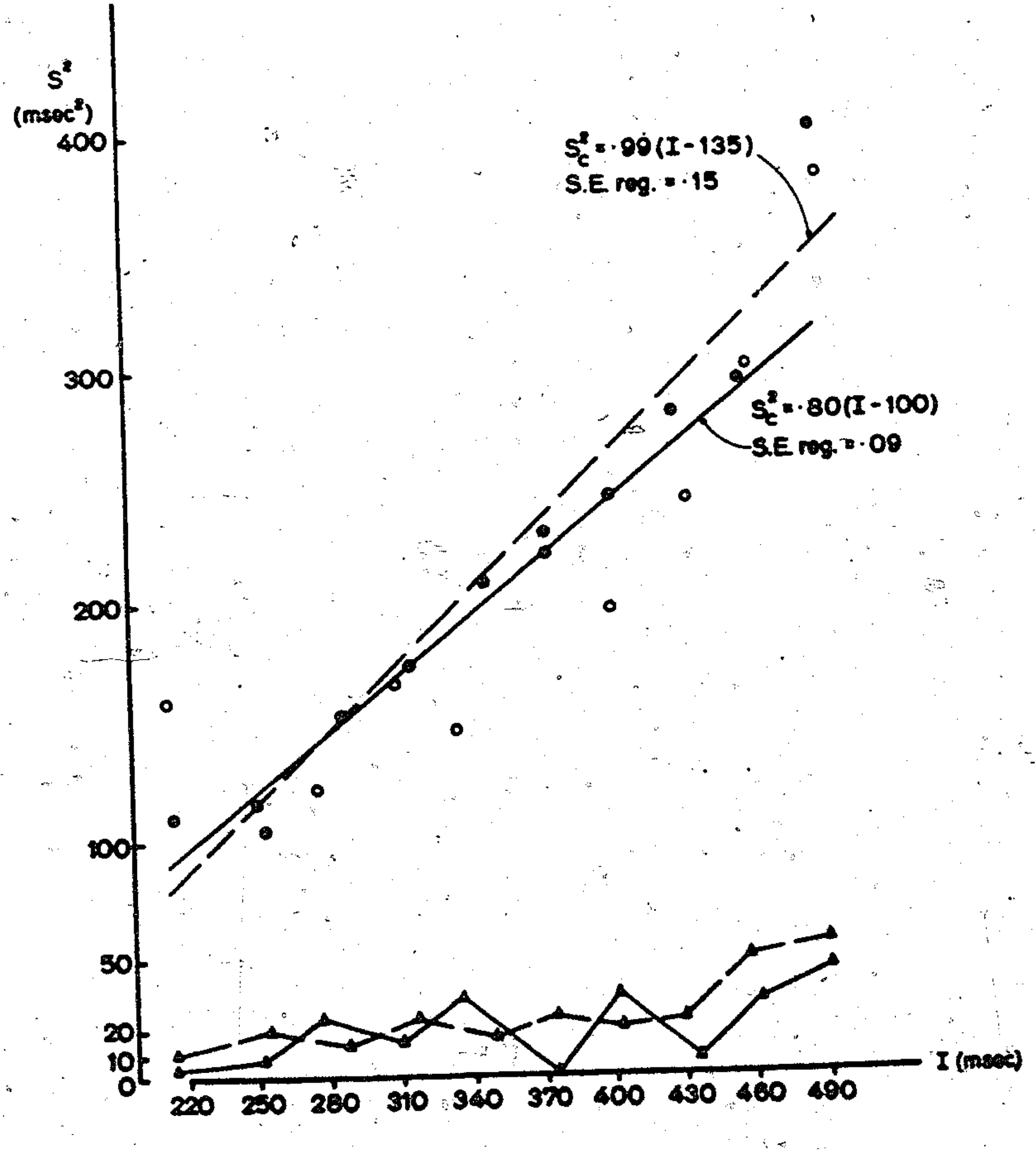

Figure 17: S_C^2 and S_D^2 versus $\bar{I}$ for BB.

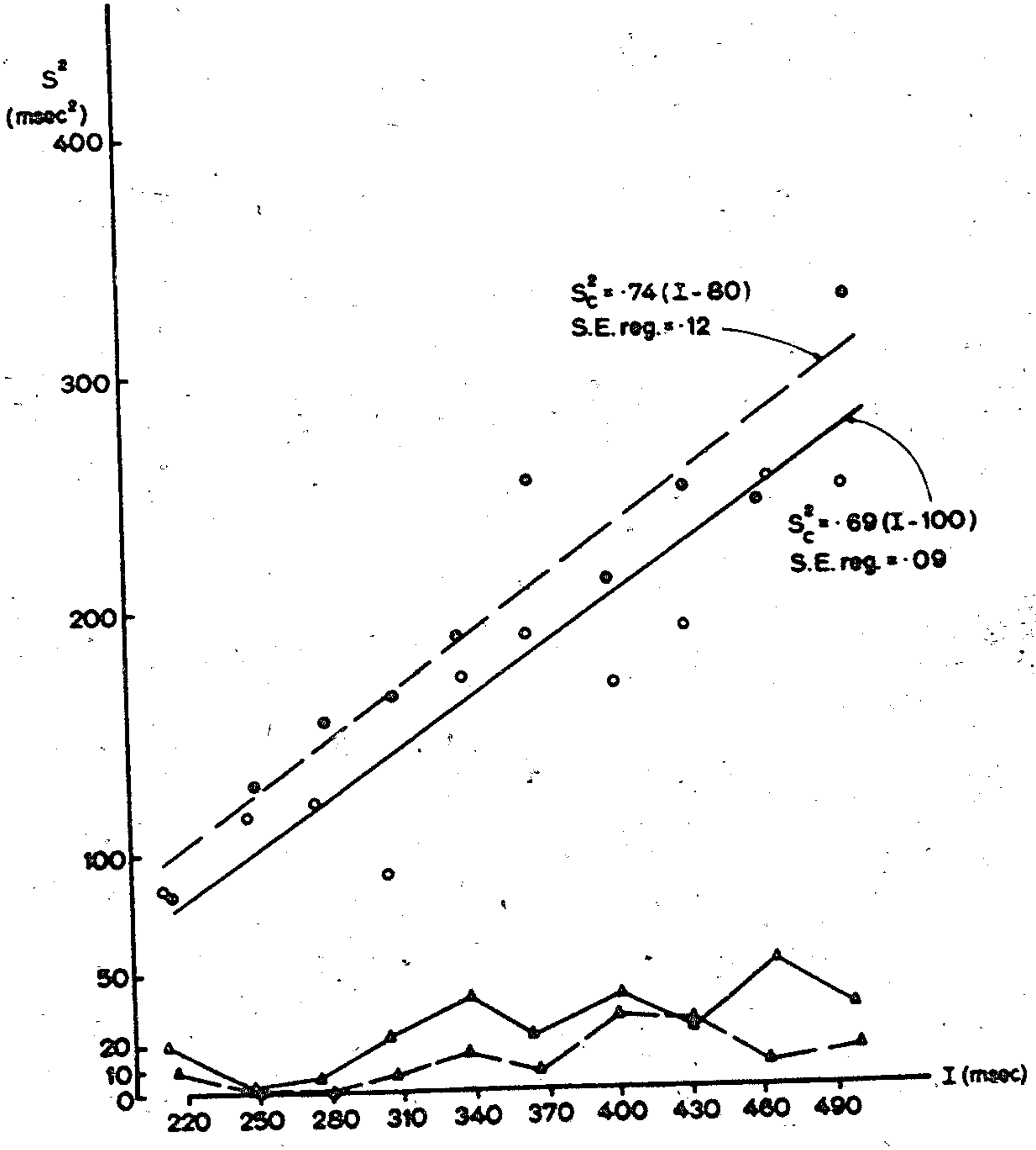

Figure 18: S_C^2 and S_D^2 versus $\bar{I}$ for JS.

Table 4

Summary of ANOVA for linear and quadratic polynomials for the relation between S_C^2 and $\bar{I}$ in the Fixed Condition.

Subject	Linear term		Quadratic term	
	Mean square error	F(1,8)	Mean square error	F(1,7)
EL	2627.77	39.00*	2718.02	0.73
SC	4710.23	45.74*	4517.90	1.34
BB	1773.58	28.21*	475.59	22.83*
JS	1106.46	35.01*	1262.82	0.01

Table 5

Summary of ANOVA for linear and quadratic polynomials for the relation between S_C^2 and $\bar{I}$ in the Random Condition.

Subject	Linear term		Quadratic term	
	Mean square error	F(1,8)	Mean square error	F(1,7)
EL	475.72	90.61*	485.39	0.84
SC	3482.64	145.18*	3961.37	0.03
BB	603.34	116.86*	369.71	6.06*
JS	613.03	69.59*	683.50	0.18

Table 6

Summary of ANOVA of S_D^2 for each S in the Fixed Condition.

Subject	Mean square error	F(9,490)
EL	4779.33	6.47*
SC	11043.20	15.89*
BB	3346.97	3.63*
JS	4045.11	2.93*

Table 7

Summary of ANOVA of S_D^2 for each S in the Random Condition.

Subject	Mean square error	F(9,490)
EL	2745.28	1.03
SC	15510.70	6.26*
BB	5202.49	2.27*
JS	2891.44	3.23*

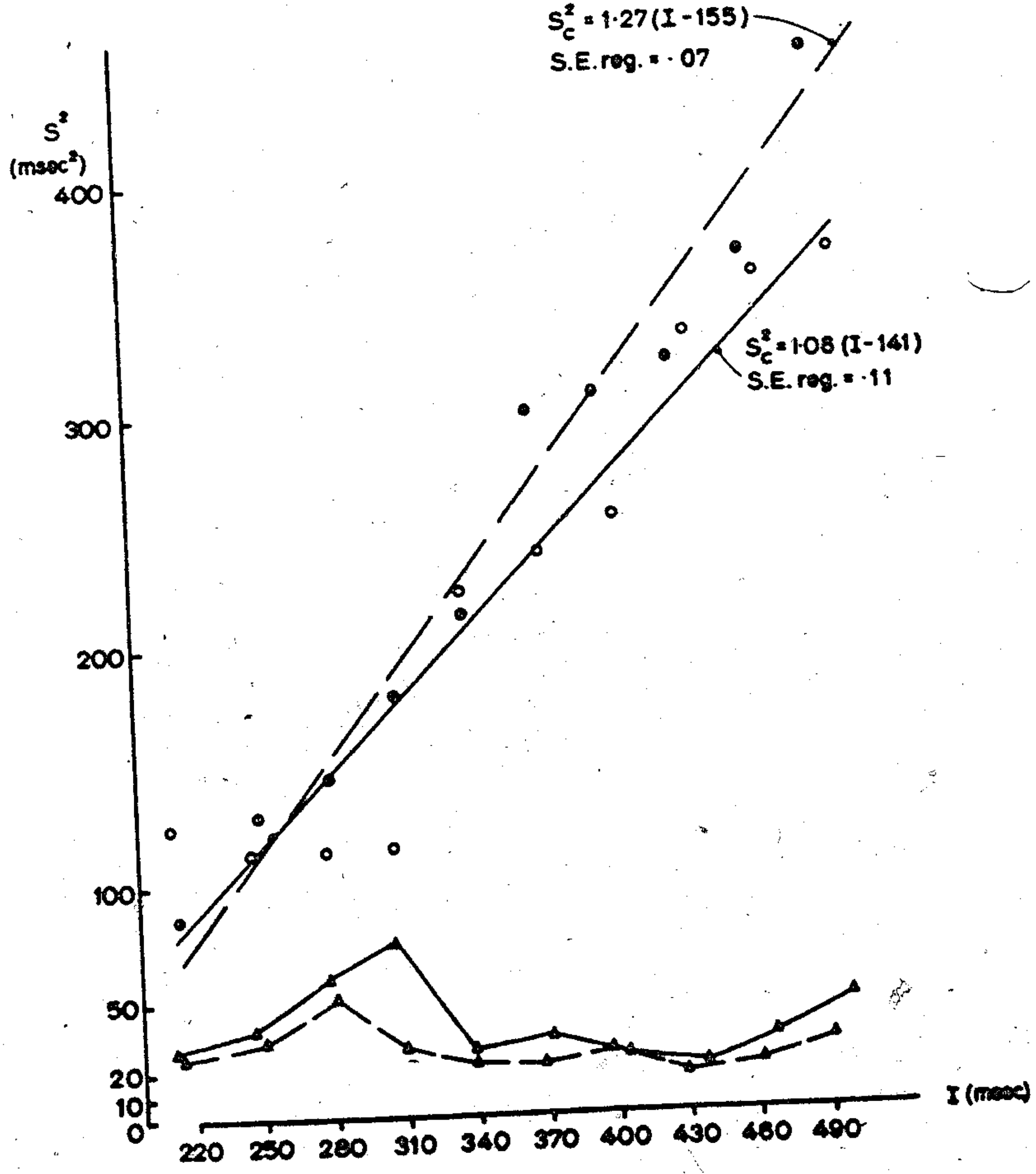

Figure 19: S_C^2 and S_D^2 versus $\bar{I}$; averaged data, Experiment 2.

Table 8

Summary of ANOVA for linear and quadratic polynomials for the relation between S_C^2 and $\bar{I}$, averaged data from Fixed and Random Condition.

Condition	Linear term		Quadratic term	
	Mean square error	F(1,8)	Mean square error	F(1,7)
Fixed	1050.25	86.99*	988.79	1.50
Random	422.74	286.86*	431.22	0.82

Discussion.

Overall there was remarkable similarity of results for individual Ss under Fixed and Random Conditions in which the standard interval was either the same throughout or else was presented in random order in each block. Thus it may be concluded that no serious systematic bias in S_C^2 or S_D^2 occurred as a result of day-to-day effects in the Fixed Condition.

Turning to the actual functions obtained, support is again found for a simple stochastic basis for the timekeeper, since increase in S_C^2 is linear with $\bar{I}$. For a Poisson process, the rate parameter in the Fixed and Random Conditions based on the average functions is 0.9 and 0.8×10^3 events per second respectively. However the average slope in the second experiment is much greater than the average slope found for the Ss in the first experiment, and furthermore, a significant change in the average value of S_D^2 was found, (from 16.2 to 33.9 msec^2; $t(78) = 2.83$, $p < .05$). It seems unlikely that these changes are due only to the change in the response equipment since, in the second experiment, there was only one practice session at each T, or its equivalent in the Random Condition, whereas in the first experiment there were four or six. Furthermore this reduction in practice was compounded with the absence of immediate synchronization error feedback in the second experiment.

In the results section it was pointed out that estimates of σ_D^2 were less consistent over T in the Fixed Condition. As an alternative to the day-to-day effect explanation, it is possible that these changes are caused by Ss being able to adopt different movements when responding at different values of T in the fixed standard condition. If it is assumed that some part of σ_D^2 is associated with the particular movement used, then it is reasonable to suppose that different movements will result in changes in σ_D^2. However, in the Random Condition, the constantly changing T is more likely to encourage Ss to adopt just one type of response movement which is roughly suited to all response rates. The suggestion that the movement used may affect σ_D^2 could also account for the change observed in S_D^2 from Experiment 1 to Experiment 2. There a change in response equipment would certainly necessitate different movements in responding. It would be necessary to assume that the component of σ_D^2 attributable to the wrist movement used in the telegraph key response is smaller than that attributable to the index finger movement of the present experiment.

The next experiment is designed specifically to assess the influence of type of movement on the variance of response delays at two response rates. Each S is run in each condition to serve as his own control. The experimental results are also analysed in terms of S_C^2 to determine whether it is relatively constant for any given S running under different conditions.

Experiment 3: Comparison of three different movements in response timing.

Method.

The same event sequence was used as in the preceding experiment. Response timing at values of T of 250 and 350 msec was examined as a function of three different movements resulting in index finger contact with the touch plate button shown in Figure 7. In Condition A, a forearm movement in a vertical plane was used such that the elbow remained stationary on the arm rest. Index finger contact with the response button was made and broken by moving the whole lower arm with fingers and wrist immobile. In Condition B, the movement was entirely in the wrist with forearm stationary on the arm rest and the fingers held immobile. The index finger movement with arm and wrist on the arm rest (as in Experiment 2) was used in Condition C. In all three conditions the normal, cupped-downward, relaxed position of the hand was adopted as being the least fatiguing for Ss. Ss were instructed to make the movements in each condition of small amplitude so that the excursion of the index finger would rarely exceed 1 cm.

After two preliminary sessions with instruction and practice at using each of the different movements, Ss were assigned to each condition for two successive sessions, the order of assignment being random. A session comprised 25 blocks of two sequences each. In each block both values of T were presented, the two orders for T being randomly determined and equiprobable.

Five paid Ss and the author took part. Two of the Ss (AW and JW) had run in Experiment 1, while the others were the Ss used in Experiment 2.

Results.

All 50 sequences run at each of the two T values for each S were used in the analysis of the Is in the continuation phase. Average differences between the mean of the first 15 and the last 15 Is for each S are shown in Table 9, (detailed tables of the average differences in mean for each S at each T may be found in Appendix A). With the largest difference being only slightly more than one percent of the mean, detrending the data prior to analysis was considered unnecessary.

Table 9

$\overline{\Delta I}$ for each S, (msec units).

	Subject					
	EL	SC	BB	JS	AW	JW
$\overline{\Delta I}$	1.6	1.9	-0.8	0.5	2.00	-1.5

To determine the effect of condition on S_C^2 and S_D^2 at each value of T, two-way ANOVAs were performed with Ss and conditions as the factors. These are summarised in Table 10 for S_C^2 and in Table 11 for S_D^2. All F-ratios exceed the .05 level of significance.

Although the only significant pairwise contrast between means is between Conditions A and C for S_D^2 at T = 250 msec, it is seen that the ordering of the magnitude of S_C^2 and of S_D^2 with Conditions A, B, C is very consistent, with the smallest variance being found under A. Furthermore,

Table 10

Summary of ANOVA of S_C^2 at T = 250 and 350 msec.

T	Mean square error	Condition	Subject	Interaction	S_C^2		
					A	B	C
250	4812.18	11.87*	17.71*	5.62*	51.4	61.5	78.7
350	13261.40	7.56*	31.24*	5.82*	127.4	131.9	161.1

Table 11

Summary of ANOVA of S_D^2 at T = 250 and 350 msec.

T	Mean square error	Condition	Subject	Interaction	S_D^2		
					A	B	C
250	1840.57	47.22*	73.08*	23.06*	23.7	42.4	57.7
350	2990.15	5.52*	51.36*	3.10*	39.6	40.9	53.1

the difference between Conditions B and C is consistently larger than that between A and B.

Discussion

This experiment clearly demonstrates an effect of type of movement on S_D^2 so that some part of σ_D^2 must be attributable to variance specific to particular response movements, even though the actual response equipment used is unchanged. Moreover, it is found that the index finger movement, which involves potentially finer movement control, displays greater S_D^2 than does the grosser arm movement. The S_D^2 associated with the wrist movement is found to be intermediate with respect to the other two values. Thus it appears that at least some of the increase in S_D^2 from Experiment 1 to Experiment 2 should be attributed to the changed movements involved.

In a discussion of factors affecting performance in the temporal synchronization of a response with one of a train of regular stimuli, Bartlett and Bartlett (1959) suggested that "one should perform better with motor units suited for fine articulated movements: for example, a finger movement might permit a better score than a foot movement." Since better synchronization would require reduced variability in response delays, the findings for S_D^2 in this experiment refute the suggestion. Indeed, from a neuroanatomical viewpoint the greater response delay variance of finger movement is not surprising. Motor systems with a greater range of articulatory movement will necessarily be more complex in their control mechanisms. The larger number of neuromuscular motor units needed will be associated with a greater range of delays in the recruitment of all the muscle fibres necessary for initiating each response.

While the interpretation of changes in S_D^2 is fairly clear, the reason for a significant effect of type of movement on S_C^2 is less obvious. A somewhat analogous problem for the Poisson event counter model for duration discrimination has been demonstrated by Abel (1973b). In the discrimination of empty time intervals, she found that the parameters of the signals which marked the start and finish of the intervals had an effect on the estimates of the rate parameter, (λ), of the Poisson source of events. So far we have said nothing specific about the location in the nervous system of the source of events which underlie timekeeping. Creelman (1962) suggested that the timekeeper might be able to receive pulses for the purposes of counting from many different sources depending on experimental conditions. Suppose we entertain a simpler hypothesis; that there is but one, centrally-located event source. How might changes in experimental conditions affect the event rate?

A factor postulated by Treisman (1963) as influencing the rate of a central timekeeper unit, (he did not actually specify a Poisson event source), was S's state of arousal, which would presumably depend on experimental conditions. Suppose it is assumed that arousal level is not given to short-term fluctuations, then within the time span of a session block the value of λ' or λ would be stable. In the case of response timing one would be able to obtain relatively constant estimates of σ_C^2, or in duration discrimination, estimates of λ should be approximately constant provided all conditions are run within a block. However, in both the present experiment and that of Abel, different conditions were run on different days so that different levels of arousal associated with each condition could have produced the changes in timekeeper characteristics.

In any event, the finding that estimates of σ_C^2 and of σ_D^2 can depend on the movement used in responding means that care should be taken in relating these quantities over different experimental conditions.

Markovian dependence in the tandem process model for response timing.

In developing the tandem process model for response timing it was assumed that the timekeeper and the response delay processes were both stochastically independent. In this section the effects of dependence on the interresponse intervals, either in successive timekeeper intervals, or, in successive response delays, are considered.

Suppose that the deviation of the interval C_j about the mean, μ_C, depends on the deviation of C_{j-1} about μ_C, but is also perturbed by a random shock reflecting the variability of the mechanism which produces C_j. Such a process, with the property that the present value of the random variable depends on previous values only through the immediately preceding value, is termed first-order autoregressive, or Markovian. The predictions of this Markovian timekeeper interval (MTI) model will be compared both with the basic, tandem process model and an alternative model in which it is assumed that the source of dependence is located in the response delay process. The latter, in which it will be assumed that successive response delays are drawn from a Markov process, will be termed the Markovian response delay (MRD) model.

The MTI model is stated:

$$c_j = \phi c_{j-1} + x_j \qquad -1 < \phi < +1 \tag{11}$$

where x is an independent random variable with $E(x) = 0$; $\gamma_x(k) = 0$, $k \neq 0$; $\gamma_x(0) = \sigma_x^2$ and $c_j = C_j - M_C$. The bounds on the correlation parameter, ϕ, ensure stationarity of the process for all j. The serial covariance function of C is given by:

$$\gamma_C(k) = E\ \left\{(C_j - M_C)\ (C_{j-k} - M_C)\right\}$$

$$= E(c_j c_{j-k})$$

$$= E(\phi c_{j-1} c_{j-k}) + E(x_j c_{j-k}).$$

For $k > 0$, the second term is zero since c_{j-k} does not include terms in x beyond x_{j-k}, and so:

$$\gamma_C(k) = \phi\,\gamma_C(k-1).$$

For $k = 0$:

$$\gamma_C(k) = \phi\,\gamma_C(-1) + \sigma_x^2$$

$$= \phi\,(\phi\,\gamma_C(0)) + \sigma_x^2$$

since serial covariance functions are symmetric, that is, $\gamma_C(k) = \gamma_C(-k)$.

Thus:

$$\gamma_C(k) = \begin{cases} \dfrac{\sigma_x^2}{1 - \phi^2} & k = 0 \\ \phi\,\gamma_C(k-1) & k > 0 \end{cases} \qquad (12)$$

For the MRD model we write:

$$d_j = \Theta d_{j-1} + y_j \qquad -1 < \Theta < +1 \qquad (13)$$

where the independent random variable, y, has properties, $E(y) = 0$; $\gamma_y(k) = 0,\ k \neq 0$; $\gamma_y(0) = \sigma_y^2$ and $d_j = D_j - \mu_D$. the serial covariance function of D is written:

$$\gamma_D(k) = \begin{cases} \dfrac{\sigma_y^2}{1 - \theta^2} & k = 0 \\ \theta\gamma_D(k-1) & k > 0 \end{cases} \tag{14}$$

In order to contrast the predictions of these two models and the basic model, it will be necessary to have a general expression for the serial covariance of the interresponse intervals as a function of lag, k, in terms of $\gamma_C(k)$ and $\gamma_D(k)$. We have:

$$\gamma_I(k) = E\left\{(I_j - M_I)(I_{j-k} - M_I)\right\}$$

Writing $i_j = I_j - \mu_I$ and using the corresponding transformations to c_j and d_j so that, from (1), we have $i_j = c_j - d_{j-1} + d_j$, then:

$$\begin{aligned} \gamma_I(k) &= E(i_j i_{j-k}) \\ &= E\left\{(c_j - d_{j-1} + d_j)(c_{j-k} - d_{j-k-1} + d_{j-k})\right\} \\ &= \gamma_C(k) + 2\gamma_D(k) - \gamma_D(k-1) - \gamma_D(k+1) \\ &\qquad - \gamma_{CD}(k+1) + \gamma_{CD}(k) - \gamma_{CD}(-k+1) + \gamma_{CD}(-k) \end{aligned}$$

since the cross-covariance,

$$\gamma_{DC}(k-n) = E(d_j c_{j-k+n}) = E(c_j d_{j+k-n}) = \gamma_{CD}(-(k-n)),$$

(but note that, in general, cross-covariance functions are not symmetric). In the models of interest at this point we assume the two processes to be statistically independent of each other so that the cross-covariances are zero and we may write:

$$\gamma_I(k) = \gamma_C(k) + 2\gamma_D(k) - \gamma_D(k-1) - \gamma_D(k+1) \tag{15}$$

It will be noted that Equations 2 and 3 for $\gamma_I(0)$ and $\gamma_I(1)$ for the basic model follow from Equation 15 since for that model, $\gamma_D(k) = 0$, $k \neq 0$; $\gamma_D(0) = \sigma_D^2$; $\gamma_C(k) = 0$, $k \neq 0$; $\gamma_C(0) = \sigma_C^2$. For completeness, the serial covariance function for the basic tandem process model is rewritten in full here:

$$\gamma_I(k) = \begin{cases} \sigma_C^2 + 2\sigma_D^2 & k = 0 \\ -\sigma_D^2 & k = 1 \\ 0 & k > 1 \end{cases} \qquad (16)$$

Thus the main features of $\gamma_I(k)$ for the basic model are the negative valued $\gamma_I(1)$ and the fact that, for lags, $k > 1$, the expectation of $\gamma_I(k)$ is zero.

Substituting (12) into (15) the serial covariance function of the interresponse intervals for the MTI model is given by:

$$\gamma_I(k) = \begin{cases} \dfrac{\sigma_x^2}{1 - \phi^2} + 2\sigma_D^2 & k = 0 \\ \dfrac{\phi\sigma_x^2}{1 - \phi^2} - \sigma_D^2 & k = 1 \\ \dfrac{\phi^2\sigma_x^2}{1 - \phi^2} & k = 2 \\ \phi\gamma_I(k-1) & k > 2 \end{cases} \qquad (17)$$

It will be noted that, if $\phi = 0$, the function (17) reduces to the form (16). But, in general, the MTI model, in contrast to the basic model, does not necessarily predict $\gamma_I(1) < 0$. In fact, $\gamma_I(1) < 0$ if $\phi < 0$ or if $(1 - \phi^2)\sigma_D^2 > \phi\sigma_x^2$ when $\phi > 0$, otherwise $\gamma_I(1) > 0$. Note that the expectation of $\gamma_I(2)$ is positive valued, and that, if $\phi > 0$, $\gamma_I(k)$ remains positive but with decrease in magnitude as k increases. If

$\phi < 0$, the function is oscillatory in sign. A selection of functions generated from (17) are presented for illustrative purposes in Figure 20.

The interresponse interval serial covariance function predicted by the MRD model is found by substituting (14) into (15):

$$\gamma_I(k) = \begin{cases} \sigma_C^2 + \dfrac{2\sigma_y^2}{1+\theta} & k = 0 \\ -\dfrac{1-\theta}{1+\theta}\,\sigma_y^2 & k = 1 \\ \theta\,\gamma_I(k-1) & k > 1 \end{cases} \qquad (18)$$

As required, the function (18) reduces to (16) if $\theta = 0$. In general, it will be seen that the expectation of $\gamma_I(1)$ is negative for the MRD model. For $k > 1$, the magnitude of $\gamma_I(k)$ damps down according to θ, with sign remaining negative if $\theta > 0$, and oscillating in sign if $\theta < 0$, (so that the sign of $\gamma_I(2)$ is complementary to that of θ). Illustrative functions generated from (18) are plotted in Figure 21.

Thus serial covariance functions which are consistently different from zero for lags greater than one may be interpreted in terms of Markovian dependence, either in the timekeeper intervals or in the response delays. In the following analysis section the data of Experiment 2 are examined in terms of the different predictions for the interresponse interval serial covariance functions by the above three models.

Analysis.

Estimates of the serial covariance ($G_I(k)$) for the data analysed in Experiment 2 were calculated for all four Ss at the ten values of T run in the Fixed and Random Conditions. Under the basic model, the

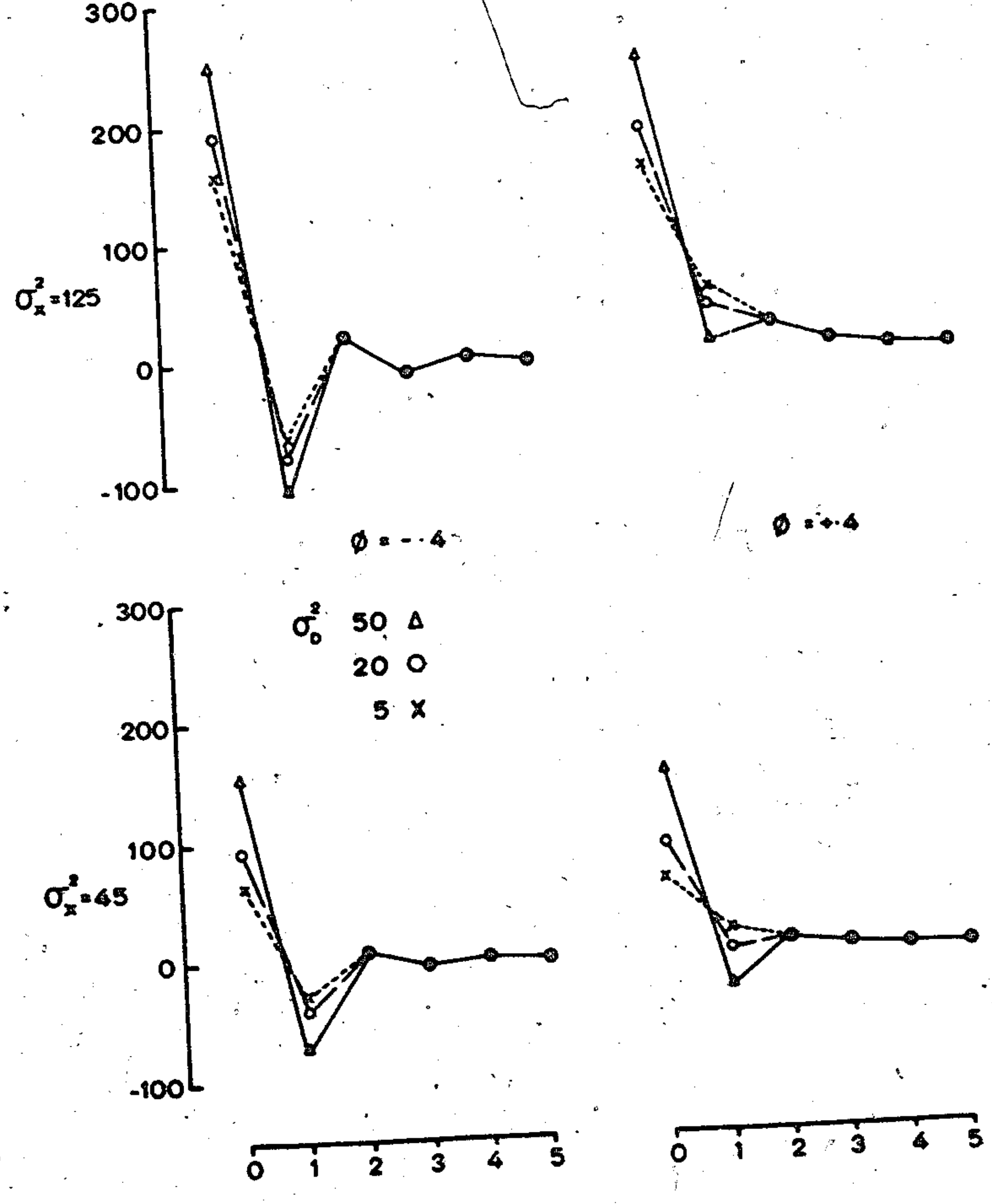

Figure 20: Some theoretical serial covariance functions ($\gamma_I(k)$) for the Markovian timekeeper interval (MTI) model.

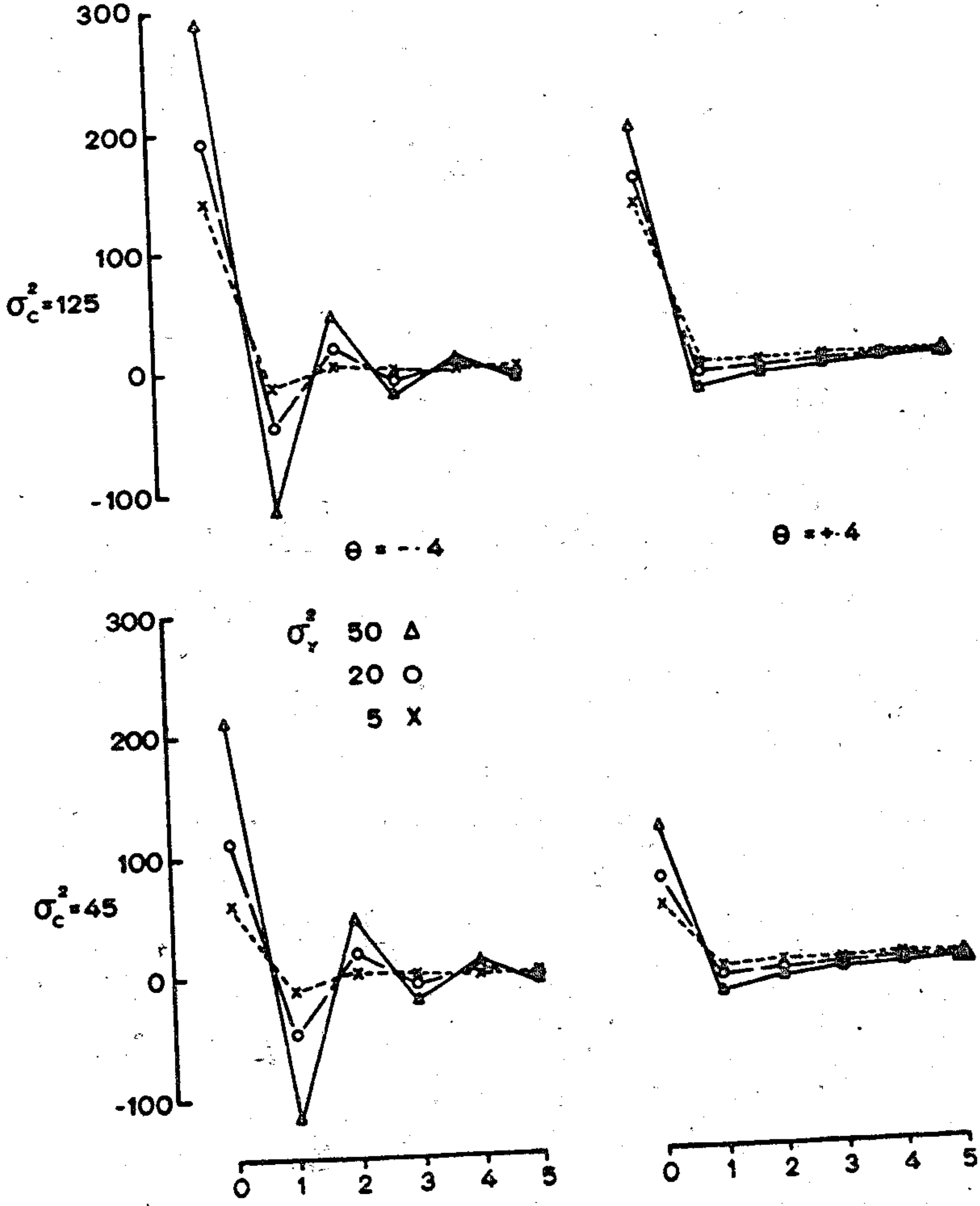

Figure 21: Some $\gamma_I(k)$ for the Markovian response delay (MRD) model.

expectation of the serial covariance of the interresponse intervals should be zero. Overall averages of $G_I(k)$ are given in Table 12 with 95% confidence intervals on the point estimates. It is found that, in all cases except at k = 4, the deviations from the predictions of the basic model are significantly different from zero.

For each of the 80 S-condition-T combinations, the best fitting theoretical functions of the MTI and MRD models to the observed serial covariance functions up to and including k = 5 were determined according to the criterion of the minimum of the sum of squared deviations. The calculations for this were performed on a CDC6400 computer using the routine ZXMARQ in the IMSL Program Library No. 3*. This routine finds the minimum of the sum of squares of k functions of n variables using a modified Marquardt algorithm, given an n-dimensional vector containing an initial guess at the minimum and a user-defined routine which evaluates the m functions for any n-dimensional argument vector. The routine provides a solution on reaching either of two stopping criteria, unless a maximum allowable number of calls to the user function-evaluation routine is exceeded. The first stopping criterion is that a minimum is accepted if the sum of the absolute values of the m functions becomes less than a prespecified amount. The second criterion for stopping is that a minimum is accepted if the largest change in the n variables going from iteration i to i+1 is less than a prespecified amount, (which may be taken to imply that the function is levelling out).

In the present application, ZXMARQ is entered with k = 6, (for

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*International, Mathematical and Statistical Libraries Inc., 6200, Hillcroft, Suite 510, Houston, Texas, U.S.A. 77036.

Table 12

Overall average serial covariance at lag k ($\overline{G_I(k)}$) for the data of Experiment 2.

	Lag, k			
	2	3	4	5
$\overline{G_I(k)}$	10.1*	-3.8*	0.9	-5.3*
2SEs	4.9	2.4	3.3	2.4

lags zero through five), each of the six functions being the difference between the observed and the theoretical serial covariance at that particular lag. The argument vector has three elements since both MTI and MRD have three free parameters, (that is $n = 3$). Since the value set for the first criterion was very small it was never reached in practice, and the second stopping criterion was the only relevant one. Thus the solution depended on finding a 3-element vector such that the largest change in two successive assigned values of the parameters agreed to within at least three decimal places. The maximum allowable number of calls to the function-evaluation routine was set at 100. In fact, with the algorithm biased toward Newton's method, it was found that many solutions were obtained within ten iterations. If no solution was found, quite often, changing the initial guess at the parameters was all that was required. In any case since a problem sometimes encountered with such methods is that of the local minimum, three repetitions of the program were run on every serial covariance function changing the initial guess vector. Occasionally no solution could be found whatever starting values were used. In such cases estimates of the parameters from the basic model were adopted, which in effect sets the dependence parameter in the MTI or MRD model to zero.

Because no constraints are placed by ZXMARQ on the range of the argument vector provided to the user's function-evaluation routine, it is sometimes necessary to make a transformation on the arguments to restrict them to some particular range of interest. For this analysis, restrictions of $-1 < (\theta, \phi) < +1$, and $(\sigma_C^2, \sigma_x^2, \sigma_D^2, \sigma_y^2) > 0$ were achieved by taking the sine of the dependence parameters and squaring the variance terms in the function-evaluation routine. The same transformations were applied to the solution argument returned by ZXMARQ.

Several test runs were made with the program incorporating ZXMARQ. Theoretical serial covariance functions, calculated for both models by substituting values for the free parameters into Equations 17 and 18, were treated as "data" and entered into the program to determine how well the true values would be recovered. The results are given in Table 13 and 14 and amply testify to the efficiency and accuracy of this method of estimation.

Parameter estimates for the two models are summarised in Table 15. Also shown are the estimates for the basic model. Each of the entries is an average over all Ss in each of the two conditions. For the MTI and MRD models the number of solutions obtained with ZXMARQ is given, (the maximum is eight), and also the estimates of σ_C^2 and σ_D^2 obtained using the Equations 12 and 14 respectively.

Goodness of fit of the MTI and MRD models may be compared in terms of the summed squared deviations (SSD) of $\gamma_I(k)$ from $G_I(k)$ over all ten values of T. For all Ss in the Fixed Condition, SSD from the MRD model was smaller than for the MTI model. In the Random Condition SSD was larger for the MRD model only in the case of EL, but nearly equal for the two models in the case of JS, (see Table 16). The reduction in SSD over all Ss and both conditions achieved by the MRD model as a percentage of the SSD of the MTI model was 42.4%, (The corresponding reduction over the basic model was 56.1%).

Thus of the two models, MRD is the more satisfactory in accounting for the $G_I(k)$. If the true state of nature were represented by the MRD

Table 13

Comparison of ZXMARQ solution parameter estimates for $\gamma_I(k)$ under the MTI model with the true values of the free parameters. Initial "guess" values for $(\phi, \sigma_x^2, \sigma_D^2)$ were (0.0, 15.0, 5.0).

True Value			ZXMARQ solution			No. of iterations
ϕ	σ_x^2	σ_D^2	$\hat{\phi}$	$\hat{\sigma}_x^2$	$\hat{\sigma}_D^2$	
- .8	5.0	35.0	- .8000	5.0000	35.0000	10
- .4	45.0	65.0	- .4017	44.5101	65.2489	8
.0	85.0	20.0	- .0000	85.0044	19.9978	12
.4	125.0	5.0	.4000	124.9998	5.0002	5
.8	165.0	50.0	.8000	164.9974	49.9987	10

Table 14

Comparison of ZXMARQ solution parameter estimates for $\gamma_I(k)$ under the MRD model with the true values of the free parameters. Initial "guess" values for $(\Theta, \sigma_C^2, \sigma_y^2)$ were (0.05, 15.0, 5.0).

True value			ZXMARQ solution			No. of iterations
Θ	σ_C^2	σ_y^2	$\hat{\Theta}$	$\hat{\sigma}_C^2$	$\hat{\sigma}_y^2$	
-.8	5.0	35.0	-.8000	5.0012	34.9996	78
-.4	45.0	65.0	-.4000	44.9989	65.0013	6
.0	85.0	20.0	-.0000	85.0000	20.0000	7
.4	125.0	5.0	-.4000	124.9967	5.0004	6
.8	165.0	50.0	.8000	165.0034	50.0011	6

Table 15

Averaged parameter estimates for the basic tandem process model, the MTI model, and the MRD model.

	$\bar{I}$									
	214.5	247.7	278.5	306.6	337.5	368.5	399.5	430.9	461.6	494.6
S_C^2	105.5	121.2	129.2	147.2	220.6	271.7	282.3	328.4	363.5	411.3
S_D^2	27.3	34.5	54.6	53.3	25.9	27.5	27.1	20.3	27.8	40.7
$\hat{\phi}$	.14	.12	.02	.14	.24	.22	.22	.15	.14	.12
$\hat{\sigma}_x^2$	89.2	134.9	175.2	151.7	141.6	206.7	209.1	255.7	309.9	348.1
$\hat{\sigma}_C^2$	91.0	136.8	175.3	154.7	150.3	217.2	219.7	261.6	316.1	353.2
$\hat{\sigma}_D^2$	28.8	21.3	22.4	43.6	59.7	55.3	59.0	51.8	51.0	68.7
N	8	7	6	7	8	8	8	8	6	7
$\hat{\theta}$	- .46	- .18	- .29	- .54	- .27	- .26	- .21	- .21	- .27	- .06
$\hat{\sigma}_C^2$	114.0	134.8	154.8	175.4	225.7	245.9	240.2	328.6	375.4	383.8
$\hat{\sigma}_y^2$	18.6	20.2	27.7	26.3	19.0	53.6	68.5	18.9	16.0	67.2
$\hat{\sigma}_D^2$	23.6	20.9	30.2	37.1	20.5	57.5	71.7	19.8	17.3	67.4
N	8	6	7	8	8	7	8	7	4	7

Table 16

Total over T of the summed squared deviations (SSD) of $G_I(k)$ from zero for k equal 0 through through 5 for each S and SSD from the best fit theoretical functions for each of the three models, (x 10^3).

Subject	Condition	Total	Model		
			Basic	MTI	MRD
EL	Fixed	839.6	7.7	4.2	3.1
	Random	498.3	6.0	3.3	4.2
SC	Fixed	2500.4	23.4	17.0	11.5
	Random	3228.6	28.3	16.1	9.9
BB	Fixed	696.9	4.0	2.9	2.1
	Random	871.8	6.4	4.2	2.6
JS	Fixed	607.9	7.2	3.8	2.2
	Random	574.0	2.4	1.9	1.9

model, the deviations of the $G_I(k)$ from the $\gamma_I(k)$ should have zero expectation. The average deviations are given in Table 17. It can be seen from the 95% confidence intervals that only the deviation at $k = 3$ is significantly different from zero, which is a considerable improvement over the finding for the basic tandem process model as summarised in Table 12. A corresponding analysis carried out for the MTI model indicates significant differences at lags three and five.

Estimates of σ_C^2 and σ_D^2 based on the MRD model are plotted in Figure 22, together with the corresponding estimates for the basic model, (data from Table 15). For both models, the S_C^2 versus $\bar{I}$ relation is adequately fit by a linear function, (see Table 18). The slope estimates for the two models are not significantly different. While there is no change in the level of S_D^2, in the MRD model there is a shift in the peak to larger values of $\bar{I}$, relative to the basic model.

Discussion.

In the preceding analysis, the presence of consistent deviations from the expected zero-valued $G_I(k)$ for $k > 1$ indicates the need for modification of the basic tandem process model which assumes stochastic independence in both timekeeper intervals and response delays. A comparison of two models, each assuming Markovian dependence in one of the processes, favours the MRD model implying that successive response delays are not independent but may be represented as in Equation 14. The correlation between successive response delays is found to be negative at all values of T in the range 220 through 490 msec. Why might this be the case? The response process is assumed to be responsible for generating

Table 17

Overall average deviation of $G_I(k)$ from the theoretical functions ($\overline{\Delta G_I(k)}$) of the MTI and MRD models.

		Lag, k					
		0	1	2	3	4	5
MTI	$\overline{\Delta G_I(k)}$	-0.1	0.7	-1.2	-5.3*	-0.7	-5.6*
	2SEs	0.6	0.8	3.0	2.3	3.1	2.4
MRD	$\overline{\Delta G_I(k)}$	0.0	0.5	1.7	3.2*	-1.6	-2.5
	2SEs	0.0	0.7	2.2	2.0	2.9	2.6

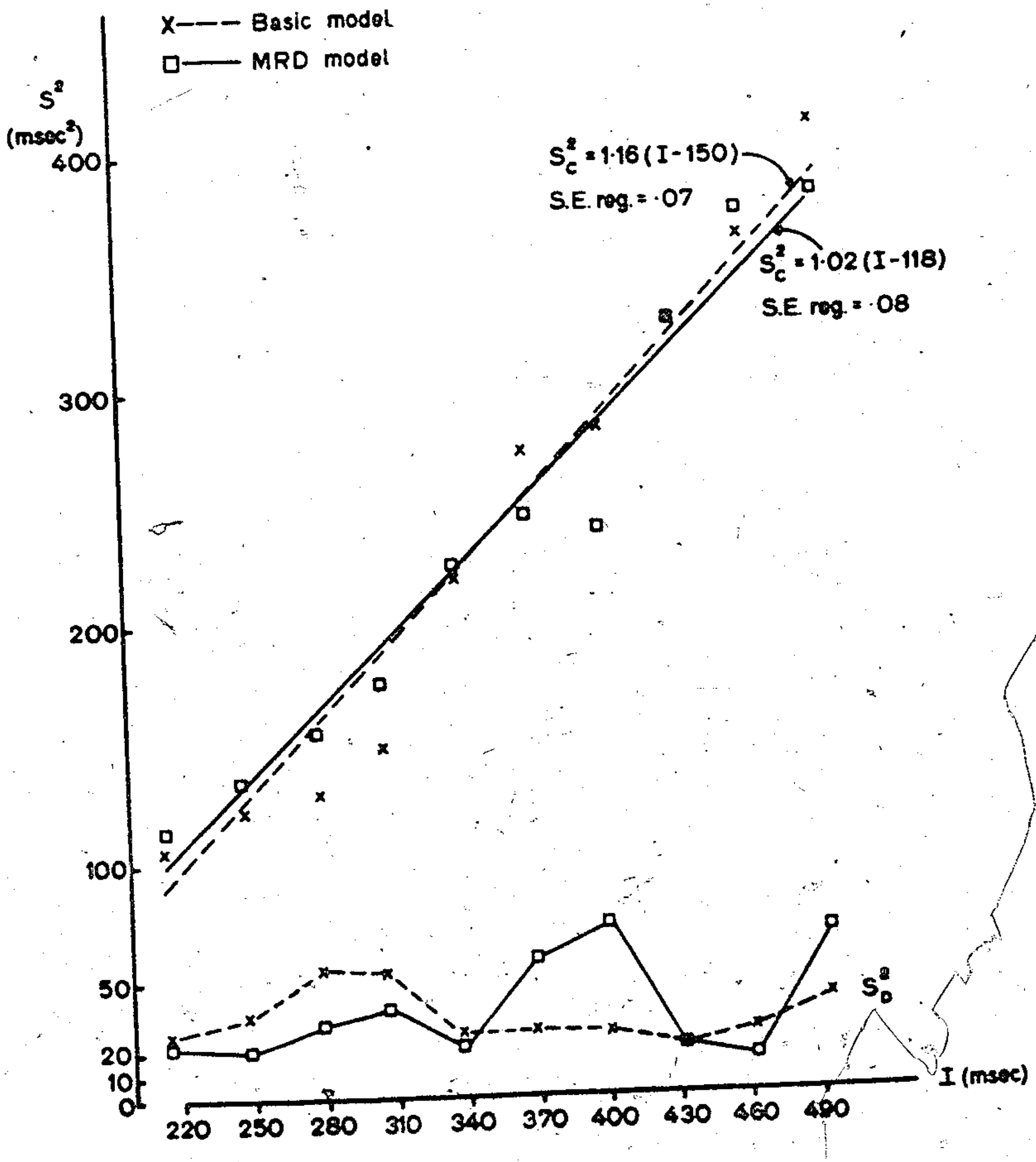

Figure 22: S_C^2 and S_D^2 versus $\bar{I}$; averaged data over both conditions, Experiment 2, analysed according to the basic tandem process model and the MRD model.

Table 18

Summary of ANOVA for linear and quadratic polynomials for the relation between S_C^2 and $\bar{I}$ estimated under the basic tandem process and MRD models.

Model	Linear term		Quadratic term	
	Mean square error	F(1,8)	Mean square error	F(1,7)
basic	388.45	271.67*	324.98	2.56
MRD	443.42	184.66*	361.67	2.81

a response when triggered by the timekeeper. However after each response it will be necessary to return the response system to a state in which it will be ready for the next trigger pulse originating with the timekeeper. Once this state is reached it must be maintained in readiness until the trigger pulse occurs. Suppose that such readiness declines with time. Then the longer the delay before the next trigger $(C_j - D_{j-1})$ relative to the average for a given response rate, the longer will be the ensuing response delay (D_j). If the previous response delay was shorter than average for the response rate this would result, on average, in a longer interval before the next trigger pulse and thus a longer than average ensuing response delay. It is interesting to note that this interpretation suggests that there may be dependence of one response delay not only on the previous response delay, as assumed in the MRD model, but also on the previous timekeeper interval. Subsequent investigation might profit from an analysis based on the following model which is somewhat more complex than either of the generalisations of the basic tandem process model treated above:

$$d_j = \Psi\,(c_j - d_{j-1}) + w_j \qquad -1 < \Psi < +1,$$

with the customary definition of the random variable, W. It explicitly incorporates the idea that what is important in determining the next response delay deviation about μ_D is the interval between the previous response and the next trigger pulse, or rather, the deviation from the average value of that interval.

For the purposes of drawing conclusions about the two processes of timekeeping and response generation on the basis of the present series of experiments, the most pertinent findings of the preceding analysis is just how little changed are the estimates of σ_C^2 and σ_D^2 given by the MRD model. This is really a reflection of the smallness of the $G_I(k)$ for $k > 1$, since it is this part of the function which is not encompassed by the basic model. The basic model achieves a total reduction in SSD of 99.13% against a corresponding reduction of 99.62% achieved by the MRD model where total reduction refers to a comparison with the SSD of $G_I(k)$ for lags zero through five. Since the characteristics of interest are well-displayed by the basic tandem process model analysis, earlier conclusions based on these estimates do not require revision.

Conclusions

Under certain conditions response timing may be controlled by a timekeeper whose stochastic properties are to be inferred from a study of the intervals between responses. If so, it is important to take explicit account of variance in the efferent delay subsequent to the initiation of each response by the timekeeper. However intervals between repetitive responses could be maintained by a reflex chaining mechanism not involving any timekeeping as such. In the Introduction the latter model and a tandem process model, which assumes a timekeeper to be operating independently of the actual responses, are compared. The sequential dependence structure of interresponse interval (I) data collected in a repetitive response paradigm are shown to support the tandem process model. However, there is reason to believe that successive response delays are negatively correlated. Differences between estimates of timekeeper and response delay variances as a function of the standard interval (T) are very small for the tandem process model and a Markovian response delay model which incorporates the assumption of dependence between successive response delays. As a first approximation it is suggested that the former model is quite adequate for the purposes of characterising the important properties of the variances of both of the processes.

The main finding for the characteristics of the component process variances is that, while estimates of the timekeeper variance (S_C^2) increase linearly with $\overline{I}$, estimates of response delay variance (S_D^2) are approximately constant for a given type of response. Extrapolating, this suggests that, at increasingly long I, S_D^2 would become negligible relative to S_C^2. In that case the correction for response delay variance afforded by the model when using interresponse interval variance to estimate timekeeper variance at long I would be unnecessary.

The fact that variable response delays will be included in observed RT distributions means that the latter are not appropriate as estimators of the signal detection stage latency distribution. If specific assumptions were made about the latency distribution of the efferent processes, the latency distribution of the remaining process could be determined by deconvolution. Such an approach is discussed by Green (1971). The difficulty exists in initially specifying any characteristics of the efferent process. In this thesis a means of estimating the variance of response delays has been given. However the estimates have been shown to depend on the response movement being used, and so it would be preferable to incorporate an RT task within the sequential response task if it is desired to relate S_D^2 to RT.

In the Introduction it was pointed out that in the case of previous data on the timing of responses, accounts in which interresponse interval variance is attributed entirely to the response delays could not be ruled out. However, in the present case such interpretations may be rejected since estimates of the timekeeper variance were found to be consistently greater than zero. For duration discrimination, a number of studies have supported simple stochastic accounts of the psychological timekeeper. The linearity of increase of S_C^2 with $\bar{I}$ in the present work is strong support for models in which it is assumed that waiting takes place for some count of events to be attained, where the interevent delays are randomly distributed. The fact that the relation between S_C^2 and $\bar{I}$ yields nonzero intercepts implies that there is some part of each timekeeper interval that is not based on the waiting time. This could be a processing delay, associated with initiating the waiting process. For example, it might be necessary to reset a cumulative event counter before counting can begin for the generation of the next interval.

In reporting the experimental results, estimates of the rate of occurrence of the events which are counted have been given assuming the events are from a Poisson source, with interevent delays given by the exponential distribution. But in the context of response timing such an assumption is not necessary. Any distribution of interevent delays would predict a linear increasing relation between the mean and variance of waiting times provided the successive delays were independent and identically distributed. Treisman (1963) has discussed a model for the psychological timekeeper based on the counting of events from a pulse source with identically distributed interpulse delays without specifying the nature of their distribution. He suggested that within time periods of a few seconds, successive interpulse delays are highly correlated in order to account for the curvilinear relation that he found between timekeeper mean and variance. The present experiments, however, reject curvilinearity in favour of linearity in describing this relation. Both findings may be incorporated within accounts of psychological timekeeping based on the waiting time to attain a given number (n') of random event occurrences. In the Introduction it was pointed out that variability in the perceived standard used by S in the generation of each interval might well be present in the paradigm used by Treisman. Such variability would be compounded with the variance in waiting times associated with n', resulting in a curvilinear relation between the mean and variance of response intervals as estimated by

Treisman. Linearity would only be expected if there were no variance in n' for a given value of T. The sequential response paradigm requires S to make many reproductions of a single value of n', set up in the synchronisation phase. Even if n' were not the same over different sequences which used the same value of T for synchronisation, variance in n' would only be a random "noise" factor. This is because timing variance estimates are based on averages over sequences of within sequence estimates.

A summary of various event rate estimates assuming the source to be Poisson is given in Table 19. The results of the present experiments are within the range of estimates based on psychophysical procedures. The similarity of the event rate estimates suggest that the same source might be used for time perception as for response timing, that is, $\lambda \equiv \lambda'$. Consider an experiment in which S is presented on a given trial with one of two intervals, T or T + ΔT, for judgment as "short" or "long". Under the Poisson event counting model it would typically be assumed that a count (n) associated with the interval is compared with a criterion, set ideally at $\lambda(T + \Delta T/2)$ if the two intervals are equiprobable. If the criterion is exceeded, S would respond "long" and errors would be assumed to arise as a result of the stochastic nature of n. With these assumptions relating measures on S's decision axis to responses, one may estimate the variance of n associated with T on the basis of responding "short" conditional on the interval presented. However, this datum does not discriminate between variance in n and variance which might be present in the criterion. The finding that performance deteriorates at longer T might be due to increasing variance in the criterion and not to changes in variance in the decision axis measure. Such an interpretation arises

Table 19

Summary of Poisson event rate estimates

Source	Mean event rate estimate (x 10^3 events counts/sec	Paradigm	T (msec)	Comments
Creelman (1962)	5.8	2AFC	40→1500	Noise bursts, used 3-parameter formulation of Poisson counter model.
Abel (1972a)	0.1 to 1.3	2AFC	0.2→ 960	Noise and tone bursts, no effect of signal parameters, λ estimates constant up to 100 msec.
Abel (1972b)	0.1 to 1.3	2AFC	0.6→ 640	Temporal gaps, parameters of noise bursts marking intervals affected λ estimates, which were constant from 10 to 160 msec.
Kinchla (1972)	0.2	Single stimulus recognition	1000 → 8000	100 Hz tones.
Wing (this thesis)	5.0	Tapping	170→ 350	Experiment 1.
	0.8, 0.9		220→ 490	Experiment 2.

if it is assumed that the response timing operation of interval generation is involved in the judgment of stimulus duration.

Suppose that the criterion is generated by S as a real time interval with expected value T + $\Delta T/2$ on the basis of a stochastic wait. If it begins contemporaneously with the stimulus interval, the judgment of the stimulus as "long" or "short" could be based on a temporal order judgment, (Kristofferson, 1973). For example, if the criterion interval terminates prior to the stimulus interval, the stimulus would be judged "long". There would probably be some variability in the "internal" interval corresponding to the stimulus as a result of variance in arrival latencies. However, criterion variance which would be expected to be a function of T would arise from the stochastic nature of the timing process generating the criterion. Thus it is possible that the timekeeping mechanism which generates time intervals examined in this thesis underlies duration perception in some situations.

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Appendix A: Trend data; Experiments 1, 2 and 3.

The entries in each of the Tables A1, A2, A3 for Experiments 1, 2 and 3 respectively were calculated in the following manner. For each sequence the means of the first 15 and the last 15 Is were calculated and the latter subtracted from the former. The differences were averaged over all sequences in a given condition to give $\overline{\Delta I}$. Also given are two standard errors about the mean, $\overline{\Delta I}$, and, for Experiment 1, the number of sequences entering into the estimates. For Experiments 2 and 3 the number of sequences was fifty in all cases.

Table A1

		T								
		170[2]	180	200	220	220[2]	250	270[2]	300	350
AW	$\overline{\Delta I}$	- .39	- .04	- .10	- .52	.01	-1.03	.05	-1.92	-2.40
	2SEs	.39	.28	.23	.30	.31	.25	.33	.33	.40
	N	182	215	219	217	216	217	219	217	216
JW	$\overline{\Delta I}$	-1.33	- .79	-2.39	-2.28	-1.61	-2.34	-1.10	- .32	- .06
	2SEs	.39	.27	.25	.31	.31	.25	.35	.32	.37
	N	198	197	214	161	213	216	218	219	206
IT	$\overline{\Delta I}$	- .68	- .93	.17	.13	- .20	-1.02	- .39	- .83	.77
	2SEs	.36	.31	.40	.38	.38	.39	.47	.56	.61
	N	215	219	216	215	217	220	216	212	207
MF	$\overline{\Delta I}$	- .15	-1.23	- .77	-2.10	- .92	-1.3	- .17	- .08	- .54
	2SEs	.39	.29	.27	.29	.32	.30	.34	.44	.48
	N	205	212	218	209	220	214	219	206	203

Table A2

			T								
		220	250	280	310	340	370	400	430	460	490
EL fixed	$\overline{\Delta I}$	- .63	- .35	- .68	- .26	.91	-4.72	-2.58	-2.67	- .93	- .32
	2SEs	1.09	1.11	1.71	1.29	1.86	1.96	2.68	2.49	2.63	2.14
random	$\overline{\Delta I}$	-4.73	-3.67	-1.08	-2.95	-3.14	-3.67	- .49	1.27	2.09	3.69
	2SEs	1.25	1.85	1.50	1.75	2.11	2.31	2.23	1.89	2.46	2.76
SC fixed	$\overline{\Delta I}$	.69	1.88	- .98	2.49	-5.34	1.0	-3.54	-3.07	-0.39	0.15
	2SEs	1.26	1.79	1.81	1.63	2.06	1.86	2.22	2.41	2.36	2.47
random	$\overline{\Delta I}$	3.2	.68	2.06	.97	2.22	1.65	1.52	-2.57	.93	-1.39
	2SEs	1.28	1.56	2.18	2.03	2.46	2.69	2.64	3.26	3.39	4.20
BB fixed	$\overline{\Delta I}$	3.34	2.09	1.84	-2.14	- .86	-2.01	- .83	-3.24	-4.92	-3.48
	2SEs	1.44	1.31	1.29	1.43	1.87	1.76	1.96	1.93	1.89	2.40
random	$\overline{\Delta I}$	2.83	-1.05	-1.40	-1.58	-3.75	-2.21	.23	-2.61	- .66	-2.37
	2SEs	1.31	1.42	1.75	1.56	1.77	2.21	2.11	2.37	2.10	2.74
JS fixed	$\overline{\Delta I}$	2.69	- .78	1.98	1.02	1.70	2.51	-2.15	-3.33	-1.88	-3.43
	2SEs	1.03	1.35	1.24	1.21	1.80	1.83	1.84	2.58	2.63	2.17
random	$\overline{\Delta I}$	2.35	-1.45	- .36	- .88	- .41	- .17	-1.25	- .89	-3.59	-5.48
	2SEs	1.03	1.49	1.52	1.40	1.81	1.98	1.74	2.34	2.10	2.74

Table A3

		A		B		C	
		T=250	T=350	T=250	T=350	T=250	T=350
EL	$\overline{\Delta I}$	- .03	1.66	.19	4.64	.61	2.54
	2SEs	1.11	1.71	.88	1.30	1.31	1.49
SC	$\overline{\Delta I}$	- .59	2.75	1.76	3.09	1.27	3.30
	2SEs	1.68	2.22	.85	1.22	1.16	1.47
BB	$\overline{\Delta I}$	-1.00	-1.81	.74	-.10	-1.45	-.92
	2SEs	1.33	1.42	.91	1.35	1.31	1.49
JS	$\overline{\Delta I}$	-1.13	.73	1.01	1.31	- .26	1.42
	2SES	.82	1.57	.91	1.44	.80	1.17
AW	$\overline{\Delta I}$	1.75	3.33	1.02	2.63	.13	3.03
	2SEs	1.05	1.62	1.13	1.42	1.06	1.58
JW	$\overline{\Delta I}$	- .87	-1.91	- .25	-1.37	-1.86	-2.64
	2SEs	.94	1.04	.76	.99	.70	1.07

Appendix B: $\bar{I}$, S_C^2, S_D^2; Experiments 1, 2 and 3

Estimates of the timekeeper and response delay variances and the mean interresponse interval are given for Experiment 1 in Table B1 and Experiment 2 in Tables B2 (EL), B3 (SC), B4 (BB), B5 (JS). These data are plotted in Figures 9 through 12 for Experiment 1 and in Figures 15 through 18 for Experiment 2. The estimates obtained in Experiment 3 are given in Table B6.

Table B1

		T								
		170[2]	180	200	220	220[2]	250	270[2]	300	350
AW	$\bar{I}$	173.0	180.6	201.6	221.1	221.0	253.7	271.7	306.5	354.7
	S_C^2	43.8	15.3	19.4	34.5	34.5	31.9	52.3	39.8	74.3
	S_D^2	47.2	30.1	17.2	20.0	20.3	10.1	24.1	18.2	35.1
JW	$\bar{I}$	171.8	179.8	204.2	223.0	224.0	254.3	274.5	297.7	346.1
	S_C^2	29.1	14.4	22.8	24.1	25.5	20.0	37.0	30.6	45.5
	S_D^2	29.1	14.5	5.5	9.7	8.0	8.9	18.3	16.4	23.8
IT	$\bar{I}$	177.4	183.4	199.9	221.8	227.9	255.1	276.4	301.2	348.4
	S_C^2	31.8	22.8	33.2	36.1	47.6	41.9	58.6	63.5	88.9
	S_D^2	9.5	11.6	23.6	8.5	7.6	6.9	10.2	14.2	9.3
MF	$\bar{I}$	169.7	182.2	200.4	227.2	223.7	251.8	271.3	300.0	349.1
	S_C^2	41.1	23.1	23.8	23.4	37.3	28.8	33.2	32.3	59.0
	S_D^2	1.5	12.1	13.3	9.5	6.3	8.7	14.9	30.0	28.8

Table B2

	T									
	220	250	280	310	340	370	400	430	460	490
Fixed $\bar{I}$	216.1	247.6	275.7	302.8	329.9	376.9	396.8	435.0	454.7	496.3
S_C^2	71.5	80.4	107.1	89.0	252.3	223.8	313.7	313.1	384.9	301.9
S_D^2	43.4	39.1	62.3	65.4	16.0	52.6	4.3	21.8	- .25	7.2
Random $\bar{I}$	218.9	247.9	277.0	304.5	332.3	363.8	387.4	416.3	449.4	474.9
S_C^2	97.6	118.2	94.9	138.0	198.3	207.8	205.7	229.9	249.5	316.1
S_D^2	26.7	17.7	26.0	15.3	11.6	8.1	10.2	5.4	13.8	6.5

Table B3

	T									
	220	250	280	310	340	370	400	430	460	490
Fixed $\bar{I}$	213.3	240.1	279.9	301.8	346.3	364.5	412.5	439.4	476.9	505.1
s_C^2	183.6	134.8	98.8	107.8	330.7	334.1	344.2	487.2	493.5	542.2
s_D^2	43.7	105.1	147.8	203.0	26.1	58.0	30.5	33.3	51.7	113.33
Random $\bar{I}$	211.6	244.6	279.5	309.3	335.7	366.3	399.7	436.4	469.0	505.0
s_C^2	54.0	172.8	183.5	246.0	268.2	513.4	571.4	529.4	686.8	764.6
s_D^2	59.7	98.4	169.5	75.0	50.2	49.1	49.0	20.1	16.5	49.3

Table B4

		T									
		220	250	280	310	340	370	400	430	460	490
Fixed	$\bar{I}$	213.5	250.4	276.5	309.1	334.5	373.2	399.6	433.1	459.4	491.3
	s_C^2	159.7	115.9	120.9	165.2	144.7	219.2	197.2	243.0	300.7	381.3
	s_D^2	3.8	7.0	23.4	13.1	31.7	- 2.3	33.1	6.6	31.2	44.5
Random	$\bar{I}$	215.3	253.2	286.3	316.2	347.4	373.1	400.8	427.1	456.4	488.7
	s_C^2	110.1	102.9	152.3	174.1	208.5	228.5	244.1	280.8	294.4	401.2
	s_D^2	11.1	18.8	10.3	24.4	16.9	24.2	19.4	22.5	48.8	56.7

Table B5

		T									
		220	250	280	310	340	370	400	430	460	490
Fixed	$\bar{I}$	211.9	247.3	274.9	302.0	337.5	364.0	400.9	430.0	465.3	496.6
	s_C^2	85.2	116.0	121.0	91.3	172.5	190.1	169.8	292.5	254.0	251.3
	s_D^2	20.8	1.6	6.3	23.0	38.8	22.7	39.2	24.0	52.9	32.2
Random	$\bar{I}$	215.7	250.2	278.6	306.9	336.5	366.4	398.4	430.3	461.8	498.7
	s_C^2	82.4	128.4	155.1	166.3	189.4	256.6	212.6	251.4	244.5	331.9
	s_D^2	9.2	- 11.8	- 8.4	7.4	15.7	8.0	31.3	28.5	10.0	15.6

Table B6

		A			B			C		
	T	S_C^2	S_D^2	$\bar{I}$	S_C^2	S_D^2	$\bar{I}$	S_C^2	S_D^2	$\bar{I}$
EL	250	61.8	4.8	244.1	75.7	48.6	241.5	57.0	24.9	246.6
	350	137.0	10.9	337.9	137.7	18.8	240.3	116.2	39.0	345.7
SC	250	33.9	16.6	245.6	11.2	118.0	246.6	90.3	121.8	247.3
	350	106.7	38.1	342.6	200.2	39.2	339.4	288.3	33.8	343.8
BB	250	48.2	- 1.1	247.3	105.8	18.9	249.2	130.5	13.6	251.0
	350	125.5	- 3.9	344.7	135.0	29.5	349.2	166.8	12.4	348.8
JS	250	32.8	30.6	248.6	52.5	20.1	249.9	64.8	20.5	253.1
	350	111.1	40.1	346.5	88.2	24.3	345.9	119.8	62.4	351.0
AW	250	88.2	70.7	245.9	93.0	39.6	249.1	89.1	104.6	249.2
	350	206.7	103.9	333.4	174.7	105.5	336.1	215.2	103.3	333.0
JW	250	43.6	20.7	247.7	31.0	9.1	251.3	40.5	60.8	252.2
	350	77.6	48.7	350.3	55.5	27.8	352.9	60.3	67.5	349.7

Appendix C: Subject data.

Subjects for each experiment were selected on the basis of the first four applicants to advertisements posted in the Psychology Department at McMaster University. All subjects were right handed. They were paid for their services at the rate of $2 per session. The following table gives information on age and sex:

Experiment	Subject	Age	Sex
1	AW	25	M
	JW	25	F
	IT	27	M
	MF	25	F
2	EL	23	F
	SC	22	F
	BB	26	F
	JS	24	M.