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DURATION DISCRIMINATION OF INTERMODAL INTERVALS

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By

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A Thesis

Submitted to the Faculty of Graduate Studies

in Partial Fulfilment of the Requirements

for the Degree

Doctor of Philosophy

McMaster University

(November) 1975

DOCTOR OF PHILOSOPHY (1975)
(Psychology)

McMASTER UNIVERSITY
Hamilton, Ontario

TITLE: Duration discrimination of intermodal intervals

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NUMBER OF PAGES: x, 170

ABSTRACT

This research is an extensive investigation of the discriminability of brief intermodal temporal intervals. For intervals of less than 700msec., the level of performance is lower than that of intramodal intervals. In that range two psychophysical methods, Many-to-Few and Single Stimulus, give very different discrimination functions. However, the duration of the markers and the type of intermodal intervals are found not to be effective variables. An empirical relationship describing SD/DT_{75} as constant is shown to hold for a number of intra and intermodal psychometric functions.

Two quantitative models developed to account for intramodal duration discrimination, describe very well intermodal discrimination in two experiments. Although none can be rejected, the onset-offset model is prefered because it represents better the totality of the results in this research. Finally, response latencies clearly indicate the operation of a real-time criterion mechanism in duration discrimination.

It is concluded that duration discrimination is under the control of a single central timekeeper.

ACKNOWLEDGEMENTS

I wish to express my gratitude to Dr. A.B. Kristofferson for his patient guidance, and continuous support in the realisation of this work. I thank him very much for having introduced me to quantitative psychophysics.

I also wish to thank Dr. Lorraine Allan for numerous discussions about my work.

I also thank fellow students Ramona Carbotte, Allan Wing, Richard Heath, David Asher. We shared the frustrations and satisfactions inherent to our common interest in research.

My thanks also go to Cy Dixon who patiently took care of the equipment, and to Michael Bishop for his help in running the experiments and careful preparation of the drawings in the thesis.

I dedicate this work to my wife Marie and to Julie and Vincent, my children.

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I. INTRODUCTION

1.1 General statement of the problem.

The assessment of the duration of a temporal interval has to be performed through the observation of a given process whose state varies reliably in time. This is true of psychological as well as physical measurement. When a human observer (O) is required to assess the duration of an interval defined by two successive external events m_1 and m_2, his assessment will then be a function of variations in the state of some internal process, I. Furthermore, it is a common conception that his ability to discriminate between two such intervals of physical duration d_o and d_1, will depend on those intervals producing discriminable states $d_o(I)$ and $d_1(I)$.

The identification of a mechanism responsible for the assessment of the temporal extent of a stimulus by a human observer has proved to be a very difficult task. Most authors, as pointed out by Michon (1967a), have proposed the existence of some internal timing device or "clock" whose nature has been taken to be anything from heart rate and cerebral alpha rhythm, to attention and neural pulse counting. These processes are assumed to operate only on the temporal dimension of the stimulation whose duration is to be evaluated and not on the total content or some other aspect of its sensory input. However, that very same assumption has been strongly questionned by many authors; Fraisse (1967) and Ornstein (1970) amongst others, consider I as being dependent on the total sensory input of the stimulus and its memory trace rather than on the activity of a so called "time sense" or clock.

This question of dependence or independence of human duration processing from non-temporal aspects of sensory input has been one of the most enduring problems in the field of time perception. As early as 1891, Nichols concluded that the major reason for the state of confusion prevailing in the research on duration was linked to the difficulty of isolating a "time sense" independent of the total content of sensory input. More than half a century later, Creelman (1962) reports: ".... this question has not yet been resolved..".

Allan & Kristofferson (1974a) reviewed recent evidence that brings some support to the assumption of independence of duration processing from non-temporal stimulus information, namely the energy content of the intervals to be discriminated. However, there always remains the possibility of complex sensory activity providing information with regard to the temporal extent of an interval. It had been proposed (Abel,1972a) that using empty intervals marked by two pulses might obviate the problem of energy content carrying temporal information. But, even in that case, modality specific sensory interactions are likely to occur and possibly interact with a central timing system. That eventuality could be greatly reduced by having intervals defined by intermodal events i.e. events occuring in different sensory modalities. Indeed, a temporal interval bounded by a light flash and a brief tone is less likely to allow for direct sensory interactions to happen during the interval. Thus, the performance of an O in a situation of duration discrimination of such intervals is likely to be mainly dependent on the characteristics of an internal timing device operating on the temporal information content of the intervals.

Then, obtaining information pertaining to such an experimental situation could be of definite value for the understanding of human duration information processing. Thus, the aim of the present thesis will be to conduct an extensive study of duration discrimination of empty intervals marked by the offset of a visual signal and the onset of an auditory one. We shall refer from now on to such a temporal pattern as an intermodal interval. In the present state of the research only a short report (Rousseau & Kristofferson,1973) is available on intermodal duration discrimination. Actually, that study was part of the present programme of research and has been summarized for publication. It will be reported as exp. 1 in the present thesis, for sake of continuity and with a much more detailed analysis than in its published form.

A major restriction will be imposed on the scope of the present work having to do with the range of durations to be studied:the observers will be presented with brief intervals of duration in the range of .1 to 3sec. Indeed, it has been stated (Ornstein,1970;Fraisse,1967;Michon,1967,a,b;Carbotte,1974) that different mechanisms are likely to be operating at different ranges of duration. Ornstein (1970) and Michon (1967) following Fraisse (1967) report that different mechanisms would be processing durations shorter and longer than 2 to 5sec. Moreover, most quantitative models of duration discrimination (Creelman,1961;Allan,Kristofferson & Wiens,1970; McKee,Allan & Kristofferson,1970;Carbotte,1974) have concentrated on brief durations, shorter than 2sec. Thus, the isolation of the characteristics of an internal process specific to duration processing is very likely to be facilitated by limiting the present investigation to a comparable range of durations.

1.2 Temporal order and successiveness discrimination.

There is currently little evidence available on the discrimination of duration of intermodal intervals. However, there exists a large body of information that may pertain to the problem coming from tasks where the Os have to process intervals of null or near zero duration. The situations, dealing with the question of temporal resolution power of a human observer can be partitioned into two major classes:1) task where the Os have to report on the successiveness or simultaneity of two events (successiveness discrimination); 2) tasks in which the Os are required to tell the order of occurence of successive signals (temporal order judgement, TOJ). Much in the same manner as for duration discrimination, there have been arguments concerning the nature of one or many mechanisms that could account for the performance of Os in such tasks. In the following review of the literature on temporal order and successiveness discrimination, we will try to ascertain the value of the rationnale of the present work as developed in the previous section. That is, we will seek to evaluate the importance of the use of intermodal signals for specifying the operating characteristics of an internal timing device independent of non-temporal information present in a given temporal pattern.

Hirsh and Sherrick (1961) obtained TOJ for pairs of intramodal and intermodal pulsed signals. They used auditory, visual and tactile signals. Each of the three intramodal conditions and the intermodal one were run separately. The result was somewhat surprising; in all four conditions, the temporal interval between the signals required for the Os to correctly report the order of presentation in 75% of the cases (DT_{75}) turned out to be constant around 20msec. Thus, the existence of a common DT_{75} value for temporal order of any pair of signals led Hirsh & Sherrick to propose the existence of a common temporal processing mechanism independent of periphal sensory interactions, i.e. a central processor.

That generalisation soon came under question on various grounds. First, in very similar testing conditions, Hirsh & Fraisse (1964) and Gengel & Hirsh (1970) report much higher DT_{75} ($\approx$60msec,) with intermodal pulsed signals. However, in both cases, the authors argued that the apparent lack of support for Hirsh & Sherrick (1961) was due to the use of highly experienced Os by the latter. Indeed, Gengel & Hirsh (1970) lowered the DT_{75} to 14msec. by providing their Os with a large amount of practice. So, while Hirsh & Fraisse (1964), Gengel & Hirsh (1970) do bring a qualification to Hirsh & Sherrick (1961), it does not affect their main reasoning.

However, much more serious were the claims that Hirsh

& Sherrick's results were dependent on the specific stimulus conditions present in their experimentation and that their interpretation of the results in terms of the existence of a common central temporal processor was not warranted. Indeed, Rutschman & Link (1964) report that the DT_{75} is increased to almost 50msec. when Os are required to judge the order of occurence of the onsets of a 10msec. tone and a 50msec. light. The importance of the duration of the signals to be ordered was further emphasised by the results of Oatley, Robinson & Scanlan (1969) in a task involving intramodal stimuli. Their Os had to give TOJ to stimuli whose onsets were displaced in time by DTmsec., and which terminated simultaneously after at least 2sec. In such a situation where all the temporal order information is contained in the signal onsets the DT_{75} was found to be around 60msec. Similar results are reported by Kristofferson (1967) in an intermodal successiveness discrimination task. A light and a tone were presented simultaneously and their offset could either be simultaneous, after a 2 sec. duration, or the tone offset could be delayed by DTmsec. on a given trial. DT_{75} for correct discrimination of offset successiveness was found to be 60msec. So, the existence of a single DT_{75} for temporal order judgements is far from being supported by the evidence. However, the fact that comparable manipulations in testing conditions induce similar results with intramodal or intermodal signals, still supports the assumption of a central processor mediating information about temporal order of events. Indeed, the very same line of thought led Efron (1970,1973) to propose the existence of a central centre for judgements of perceived simultaneity of onsets of intermodal and intramodal stimuli. In a typical situation, the O had to adjust the onset of a brief index stimulus to either the onset or the offset, according to the experimental condition, of a test stimulus whose duration could be varied at random over trials. In such a task, the Os showed a systematic error when adjusting the index stimulus onset to the test stimulus offset. The error is a slope 1 linear function of the test stimulus duration up to a critical point around 130msec. where it becomes a constant. Thus, the internal representation of intermodal and intramodal test stimulus is claimed to be of constant duration up to 130msec. Such results support the possibility that temporal organisation of stimuli is performed by a common central mechanism.

However, there are reports in which the temporal resolution power for intramodal signals is markedly superior to any value obtained with intermodal signals. Robinson (1967) obtained TOJ for luminous triangle and square. Under binocular presentation his results replicate Hirsh & Sherrick's (1961). However, for dichoptic stimulation the DT_{75} was less than 5msec. Thus, the existence of a constant DT_{75} for TOJ claimed by Hirsh & Sherrick is very likely to be dependent on specific experimental conditions. This possibility is further supported by many findings in the domain of audition. Green (1971) reports that TOJ for tones of different frequencies can yield DT_{75} of 5msec and as low as 6μsec. under certain conditions. Furthermore, Collyer (1971) showed that for successiveness discrimination of onset of response terminated tones of different frequencies DT_{75} was 6msec. Moreover, modifications in the size of the difference in frequency produced appreciable shifts in the value of the DT_{75}. Such results do suggest the existence of an action of sensory interactions on the judgement of temporal sequence of signals.

Actually, direct evidence of sensory interactions on the judgement providing cues for TOJ has been presented by Babkoff & Sutton (1963). Their Os were presented dichotically with equal energy clicks and had to identify the ear which was stimulated first. They reported a DT_{75} of 15 to 20msec., comparable to what Hirsh & Sherrick (1961) obtained under comparable conditions. However, they also required their Os to make judgements on the relative loudness of the clicks, at the same time as the TOJ were made. The results show that as DT is increased from 12 to 20msec. the probability of <u>equal</u> loudness judgements goes from 0 to 1.0 while that of a correct TOJ drops from 1.0 to .70. So, it is very likely that in the present case the TOJ were mediated partly by the end-result of sensory interactions between the clicks, namely the difference in loudness between the signals. Furthermore, such a result points out that similarity in performance in two experimental conditions can be by itself misleading and is not necessarily an indication of a common mechanism underlying both sets of results. Thus, this casts some doubts on the argumentation presented by Hirsh & Sherrick, and also Efron, which was based on the comparable level of performance obtained for intramodal and intermodal conditions of stimulation. So, while under certain circumstances it can be argued that the temporal resolution capacity of human observers is mediated by a central processor, it is evident that it is far from being the sole means of discriminating order or successiveness of sensory events. However, this is not to say that the evidence just reviewed rules out the existence of a central processor, but it does point out the importance of controlling for confounding variables when dealing with temporal order or successiveness judgements of intramodal signals.

In a recent review on the problem of temporal order judgement Sternberg & Knoll (1973) commented on the desirability of using intermodal signals to reduce the likelihood of sensory interactions, thus making the performance more likely to depend on the temporal characteristics of the stimuli to be ordered. Collyer (1974) reports evidence which supports Sternberg's position. In a situation similar to Collyer (1971) the Os were asked to discriminate the successiveness of onsets of response terminated stimuli. Three types of signal pairs were used; in a given pair, the stimuli could either be two tones of same frequency (ST), two tones of different frequency (DT) or a light and a tone (LT). The conditions were run in separate blocks of trials within a session. The values for DT_{75} were 6msec. in condition ST, 15msec, in DT and, 50msec, in LT, values which replicate those previously obtained in comparable situations. However, the main feature of the report is that the individual performances in condition LT could be very well accounted for by a quantitative model assuming that the O is using only the temporal information provided by the signals. On the other hand, the same model gave a poor fit for the performance in both intramodal conditions.

Thus, it appears that for intervals of null or near zero duration, the use of intermodal signals minimises the occurrence of sensory interactions, and therefore is likely to provide a more valid means of isolating the operating characteristics of a central timing mechanism. It could be argued that while this is the case when dealing with very brief temporal intervals the possibility of occurrence of intramodal sensory interactions could be reduced in situations involving longer durations, as is the case in duration discrimination. However, intermodal intervals would enable one to assume a central mechanism to process duration over a large range of durations without having to consider some other mechanism as being concurrently active in some part of the range as could be the case if sensory interactions would provide cues on the temporal extent of a given interval.

1.3 Duration discrimination of brief empty intervals.

In the present section we will first discuss the conditions under which intermodal duration discrimination could be assumed to be comparable to TOJ and successiveness discrimination conditions which have supported the rationnale developed in section 1.1. Then, we will proceed to describe systematically a duration discrimination task. Finally, we will review the evidence available on the effect of non-temporal stimulus variables on performance in duration discrimination of intramodal empty intervals.

1.3.1 The distinction between filled and empty intervals.

Since the inception of the psychophysics of duration, a distinction has been made between a filled interval of time marked by a continuous stimulus, and an empty interval defined by the gap between two stimuli. Recently, authors have agreed, from different points of view, on the conclusion that the distinction was of minimal value. Fraisse (1967) reports that the difference in performance between filled and empty intervals is not significant. Furthermore, Allan & Kristofferson (1974a) claim that the distinction is not of importance with regard to the elaboration of theoretical models of duration processing. However, we would like to argue that the filled vs empty intervals distinction is of importance when dealing with intermodal signals.

In section 1.1 intermodal intervals were defined as empty intervals bounded by stimuli presented to different sensory modalities. Moreover, it was shown through section 1.2 that for very brief durations, such intervals may provide a means of access to a central temporal processor. However, the mere use of intermodal signals in a duration discrimination task is not a sufficient condition to minimise the existence of non-temporal cues of sensory origin as one can argue from reports of studies performed with filled intermodal intervals. In some cases (Eijkman & Vendrik,1965; Tanner, Patton & Atkinson,1965) the O had to discriminate between auditory and visual intervals, whereas in others (Goldstone, Boardman & Lhamon,1959;Behar & Bevan,1961) an absolute rating of the perceived duration of heterogeneous stimuli was required. The crucial point in all these studies is that the stimulus defining a given temporal interval is always completely presented to a given sensory modality. So, while the comparison of durations is intermodal, the processing of any one interval is intramodal. Consequently, any specific sensory processing mechanism which could be operating with intramodal stimuli is still available to the O with intermodal filled intervals. Thus, the relevance of such work for the isolation of a central timing mechanism is at least doubtful and does not follow the reasoning developed in section 1.2.

Again, this is not to say that a central timing mechanism could not be operating in situations involving filled intermodal intervals. It is simply that in that case the logical limits imposed on the class of possible mechanisms by the experimental situation is not really different than for intramodal interval situations. On the contrary, intermodal intervals as defined in the present work are directly comparable to the intermodal stimulus situations presented in the preceding section.

1.3.2 Some methodological considerations.

Whilst we have hitherto used the term discrimination quite loosely we will now proceed to describe systematically the structure of a duration discrimination task. In such a task, a set D of n intervals of non-zero duration: $d_o, d_1, \ldots, d_i, d_n$, is arbitrarily partitioned into two subsets, D_s (short durations) and D_l (long durations), and the O's task is to tell apart elements of either set. Classically, the partitioning of the main set D has been done in two ways: type A) the short subset D_s contains only one element d_o which is called standard or base duration, and the n-1 remaining intervals in D: $d_1, d_2, \ldots, d_i, d_n$ form D_l and are called comparison stimuli. All the elements of D_l can be defined as $d_i = d_o + DT$; (or sometimes $d_o \pm DT$); type B) the main set D is partitioned into D_s and D_l by a criterion value which is not an element of D. That criterion, M.P. is arbitrarily defined as the mid-point value in real time, between the two elements from each subset being the closest from each another. Each element d_i of D can be described as d_i=M.P.±DT. Within either partitioning type, there are two basic methods of presenting the stimuli to the O on any trial. The choice of a given method determines the type of response required. In the single stimulus (SS) method, on any trial the O is presented with a single interval, d_i, and has to tell whether it is a member of D_s, by a response R_o and conversely, a member of D_l an R_l (long). In the two alternative forced choice method (2AFC) two intervals, one from each subset, are given sequentially to the O and his task is then to identify in which position, first, R_1, or second, R_2, the member of a given subset was presented. The classical method of constant stimuli is a 2AFC set up with a Type A partitioning. Recently, some experiments (e.g. Kristofferson 1973, Allan & Kristofferson, 1974b) have been performed with a method called "many-to-few" M.-F. which is a SS method with a Type B partitioning.

The principal means of representing the performance observed under any of the conditions described above is the psychometric function where some index of performance, say, the probability of a correct response P(c) is shown as a function of all d_i or DT. Furthermore, the keenness of the discrimination is commonly shown as the ratio of the DT_{75} over the base duration d_o or the mid-point criterion, DT_{75}/M.P. commonly referred to as the Weber ratio.

1.3.3 The effect of non-temporal stimulus variables on duration discrimination of empty intervals.

Unlike the situation encountered with TOJ and successiveness discrimination, very little is known concerning the importance of stimulus variables in gap duration discrimination. However, as pointed out by Allan & Kristofferson (1974a) the acquisition of precise information on the effect of stimulus variables is of importance for the development of quantitative models of duration processing. Indeed, as will be shown in the next section, all current quantitative models assume the temporal stimulus dimension as being the sole information used by an O in a duration discrimination situation.

Currently, the information concerning the influence of stimulus variables is mainly provided by studies in which the energy content of the markers has been manipulated. Abel (1972a) varied the duration and the intensity of gaussian noise burst markers over a range of gap durations from .63 to 640msec. Three conditions were run successively with the markers specified as follows: 1) 10msec. 85dB, 2) 300msec. 70dB, 3) 10msec. 70dB. The results show a constant superiority in performance over the whole range of durations for condition 1 by comparison with condition 3. However, certain features of the results call for caution with regard to the claim of an effect of marker intensity. For conditions 1 and 2 the data are pooled over 3 Os while for condition 3 over 2 Os only. Furthermore, no individual data or statistical measure of dispersion was provided. So, one is entitled to wonder on the relative importance of having dropped one O on the observed difference between conditions 1 and 3. Moreover, the overall level of performance is much lower than in previously reported comparable work (Blakely,1933;Kristofferson,1973; Carbotte & Kristofferson,1972). On the other hand, Carbotte & Kristofferson (1973) measured variations in P(c) as a function of different intensity levels of 2kHz 10msec. pure tone markers for base durations of: 50,150 and 250msec., and a constant 10msec DT. They used mainly two intensity levels: 61dB and 98dB. In such a situation where the difference in intensity between the experimental conditions (37dB) is much larger than that of Abel (1972a),hardly any difference in P(c) was observed between marker intensity conditions; for the d_o=150msec. there is a definite trend for the high intensity (98dB) condition to show a better performance, but even then the improvement is rather small, around 5%. A further insight on the problem comes from Nilsson (1969). He obtained psychometric functions for 6 values of d_o ranging from 0 to 75msec. at three levels of luminance 50,200 and 2000mL of 1msec. light flash markers. An analysis of variance showed no effect of the luminance levels on the performance. A similar lack of evidence on the influence of the energy content of the temporal patterns to be discriminated has been reported in several studies involving filled intervals (Henry,1947;Allan,Kristofferson & Wiens,1971; Creelman,1962;Abel,1972b).

Thus, the energy content of the stimuli marking an empty temporal interval does not seem to be a crucial variable in a duration discrimination task. However, the argumentation presented in 1.2 concerning the minimisation of sensory cues in situations dealing with duration processing is relevant. A case can be made for the use of intermodal intervals in order to reduce the emergence of non-temporal cues of sensory origin.

1.4 Theoretical analysis of duration discrimination.

Up to the last decade, the theorizing on processing of short intervals of time was rather poor. Indeed, most theories had been proposed around the turn of the century and were essentially descriptive and supported by a small amount of experimental work (Nichols,1891;Woodrow,1951). As a result, the research performed before the sixties (Woodrow,1928;Blakely, 1933;Henry,1948) was primarily empirical and not theory inspired. Such studies were, in fact, typical offsprings of classical psychophysics and are best understood within its context.

However, over the last 20 years the rise of new psychophysical theories, mainly the Theory of Signal Detection (Green & Swets,1966), has led to the development of quantitative models of processing of short duration (e.g. Creelman, 1961;Allan,Kristofferson & Wiens,1971). So, the experimental work which followed was often directed towards an evaluation of the models in terms quite different than those of classical psychophysics. In this section we intend to present separately these two approaches.

1.4.1 Classical psychophysics of duration discrimination.

The basic measure of performance of classical psychophysics is the threshold. In the case of discrimination it is usually the difference (DS) between two stimulus values, on the physical dimension (S), sufficient to achieve a 75% correct level of performance. In the case of duration discrimination such an occurence has been previously defined as DT_{75}. This threshold has been found to be a function of the absolute magnitude of the stimulus values on the physical dimension under study. The relationship between the threshold DT_{75} and the physical magnitude of the stimuli S, $DT_{75}=f(S)$, has been considered as showing the functional relationship between input and output of a processor (Treisman,1964) or between physical and psychological dimensions (Guilford,1954). Thus, establishing the shape of this function could be useful in setting logical limits upon the possible class of mechanisms considered for quantitative modeling.

The classical representation of the relationship $DT_{75}=f(S)$ is the well known Weber law DT=kS or DT/S=k. So, in duration discrimination, the function would show DT_{75} vs T as a straight line with slope k and zero intercept and a Weber ratio DT/T equal to k. Very early, (Nichols,1891) such a function was reported not to be an accurate representation of the results observed in most studies. The Weber ratio was not a constant but rather a decreasing function of T at short values down to a local minimum around 600msec. and then constant up to 2 or 3sec., where it becomes an increasing function of T. It is readily apparent that in such a function DT will not be a slope k zero-intercept function of T. Consequently, the DT=f(T) function was reported to be better fitted by a power transformation of Weber's law, $DT=kT^a$ (Henry,1947) with $.5<a<1$,or by a linear transform, DT=k(t+a) (Treisman,1963). However, in these cases DT was always a monotonic function of T. Recently, authors (Abel,1972a,1972b;Kristofferson,1973; Allan & Kristofferson,1974b;Rousseau & Kristofferson,1972) have reported functions where DT is constant over a large range of T values and then shifts abruptly to a larger value as T is further increased. Thus, it is likely that quantitative models assuming a simple monotonic relationship between DT and T will have difficulty in accounting for some results. Unfortunately, one cannot hope to find, from the variety of proposed functions some indication with regard to a single best fitting function in a duration discrimination situation.

As we have mentioned before, classical psychophysics has been recognised mainly as having empirical value. That is to say, it was an objective means of measuring performance in a controlled situation with reliable methods. In such a context, the classical Weber function has been widely accepted as a good approximation of the DT vs T function for values of T not too close to the absolute threshold. In that way, the Weber ratio has been widely used as an index of the keenness of discrimination. The ratio is very useful when comparing the differential sensitivity of Os under different experimental conditions. Table 1 gives a summary of the Weber ratio reported by different authors with different stimuli marking the

Table 1

Estimated Weber (DT_{75}/T) for $T<2000$, for duration discrimination of filled (F) and empty (E) intervals under various stimulus conditions

Authors	Type of intervals	DT/T	Stimulus conditions	Range of T (msec.)
Blakely (1933)	E	.07	auditory click	200-2000
	E	.15	auditory click	>2000
Goodfellow (1934)	E	.07	auditory stimuli	1000
	E	.095	tactile stimuli	1000
	E	.115	visual stimuli	1000
Carbotte & Kristofferson (1973)	E	.08	pure tones 2kHz	100-200
Kristofferson (1973)	E	.06	pure tones 2kHz	50-1200
Abel (1972a)	E	.25	noise bursts	160-640
Abel (1972b)	F	.12	pure tones white noise	10-500
Stott (1933)	F	.13	pure tones	200-2000
Henry (1947)	F	.20	pure tones white noise	50-500
Small & Campbell (1962)	F	.20	pure tones white noise	40-400
Treisman (1963)	F	.12	visual stimuli	250-3000

intervals. The Weber ratios thus reported are averaged over Os and approximated by eye over the range given for each experiment. It is interesting to note the agreement between all the values reported with the exception of those of Abel (1972a) Henry (1947) and, Small & Campbell (1962). Furthermore, one should note the small number of stimulus variables that have been investigated. However, some experiments which did investigate other variables (e.g. Carbotte & Kristofferson (1973) varying intensity of markers) cannot yield Weber fractions because the data does not provide the required psychometric functions.

1.4.2 Quantitative models of duration discrimination.

It was said in section 1.1 that different stimulus cues could be operating in duration discrimination of short intervals. However, all major quantitative models (Creelman, 1962;Allan,Kristofferson & Wiens,1971;Kinchla,1972;Carbotte, 1972) have assumed the temporal stimulus dimension as being the only source of information on which timing mechanisms are operating. That is to say, in duration discrimination, performance should be independent of non-temporal stimulus dimensions. However, the models disagree on the locus, within the timing device, where the variability observed in the performance originates. Furthermore, they also differ on the nature of the psychological transform of the temporal information. Most models assume the internal representation $d_i(I)$

of an external duration d_i to be a continuous variable. That is to say, repeated presentations of a given value d_i yields a probability distribution $f(I|d_i)$ specified by the model. On the other hand some models assume I to be discrete. So, repeated presentations of d_i will give rise to a finite set of states of I, each state being associated with a probability of occurence. Up to now all finite state models have assumed the timing device to be a periodical clock with a constant rate.

1.4.2.1 Poisson counter model.

The basic element of the model proposed by Creelman (1962) consists of a large pool of independent elements firing at random. The probability that any element is emitting a pulse at a given moment is a constant, λ. Such a system will produce over d_i, a total number of pulses N whose statistical properties are those of a homogeneous Poisson process. When the quantity λd_i is large, the probability distribution of counts for the interval is approximated by a normal distribution $N\sim(\lambda d_i, \lambda d_i)$. The original model had two additional parameters which were specific to the method and stimulus conditions used in Creelman (1962). However, further tests of the model were carried on the one parameter (λ) version (Allan, Kristofferson & Wiens, 1971; Abel, 1972a,b; Carbotte, 1972).

The basic consequence of the mechanism described above is that an increase in d_i will yield an increase in both the mean and variance of $d_i(I)$. Thus, when an O has to discriminate between two intervals d_o and d_1, these intervals are assumed to have an internal representation with mean and variance of λd_i. Furthermore, the O is assumed to keep a variance free decision criterion of K counts which is compared on a given trial to the number of counts N obtained, in order to produce either a R_o response if $N<K$ or an R_1 response for $N>K$. Then, a index of discriminability d'_c can be defined as follows: $d'_c = \frac{\lambda^{\frac{1}{2}} DT}{d_o^{\frac{1}{2}}}$ where d'_c represents the distance between the mean of $d_o(I)$ and $d_1(I)$ in terms of the standard deviation of $d_o(I)$. However, Creelman tested his model in a 2AFC situation where the O is assumed to substract the counts obtained under each observation interval, thus producing a difference distribution of mean $\pm\lambda\Delta d$ and variance $\lambda(2d_o+\Delta d)$ where $\Delta d = d_1 - d_o$ The decision is taken relative to a criterion difference at best positioned at 0 difference. The main prediction to come from the model is that because of the functional relationship between the variance of the distribution and T, there will be a decrement in performance as a function of an increase in T for a given Δd.

1.4.2.2 Onset-offset model

Allan, Kristofferson & Wiens (1971) proposed a model which assumed the variability of the discriminating system as having its source in the transfer of the onset and offset of the interval to be timed to a perfect timing device. In fact, the delay between the occurence of a physical event (onset or offset) and its registration by a central timekeeper was assumed to be a random variable uniformly distributed with a range of 0-q msec. Thus, for an interval of duration d_i the probability distribution of its internal representation is obtained by convoluting the two uniform distributions yielding a triangular probability distribution with mean d_i and variance $q^2/6$, spanning 2q. So, the variance of the distribution is not a function of d but only of q, and the mean of the internal representation is identical to the duration of the physical interval. The parameter q is assumed to be constant over large ranges of values on T. Thus, when an O is required to discriminate between two intervals d_o and d_1, these will produce equal variance distributions of internal time with mean d_o and d_1. The decision making procedure is very similar to the one described in Creelman's model. The O is assumed to keep an internal duration criterion of K msec. and on a given trial to compare the extent of the internal duration with K and give a R_o when $I<K$ and a R_1 for $I>K$. The level of discriminability of the two intervals will be dependent only on ΔT. So, a criterion free measure of discriminability was defined: $dq=\Delta T/q$ which states simply that the discriminability is a linear function of ΔT expressed in q units.

The assumption of constancy of q leads to the prediction that for a given ΔT the performance should not be a function of the absolute value of the durations to be discriminated. Furthermore, by definition, dq should be a linear function of ΔT with slope $1/q$. Because the triangular distribution does reach zero at d-q and d+q the psychometric function reaches 0 and 1 at these values. The equal variance assumption of the internal distributions leads to the prediction of linear ROC functions, with triangular deviates, whose slope should be 1.

1.4.2.3 Kinchla's (1972) model

While this model has been tested less often than the previous ones, it is of logical value because its mathematical expression is a sort of mid-point between Allan et al's and Creelman's models. Indeed, whereas in Creelman's model both the expected value and the variance of $d_i(I)$ are some increasing function of T, in Allan et al's while the expected value is an increasing function of T, the variance is independent of T over large ranges of T.

Kinchla proposes a model which assumes $d_i(I)$, to be a Gaussian random variable of mean d_i and variance $VAR(I)=\phi d_i$, ϕ being a constant of proportionality. For sake of simplicity it is proposed that for a small Δd, where $\Delta d=d_1-d_o$, the difference between the variances ϕd_o and ϕd_1 is small and their ratio can be assumed to be equal to 1. So, the decision making strategy will be applied to equal variance distributions. In a discrimination task the O will keep a criterion, K which will partition the internal distributions in a manner similar to the one described in the two previous models. A discriminability measure d', can be defined as $d'=\frac{d_1-d_o}{(\phi d_o)^{\frac{1}{2}}}$ Since $\phi d_o=\phi d_1=VAR(I)$ by definition, $\phi=\frac{(\Delta d)^2}{(d')^2 d_o}$ and the $VAR(I)=\frac{\Delta d^2}{(d')^2}$. So, VAR(I) is a linear function of d_o with a slope of ϕ. It is interesting to note that it follows that the standard deviation $SD(I)=\frac{\Delta d}{d'}$ which yields a relation extremely close to the expression $q=\frac{\Delta d}{d_q}$ as derived in the onset-offset model.

1.4.2.4 Quantal counting model.

The basic model proposed by Kristofferson (1967) assumes a discrete state perfect clock with a period of q msec. That clock is constantly on-going and thus independent of the occurence of external events marking an interval to be timed. That independence produces a variability in the total number of counts registered during d_i. More specifically, for $nq<d_i<(n+1)q$, where n is a non-negative integer, the interval d_i will yield a count of n pulses with probability $P(N)=\frac{(n-1)q-d_i}{q}$, and, consequently a count of n+1 pulses will occur with probability 1-P(n). From this basic system a number of different decision making procedures have been proposed (Carbotte & Kristofferson,1972) which makes it difficult to give any specific predictions with regards to the shape of the psychometric functions. However, the basic model shares an important characteristic with the onset-offset model: the discriminability is a function of q whose value is independent of T.

1.5 Summary of the experiments.

The aim of the present work is to examine the possibility that intermodal duration discrimination would provide information on the functional characteristics of a central duration processor. In order to achieve that goal a double approach is needed: first, obtain basic knowledge on the differential sensitivity of observers in an intermodal duration discrimination task, and then, obtain detailed psychometric functions in order to evaluate the capacity of current quantitative models to account for the performance in that situation.

The first four experiments, Chap. II were run in order to obtain data that could be discussed in terms of the classical psychophysics. Experiments 1 and 4 provided Weber functions. In experiment 1, four groups of Os ran each at a different base durations in the range of 100-2000msec. whereas 4 individual Os went through a series of durations ranging from 175 to 1200msec. in expt 4. Experiments 2 and 3 were performed as controls for the possible existence of non-temporal stimulus cues which could conceal the operation of a timing mechanism in expt 1. In expt 2 a check was run for the possibility of the Os' using the onset of the first marker to define the temporal intervals rather than the offset as instructed. The effect of the specific sequence light-tone was studied in expt 3 by comparing the performance within the same Os between a light-tone and a tone-light sequence. In Chap. III detailed psychometric functions were obtained at mid-point of 600msec. in experiment 5, and 300msec. in experiment 6. Special care was taken in order to have asymptotic performance. Expt 6 also provided a three point ROC function thus permitting further checks of the quantitative models. Finally, in experiment 7 two Os were run for a long period of time in a reaction time situation. This last experiment was very exploratory but provided interesting information on the nature of a possible central timing mechanism.

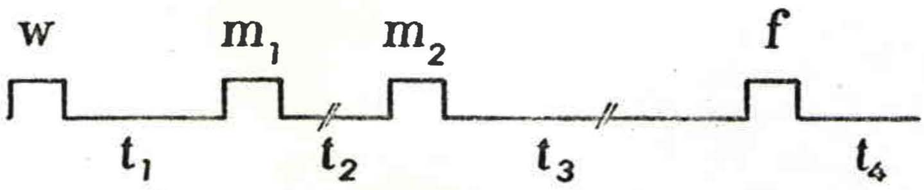
1.6 General procedure and apparatus.

A total of thirty-four Os were used throughout the experimentation. They were all volunteers and they were paid $2.00 per session except in expt 7 where the rate was increased to $3.00. Two Os were dropped, one for sickness and the other for consistently omitting a large number of responses. Each O was given an identification number; an O who performed in more than one experiment was constantly represented by the same number.

Each O was run in an individual sound attenuated testing chamber. In most cases there was a single session per day, although on some occasions two. Each session would last between 25 to 40 minutes depending on the specific experiment. It was subdivided into 2 to 4 blocks of 10 to 15 minutes with a one minute rest period between blocks.

The sequence of events in a trial was quite similar for all the experiments; the basic sequence is described in Fig 1.

The visual signals were presented to the O from a metal box display at a distance of about 2 ft. under conditions of unrestricted observation. There were 4 tungsten miniature lamps (cue lights) at each corner and a glow modulator (Sylvania R1131C) emitting through a 4mm aperture in the center of the box, whose luminance was set at 50 ft-L (150 UB Photo Research Photometer). The glow modulator was driven



w = Warning signal (In exp. 3, 4, 6 & 7).
, Visuaul signal (Cue light).
100 msec.

t_1 = 1 sec. interval.

m_1 = Marker 1. Visual signal (Glow modulator).
10 msec. (Except in exp. 1 & 2).

t_2 = d_i interval to be discriminated.

m_2 = Marker 2. Auditory signal (2kH tone).
10 msec. (Except in exp. 1 & 2).

t_3 = Response interval.
3 sec. (Except in exp. 1&2 = 4 sec.).

f = Feedback signal.
Visual signal (Glow modulator in exp. 1, 2 & 5).
(Cue light in exp. 3, 4, 6 & 7).

t_4 = Intertrial interval
1 sec.

FIGURE 1. Stimulus events in a typical trial.

by an Iconix power supply (Model 6195-4). The bottom left cue light served as warning signal and the top two as feedback signals identifying the type of interval (short or long) to the O on a given trial. In the experiments where the glow modulator was used as feedback signal it would flash only to identify an interval of the short subset.

In expts 1,3, and 5, the tone signal was controlled by gating the output of a Hewlett Packard audio oscillator (Model 201C) through a Grason Stadler Electronic switch (Model 929E) under computer control. For the other experiments the signal was produced by a Wavetek programmable oscillator under direct computer gating. In both cases the signal was a 2KH pure tone with rise-decay times of 2.5msec. and calibrated at the ear at 68dB. The auditory signals were presented binaurally through crystal earphones; they were always readily detectable. The O would give his answer by depressing one of two push buttons placed on the right armrest of his chair. He was instructed to answer on every trial even if in doubt. The timing was completely under computer control (Digital Equipment Company PDP-8).

All the experiments were run with a single stimulus method. In expts 1 and 2 a type A partitioning was used while the other experiments were run with a"Many-to-few" method. Thus on any trial the Os were always presented with only a single interval d_i on which to base their decision and the duration of this interval was always defined in the instructions to the Os as the gap between the offset of the first marker and the onset of the second one.

II CLASSICAL PSYCHOPHYSICS OF INTERMODAL DURATION DISCRIMINATION.

2.1 Experiment 1: Varying base duration.

It has been shown throughout section 1.4 that the DT_{75} vs T function was the principal and most general means of functional analysis of duration discrimination performance. Thus, it appeared logical to begin investigating intermodal duration discrimination by obtaining such a function.

Furthermore, it was shown in section 1.2 that in TOJ and successiveness discrimination tasks, reports of comparable levels of performance in inter and intramodal stimulus conditions were taken to be evidence for the existence of a common central mechanism (Hirsh & Sherrick,1961;Efron,1973). Then, that rationale would receive strong support from intermodal duration discrimination yielding a level of performance similar to that of intramodal discrimination.

General features of quantitative models reviewed in 1.4 can be tested against the shape of the Weber function. Indeed, the onset-offset model received its basic support from reports of non-monotonicity of the DT_{75} vs T function by Allan et al (1971) and Allan & Kristofferson (1974b)

The present experiment was meant to provide as wide a range of information as possible. Consequently, a large range of base durations was studied at only a few points within that range. That is to say, we prefered to have an approximated function covering a larger distance on T rather than detailed information on shorter range. Again, such a decision was justified mainly by the total lack of information on intramodal duration discrimination. Four different base durations were chosen, and a different group of naive observers was run at each one, in order to avoid unwanted interaction that could arise from the same Os having been subjected to more than one range of durations.

Procedure.

Twenty-one Os were used for the experimentation. They were volunteers paid at the usual rate. None had any experience in duration discrimination tasks.

The duration of both markers was set at 500msec. and the warning signal was omitted throughout the experiment. Feedback was provided to the Os by flashing the signal light after the response period on d_o trials. The other details of the temporal sequence of events in a trial are as described in the general procedure.

The single stimulus method with a type A partitioning was used throughout the experiment with D=6. A single value d_i was used within a session and the sequence of presentation of the d_i over sessions was randomised. The experimental data were collected over two such random sequences. The 4 D sets were:1) d_o:100, d_1:150, d_2:250, d_3:350, d_4:450, d_5:700, 2) 600, 650, 750, 850, 950, 1050, 3) 1200, 1250, 1350, 1450, 1550, 1800, and 4) 2000, 2100, 2200, 2300, 2400, 2600msec. In the discussion of the results the d_i will often be referred to under the form $d_i=d_o+DT$. The experiment proper was preceded by two to three thousand trials of practice at a DT of 100msec. for d_o of 100, 600 and 1200msec. and a DT of 400msec. for the d_o=2000msec. There were 4 blocks of 70 trials within a session each stimulus d_o and d_i being presented equally often in random order in a block. For each value of d_i there were two such experimental sessions. Four Os were run at a d_o=100msec. 6 at d_o=600 and 1200msec., and 5 at d_o=2000msec.

Results.

The individual results are summarized in Tables A1, A2, A3, A4, in Appendix A. Individual P(c) were calculated for each d_o vs d_i pair on the pooled results of the two experimental cycles.

The Weber function.

Table 2 shows the individual and averaged values for DT_{75} at each based base duration. These DT_{75} were estimated with a linear interpolation method. While this may not be the most powerful method for estimating parameters, it avoids undue assumptions about the theoretical shape of the psychome-

Table 2

Values of DT_{75} (in Milliseconds) and DT/d_o ratios for 21 Observers and four base durations.

	Base duration 100	600	1200	2000
	143	84	132	156
	243	176	137	107
	113	138	154	267
	157	177	226	134
		277	270	151
		125	111	
Mean	164	163	171	163
SD	56	66	62	61
DT/d_o	1.64	.2716	.1425	.0815

tric functions. It is evident from Table 2 that DT_{75} is independent of d_o, under the conditions of this experiment. Indeed, it is almost constant at 165msec. and the DT_{75} vs T function shows no increasing trend as is commonly reported, (e.g. Abel,1972a;Kristofferson,1973). It is also worth noting the similarity between the standard deviations (SD) of the DT_{75} in each group. So, although there are large individual differences, the lack of effect of base duration is clear and is not likely to come from difference in sensitivity between groups.

A comparison of the Weber ratios with those reported in Table 1 shows that for the 600msec. and 100msec. base durations the intermodal values are markedly larger, mainly at d_o=100msec. However, comparable ratios (>1.0) were reported with intramodal empty auditory intervals by Abel,(1972) at base durations smaller than 10msec. Similarly, Small & Campbell (1962) obtained ratios up to 3.0 at a d_o=0.4msec. with filled auditory intervals.

The psychometric functions.

A comparison of psychometric functions at each base provides more complete information than considering only DT_{75}. It could happen that quite different psychometric functions would cross the P(c)=.75 value at identical DT values. Averaged psychometric functions are showed in Fig. 2, where P(c) is a function of DT. The averaged functions were obtained

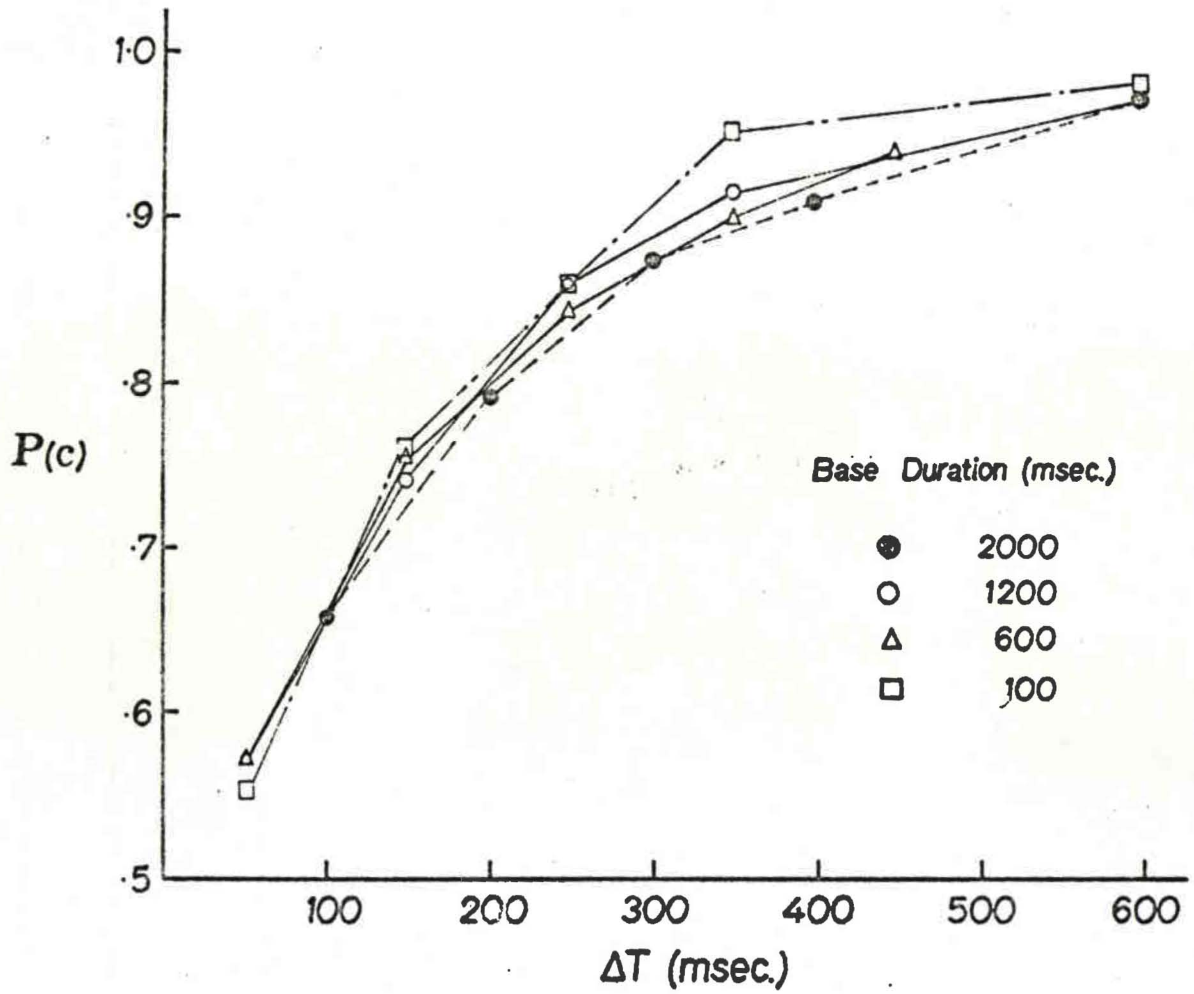


FIGURE 2. Averaged psychometric functions at four base durations.

by averaging individual P(c) values at each DT. The similarity between these functions is striking, which supports the possibility of the same mechanism with constant parameters operating over the whole range of base durations.

Since these results represent the first account of differential sensitivity of Os in intermodal duration discrimination, it would be of definite interest to compare psychometric functions obtained in intra-and intermodal situations. Four psychometric functions were chosen from various published experiments for their representativeness of inter and intramodal situations: Carbotte & Kristofferson (1972) auditory empty intervals, Allan et al (1971) filled visual intervals, McKee et al (1970) empty visual intervals and the d_0=100msec. function in the present experiment. Because of the differences in DT_{75} between the four experiments it is evident that one cannot describe all the functions with a single equation. Actually, the problem comes from differences in the psychometric range i.e. the extent on the DT axis required for P(c) to go from .5 to 1.0. It is quite likely that some transformation of either axis of the psychometric function (e.g. the use of log DT) could make feasible the description of all four functions by a general equation. Unfortunately, such arbitrary transformations lead very easily to theoretical ambiguity since they do not originate in specific functional predictions from models. Such pitfalls could be avoided by a simple examination of the relationship between DT_{75} and the span of the psychometric function. However, it is difficult to obtain a precise value of the span because of the larger variability at high P(c) values. If P(c) values are transformed into Z(c), the span is a direct function of the slope of the Z(c) vs DT function. Similarly, the standard deviation, SD, which is a constant proportion of the total span will be a function of the slope of the same function. So, we will use SD, as an approximation of the span of the psychometric function and seek to determine the SD vs DT_{75} relation. Averaged P(c) were transformed into Z(c) and a straight line was fitted to the Z(c) vs DT function with a least square procedure. From the estimates of the slope and intercept, DT_{75} and SD were obtained. More precisely SD was defined as:

$$SD=DT_1-DT_0 \qquad (1)$$

where subscripts represent values of Z(c) for which the DT were estimated. A ratio SD/DT_{75} was obtained for each function. The results presented in Table 3, show the SD/DT_{75} varying from 1.4 to 2.0. The ratio yielded by the McKee at al (1970) is somewhat lower than the others. However, the ratios are in general close enough to one another to allow for the conclusion that they belong to a common family. The modification of stimulus conditions does affect the variance of the psychometric function but the basic structure of the function is maintained: DT_{75} is a constant proportion of SD. So, the constancy of the SD/DT_{75} ratio could very well be interpreted as evidence sup-

Table 3

Estimates of SD, DT_{75}, and SD/DT_{75} for the four functions presented in Fig. 2

Experiment	SD	DT_{75}	SD/DT_{75}
A) Carbotte & Kristofferson (1971)	14.52	7.34	1.98
B) Allan et al (1971)	25.64	15.38	1.666
C) McKee et al (1970)	34.01	24.42	1.39
D) Intermodal intervals	297.56	148.47	2.00

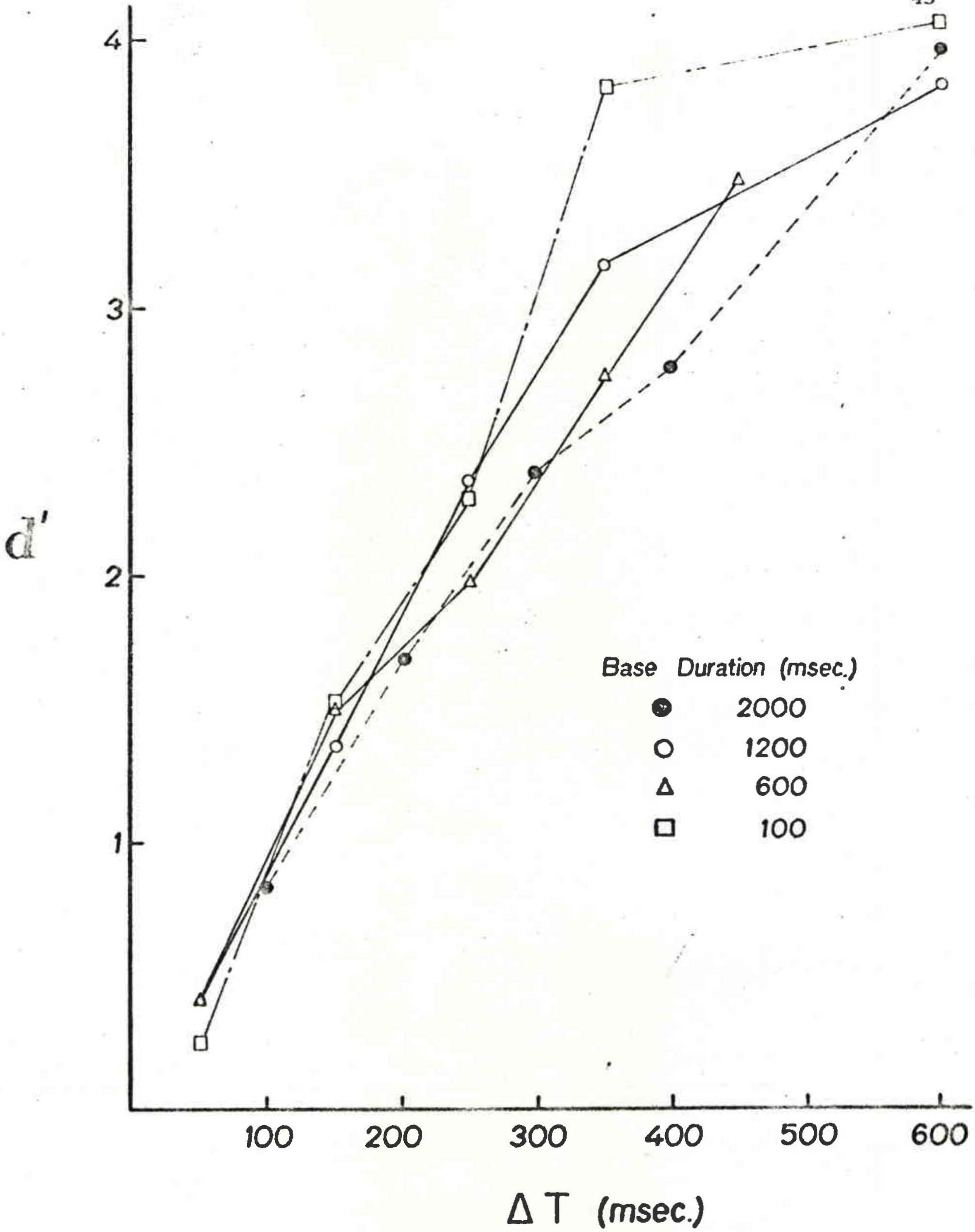


FIGURE 3. Averaged equal variance d' at four base durations.

porting the operation of a common mechanism in all conditions.

Finally, equal variance d' (Green & Swets 1964) were calculated for each individual performance. Again this was done for the empirical goal of comparing performance as displayed by a criterion-free index against the results of other experimenters. The main feature of the d' vs DT functions that was previously reported (e.g. Creelman,1962;Allan et al, 1971) were the linearity of the functions. Fig 3 shows averaged d' as a function of DT for each base duration. The functions are quite similar in slope and the linearity is good up to d'=3. However, this is not unexpected given the unreliability of the d' measure at such high levels of performance. Furthermore, individual functions were fit through a least square procedure and the results are reported in Table A5 (Appendix A). In all but one function the linear fit could account for more than 90% of the variance when values of d'>3.0 were omitted.

Discussion

The main features of the results just described are the constancy of DT_{75} as a function of d_o and, consequently the lower level of performance observed at d_o=100msec. and 600msec. As we have previously seen, at very short base durations very efficient modality specific mechanisms are available (Oatley,1969;Green,1971). Could it be that such mechanisms would not be available in an intermodal situation, in a comparable range of intervals. On the other hand, at longer d_o (>1.0sec) equivalent mechanisms could be used thus yielding comparable levels of performance. The problem with such argumentation is that when psychometric functions from intra and intermodal situations were compared (re Fig.2) they turned out to be comparable. Indeed, in Collyer (1974) modality specific mechanisms produced psychometric functions that were clearly different in shape. So, it would be difficult to argue that different mechanisms are operating in inter and intramodal tasks at d_o=100msec. It could happen that while the same mechanism is in operation in both situations, it is very inefficient for intermodal intervals at short d_o.

On the other hand, some interference from stimulus variables could produce the sharp increase in the Weber ratio observed at short d_o. Indeed, there is a possibility that, the Os rather than using the offset of the light marker to trigger an internal timekeeper would use its onset, thus effectively lengthening the duration of a given interval by 500msec. In such a case they would have never been involved in measuring intervals shorter than 600msec. Or else, the results could be linked to the actual light-tone sequence and not typical of any intermodal situation. Indeed, the small size of the light flash and its relatively low contrast, (the room was dimly lit) could make it relatively inefficient to maintain the attention of the O. Consequently, the triggering of the central timekeeper would be less accurate, the overall process of transforming a given duration into an internal dimension made more variable and so, the discrimination less accurate.

Furthermore, one cannot help but wonder at the effect of having used random groups of Os in each base duration. Such a procedure could yield results that cannot be compared with those from studies in which base duration is varied within Os'. Woodrow (1934) ran 5 groups of Os in an auditory interval reproduction experiment for durations ranging from 300msec. to 4000msec. The Weber function he obtained was very similar to that reported by Blackwell (1933) in a duration discrimination task over the same range on individual Os. So, that particular feature could be considered as having had a minimal effect on the performance.

Thus, the picture we have obtained of intermodal duration discrimination is somewhat difficult to understand at this moment. On one hand, some parts of the results do bear a resemblance with intramodal intervals results. Indeed, the onset-offset model which was shown to account for performance in certain intramodal situations is given a strong support from the present results. The stability of performance over a large range of durations is a surprising result which cannot be accounted for by the other continuous models. However, the clear violation of Weber's law makes the present performance very different from all other intramodal ones having gone through such a large range. Yet, the psychometric functions can be shown to be of the same family.

2.2 Experiment 2: Varying the duration of the first marker.

In the preceding section we considered the possibility that the Os were using the onset of the light marker, m_1, to trigger a timing device at short d_o. In such a case the duration of m_1 becomes of importance. One might expect a change in performance with variations in the duration of m_1 since the effective interval to be evaluated would be varied. In a TOJ task Rutschman & Link (1964) found a decrement in performance with an increase in marker duration when Os had to judge the order of occurence of a light flash and a tone. Oatley et al (1969) reported a similar result with intramodal signals. Abel (1972a) varied the duration of 70dB noise burst markers in a duration discrimination task. For durations of 10 and 300msec. of the markers no effect was reported. In the following experiment, large variations in the duration of m_1 were introduced in order to examine their effects upon performance.

Method

Four Os were used, 101, 102, 103 and 1. The first three were naive volunteers paid at the usual rate and O 1, the author, was unpaid and experienced.

The structure of the trials as well as psychophysical procedure were the same as in expt 1. The main set D contained only 2 elements d_o=100msec. and d_1=250msec.

Three durations of the light marker were used: 10,500 and 4000msec. The tone marker (m_2) was kept constant at 500 msec. The duration of m_1 was varied over blocks of 100 trials with each d_i being presented 50 times in random order. In a given session the Os would run through one of the six possible combinations of orders of the durations of m_1. So, over six sessions all combinations were exhausted. One such cycle was run as practice and the following one provided the experimental data. There was 600 trials per duration of m_1. O 102 dropped out of the experiment after three of the six experimental sessions.

Results and Discussion

The individual values of P(c) for each experimental session are presented in Appendix A, Table A6. Estimates of $P(R_1|d_1)$, $P(R_1|d_o)$ and P(c) obtained from the pooled results of the experimental session are shown in Table 4. From the individual and averaged results it is evident that there is no systematic effect of the duration of m_1 on any of the estimates. If anything, there is a tendency for P(c) to be slightly lower at m_1=10msec. mainly for Os 101 and 103. The lack of effect of the duration of m_1 is further displayed

Table 4

Estimates $P(R_1|d_1)$, $P(R_1|d_o)$, and $P(c)$ for three durations of the light markers. (1)

	Duration of Light marker.								
	10			500			4000		
Observer	$P(R_1\|d_1)$	$P(R_1\|d_o)$	$P(c)$	$P(R_1\|d_1)$	$P(R_1\|d_o)$	$P(c)$	$P(R_1\|d_1)$	$P(R_1\|d_o)$	$P(c)$
101	.885	.153	.866	.963	.077	.943	.939	.043	.948
102	.613	.188	.712	.640	.248	.696	.591	.180	.706
103	.505	.378	.564	.649	.455	.597	.660	.510	.575
1	.791	.244	.771	.780	.174	.803	.761	.172	.795
$\bar{X}$	.698	.240	.724	.758	.238	.758	.738	.226	.744

(1) Each individual estimate is based on 600 trials except for O 102 for whom there are only 300 trials.

when the results are compared with those of expt 1 which was run under comparable conditions. Indeed, for the condition m_1=500msec. the situation is directly comparable to expt 1 and, the averaged P(c) is .758 in the present case, while it was .764 in expt 1. This replication of the results obtained in the previous experiment makes it even more unlikely that the low level of performance could be due to a group of less sensitive Os having been run by chance in expt 1. Moreover, large individual differences are here again a feature of the results. Thus the lack of effect of the duration of m_1 supports the related finding of Abel (1972a).

It is interesting to note that in the conditions where m_1=10 and 4000msec. the durations of the pair of markers are assymetrical i.e. in one case the sequence is a short (S) marker followed by a long one (L) and in the other case the sequence is L-S. The effect of assymetry of marker duration was studied by Woodrow (1928). He reported marked biases in the perceived length of an interval as a function of a given sequence which he called an illusion. Indeed an interval of 500msec. marked by auditory pulses with durations L-S is perceived as equal to a 660msec. interval marked by a S-L sequence. One way to examine the present results for such an effect is to see if $P(R_1|d_1)$ and $P(R_1|d_o)$ vary systematically as a function of m_1 duration. Only Os 101 and 103 show a consistent trend, and unfortunately the direction of the trend is inverted from one O to the other for $P(R_1|d_o)$. Thus, it would seem that in the present conditions, the relative durations of m_1 and m_2 did not produce marked systematic biases in the Os. However, the attenuation of the effect is likely to be due in great part to the presence of feedback in the present study contrary to Woodrow's (1928).

2.3 2.3 Experiment 3: Tone-Light versus Light-tone markers.

In the discussion of the results obtained in expt 1 we commented on the possibility that the low level performance observed at short d_o could be related to the use of a light-tone sequence. In such a sequence, the light marker could be an unreliable signal for the triggering of a central timing device. Thus, the important feature of the experimental situation in expt 1 would not be so much intermodality but rather the use of a special condition of intermodal signals. It appeared that comparing a light-tone sequence to a tone-light one could give an answer to two questions. First, it could enable us to generalise the results obtained so far to another intermodal condition. Second, it would provide a check on one possible factor that could render the light marker less efficient in a light-tone sequence. The offset of the light flash is the precise stimulus event which indicates the beginning of the interval and that unefficiency could have its source in a larger variability of afferent latency for the light offset by contrast with the light onset. Or else, mean afferent latency could be longer for the light offset than for the tone offset. Thus, in the tone-light sequence, the precise external event which terminates the interval is a light onset and in the event that it is a better marker one should observe an improvement in performance while remaining in an intermodal situation.

In the present experiment the methodology was somewhat modified. The two major changes were: the use of the M.-F. method at M.P.=250 msec., and the increase in the amount of practice that was given to each O under each experimental condition. The conditions were not alternated as was the case in expt 2. The Os' performance was stabilised successively under each condition before obtaining the experimental data.

Method

Six naive Os were run in the experiment. They were as usual paid volunteers. Each O ran in both stimulus conditions, light-tone (L-T) and tone-light (T-L) sequence. Three Os 602, 603 and 604 did the L-T and then the T-L condition whereas three other Os, 503, 601 and 605 did the opposite.

Each trial began with a visual warning signal and the markers duration was set at 10msec. The main set D had 4 elements d_o=100, d_1=200, d_2=300, and d_3=400msec. However, O 601 ran with d_1=215 and d_2=285 from session 15 to session 27 in condition T-L and for the first three sessions in condition L-T. The Os were instructed to give an R_o to d_o and d_1 and an R_1 to d_2 and d_3. A session had three blocks of 100 trials in which each d_i was presented 25 times in a random order.

For each O, efforts were made to collect the experimental data under asymptotic performance. In order to achieve that goal the Os were run for at least 19 sessions in the first condition and 12 sessions in the second one. The total number of sessions ran by each O in each condition is presented in Table 6. The criterion for asymptotic performance was a minimal drift in P(c) over 8 sessions. A maximum of 20-25 sessions was set as the limit in each condition even if asymptote was not reached. Thus, for each O under each condition the experimental sessions will be the last 8 sessions. Overall, there were 600 trials/d_i in each condition.

Results and Discussion

Since the last 8 sessions were to be used for data analysis a linear least square analysis was run on the individual P(c) functions in order to check the stationarity of the function. The test was performed on the overall P(c) from the pooled correct responses to all four d_i. The results of the curve fitting are reported in Table 5. The largest slope is .052 in P(c), and on the average the slope is .003, which is a .024 change from day 1 to day 8. Thus probability estimates will be averaged over the last 8 sessions.

The overall P(c) for the last 8 days under each condition is shown in Fig. 4. Except for O 601, the functions display small variations about the mean. Actual values of that variability are reported in Table 6 where the individual P(c) averaged over the 8 sessions is given with the standard deviation, SD, and the total number of sessions, N, run in each condition. The SD reflect the small variability around the mean P(c) and corroborates the observation that O 601

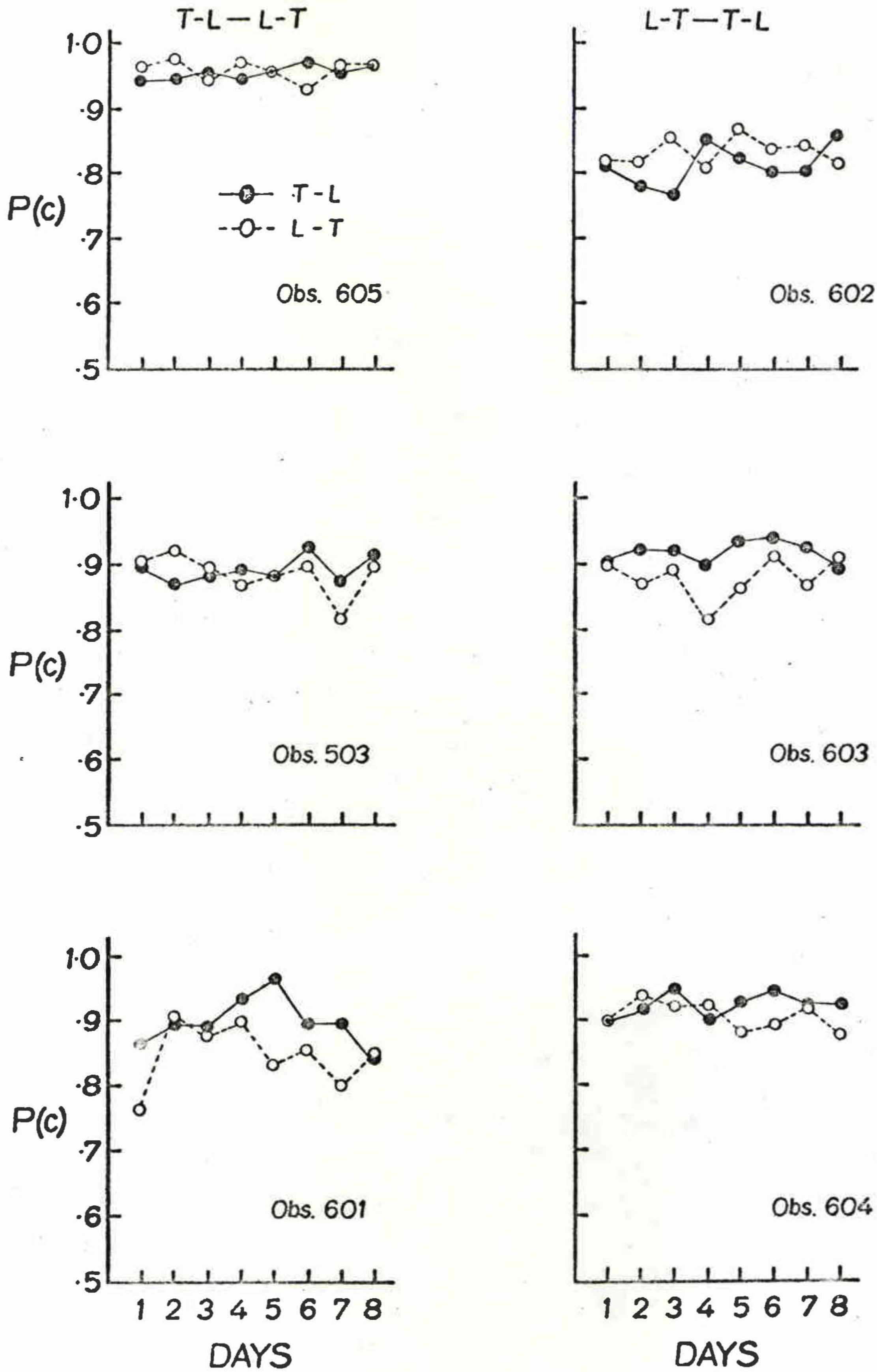


FIGURE 4. Probability correct for 6 Os over the last 8 sessions of experimentation in both experimental conditions.

Table 5

Estimates of the parameters of a linear least square fit performed on the last 8 sessions of each condition for 6 Os

Observer	Condition	Least square fit parameters: slope	intercept	r^2
602	L-T	.0015	.826	.030
	T-L	.0065	.7839	.23
603	L-T	.0023	.8664	.037
	T-L	.00009	.9164	.0002
604	L-T	-.004	.9236	.25
	T-L	.002	.9076	.14
605	T-L	.0036	.9360	.60
	L-T	-.004	.9644	.05
503	T-L	.0036	.8766	.19
	L-T	-.006	.9104	.24
601	T-L	-.002	.9051	.016
	L-T	-.0008	.8504	.001

Table 6

Average overall P(c), standard deviation, and total number of sessions (N) for 6 Os under each condition.

Observer	Condition	P(c)	SD	N
605	T-L	.9529	.0113	22
	L-T	.9574	.0145	16
503	T-L	.8931	.0201	23
	L-T	.8823	.0311	24
601	T-L	.8958	.0402	27
	L-T	.8466	.0463	15
602	L-T	.8335	.0212	24
	T-L	.8133	.0330	12
603	L-T	.8772	.0301	24
	T-L	.9169	.0162	16
604	L-T	.9036	.0216	19
	T-L	.9200	.0181	19

was more variable than the other Os. From Fig. 4 and from the averaged P(c) in Table 6 it becomes apparent that the experimental manipulaton had a minimal effect on the overall probability of a correct response. The P(c) averaged over all Os for each condition is .8986 for T-L and .883 for L-T, showing an increase of 0.015 from L-T to T-L. Actually, only two Os, 601 and 603 show a difference between conditions which is larger than 0.02.

The individual psychometric functions are reported in Table 7 for both experimental conditions. A visual observation of the functions shows that the difference in P(c) between T-L and L-T reported for Os 601 and 603 is accounted for by an improvement in performance at d_1 and d_2. Furthermore, O 503 and to lesser extent O 604 display a shift in decision criterion across experimental conditions That is, $P(R_1|d_1)$ and $P(R_1|d_2)$ increased by a comparable amount from L-T to T-L thus maintaining overall performance level constant since the improvement of correct R_1 to d_2 was balanced by an increase in erroneous R_1 to d_1. Thus, the conclusion drawn from examination of overall P(c) is corroborated by an analysis of the complete psychometric functions.

It is interesting to compare the level of performance in the present experiment with that of expt 1 and other intramodal experiments as shown in Table 1. Estimates of DT_{75} were obtained by linear interpolation from $P(R_1|d_1)$ and $P(R_1|d_2)$. The individual estimates were averaged yielding a DT_{75}=80.59

Table 7

Individual $P(R_1|d_i)$ from data pooled over the last 8 sessions under each condition.

O	Condition	d_i 100	200	300	400
605	L-T	.005	.085	.9183	.996
	T-L	.002	.096	.915	.993
503	L-T	.003	.085	.690	.926
	T-L	.005	.216	.825	.963
603	L-T	.022	.220	.798	.946
	T-L	.033	.145	.861	.958
604	L-T	.006	.105	.751	.975
	T-L	.001	.135	.825	.966
602	L-T	.083	.261	.736	.936
	T-L	.143	.288	.751	.901
601	L-T	.018	.168	.626	.940
	T-L	.005	.155	.753	.986

msec. in condition L-T and 73.73msec. in condition T-L. The computation of the Weber ratio with base duration d_1 and without O 601(his inside values were different) yields values of .475 in condition L-T and .384 in condition T-L. By comparison with intramodal results these ratios are still larger and indicate that intermodal markers give rise to a performance which is generally poorer than in intramodal conditions at shorter values of T. On the other hand, they differ markedly from those reported in expt 1. Indeed, the averaged DT_{75} is around 80msec. in condition T-L, half the value of 160msec. reported in expt 1. It is difficult to pinpoint the actual reason for such an occurrence, but it is likely to be related to the method used in the present experiment. Maybe the fact that both in practice and in experimental sessions the set of d_i was never changed makes the practice more important and useful in the experimental sessions. In any case, it seems that the methodology would be a variable of great importance more so than stimulus conditions as shown by the present results and those of expt 2. The next experiment gives more information on this question.

2.4 Experiment 4: Individual Weber functions.

In the present experiment individual Weber functions were obtained from four Os for M.P. between 175 and 1200msec. with the M.-F. method. Establishing the shape of the function could give some information on the possibility that the M.-F. method calls for the utilisation of a mechanism different from the one operating when an SS method is used, as was the case in expt 1. That could be the case if the functions turned out to be markedly different from the one reported in expt. 1. But, if the zero-slope function should hold in the present study, within individuals, it would definitely reduce the importance of any difference in level of performance which could be observed. Indeed, if corroborated the surprising violation of Weber's law would become determinant for the definition of the type of mechanism in operation in intermodal duration discrimination.

Method

Four Os were used in the experiment. Three were naive Os 301,302, and 304; one was experienced O 1. Each naive O ran through a pre-test of 10 sessions of 300 trials each with d_o=100msec. and d_1=250msec.

The sequence of events in a trial was similar to the one used in the previous experiment in the L-T condition. The stimuli were presented according to the M.-F. method. The main set D contained 4 intervals distributed symmetrically around the M.P. The first M.P. was 175msec. for Os 302,304, and 1; the second one was 200msec. After that, M.P. was shifted by increments of 100msec. every 3 sessions. O 301 started at an M.P. of 300msec. and continued with 100msec. increments. O 302 carried on to an M.P. of 900msec. while O 301 and O 1 went up to 1100msec.; O 304 reached 1200msec. The values of each individual set D are reported in Appendix A, Table A7. Because of a difference in keenness of discrimination a different set D was used for O 301 but, a similar one was kept for the other three Os. Furthermore, the distance to each d_i from M.P. was not kept constant over the whole range of M.P. in order to maintain the overall P(c) as constant as possible. Unfortunately this proved to be a hard task and overall P(c) did vary.

The first session under each M.P. value was used as practice and the experimental data came from the other two sessions. Each session had three blocks of 100 trials where every d_i was presented 25 times in a random order. Thus, at each M.P. a psychometric function was obtained with 150 trials per point.

Results and Discussion

The individual $P(R_1|d_i)$ for each d_i at all M.P. are reported in Table A7. These $P(R_1|d_i)$ are averages of the last two sessions at each M.P. unless otherwise indicated. Detailed analysis of the psychometric functions will not be done because of the small number of points available. In Chap.III expts 5 and 6 will provide data more suitable to study the effect of shifts in D on performance. Moreover, because the distance from each d_i to M.P. was not kept constant the variations in overall P(c) observed from M.P. to M.P. cannot be assumed to be related solely to the changes in M.P. Thus, the analysis of the results will concentrate mainly on the individual estimates of DT_{75} estimated by linear interpolation from $P(R_1|d_1)$ and $P(R_1|d_2)$ and reported in Table 8. The averaged DT_{75} vs M.P. function was fitted by a straight line with a least-square procedure which showed DT_{75}=.1904 M.P.+34.03. The linear linear fit, as displayed by the coefficient of determination r^2, accounts for 97% of the variance in the data. Thus, while the averaged function does not support the exact Weber's law, it does show DT_{75} as proportional to M.P. Treisman (1963) has also reported a linear DT vs T function for a comparable range of durations of empty auditory intervals. The fact that the function has a non-zero intercept indicates that the DT_{75}/M.P. vs M.P. function will not be a straight line because the ratio is increased by an amount of 34.03/M.P. However, this increment will become negligable as M.P. becomes larger and DT/M.P. will tend to be asymptotic as a function of M.P. Such a relationship is clearly displayed in Fig.5 where individual and averaged Weber ratios are presented as a function of M.P. The averaged function is stable around .23 from 500msec. to

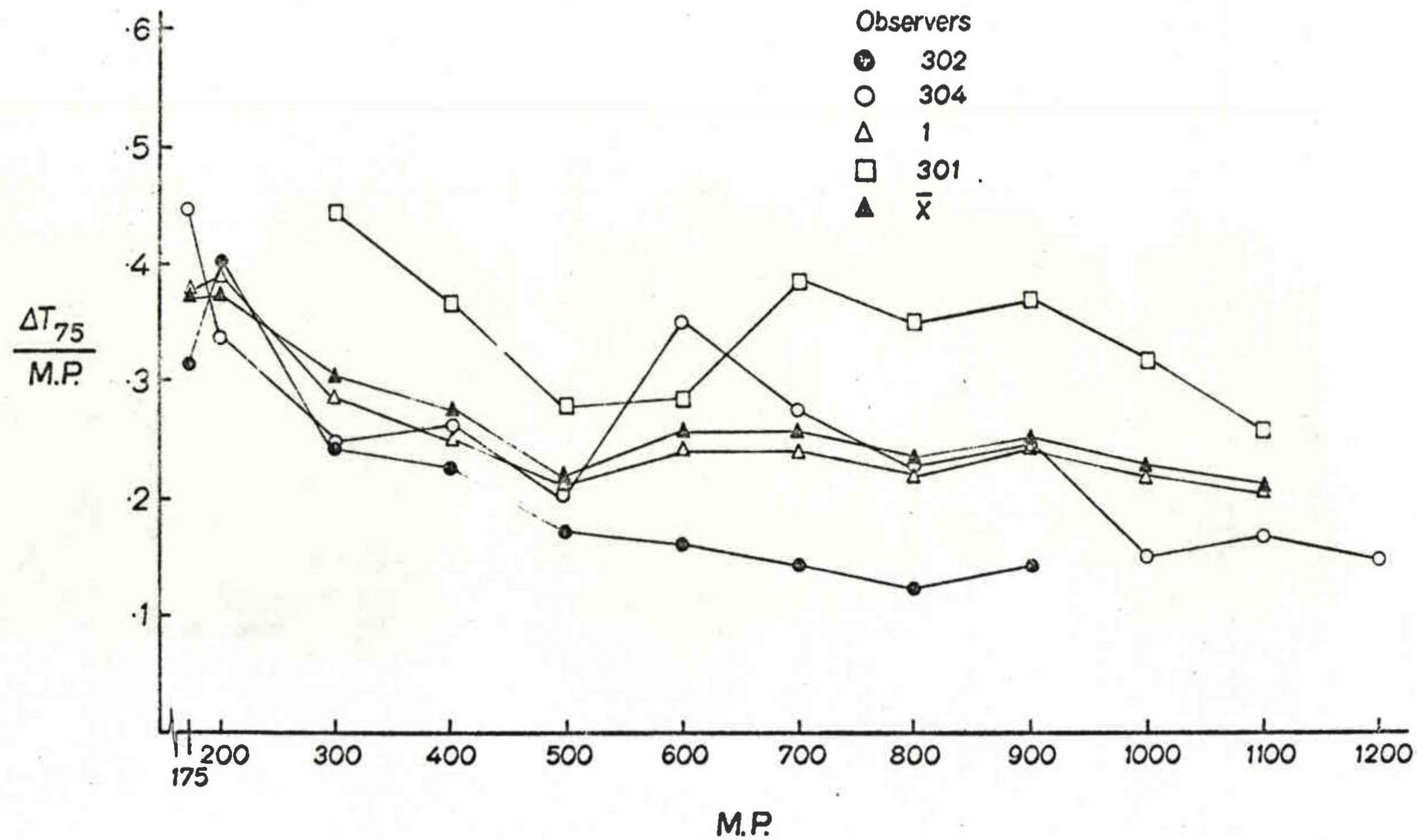


FIGURE 5. Individual estimates of the Weber ratio where T=M.P.

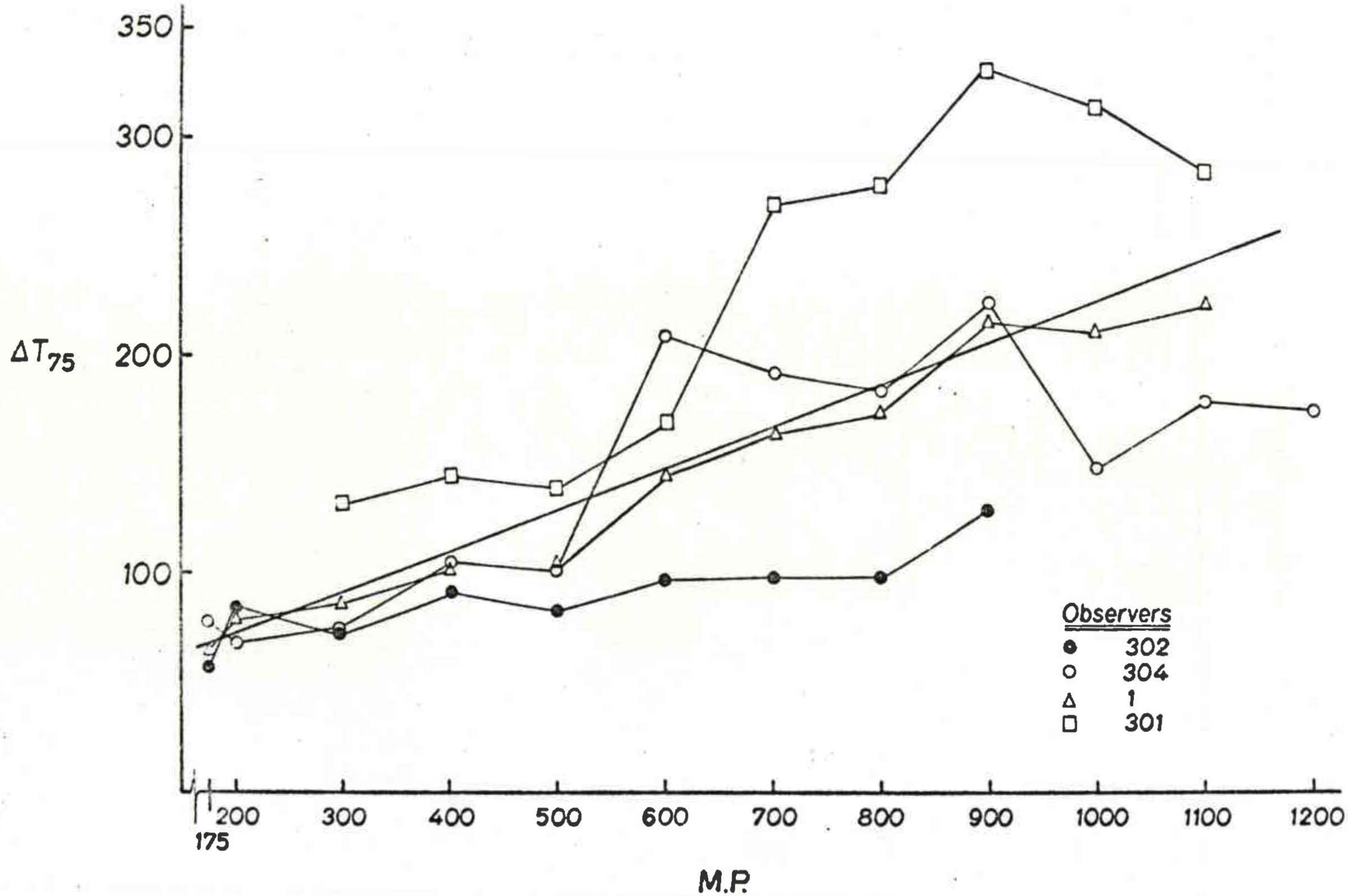


FIGURE 6. Individual DT_{75} as a function of M.P. for each of D.

1100msec. This ratio of .23 is larger than most values reported in Table 1. It is interesting to note in Fig.5 that at M.P. 600 the ratio is .26 whereas it was .2715 in experiment 1 at d_o=600msec. Thus, by that point, the improvement in performance which was observed in the early part of the function would seem to have disappeared. Unfortunately, the individual functions do not give such a simple picture. Indeed visual observation of the DT_{75} vs M.P. functions in Fig. 6 shows those of Os 1 and 302 to be somewhat linear, whereas those of Os 304 and 302 have marked non linearity and even non monotonicity. Actually, for O 304 the middle portion (M.P.=600 to M.P.=900msec.) of the function is very different in slope and level from the other two portions. Similarly, O 301 shows a function which would be best fitted by two segments, one from 300 to 600msec. and the other from 700 to 1200msec. This seems to be somewhat the case for all Os. Os 304, 302 and 1 display almost identical functions up to an M.P. of 500msec. after which they become different. However, it is hard to decide on the reason for such a shift around M.P.=600msec. The extended practice that the Os had at M.P. 175 during the pretest might have influenced the early part of the function after which some Os became more variable. That is not to say that they were using a different mechanism but simply that they might have needed more practice to obtain optimal performance.

So, while expt 1 produced a DT_{75} vs T function which

Table 8

Estimates of DT_{75} at Midpoint (M.P.) values ranging from 175msec, to 1200msec. for four Observers.

M.P.	Observer				
	304	302	1	301	X
175	77.68		65.104		65.98
200	67.02	80.64	78.49		75.38
300	73.52	72.78 (1)	85.76	132.62	91.17
400	104.38	90.74 (1)	101.42	145.77	110.77
500 (1)	100.60	85.47	105.26	139.66	107.74
600	207.46	96.15	145.34	169.49	154.64
700	190.07	98.81	163.93	267.37	180.04
800	182.48	97.08	173.01	278.39	182.74
900	222.06	127.87	216.45	330.46	224.21
1000	147.05		213.67	312.50	224.44
1100	178.57		(1) 223.14	263.60	228.40
1200	174.50				

(1) These values were obtained from one experimental session only. All the other ones are averages of the estimates of two sessions.

was in clear violation of Weber's law the present one shows DT_{75} as an increasing function of M.P. However, the large individual differences in the form of DT_{75} vs M.P. function do not allow for the specification of a generalised relationship. At best, the function presented in Fig. 6 can be described as being formed of two regions, one above, B, and one below, A, 500msec. For all the Os the A-region shows DT_{75} as a slightly increasing function of M.P. Furthermore, the functions are very linear and display little variability. On the other hand, the B-function in the case of Os 1 and 302 is the continuation of the A-region and shows similar characteristics of linearity and stability. For the other two Os the variability is larger and DT_{75} is roughly constant around a mean value twice that of the A-region. Thus, it is difficult to describe precisely the Weber function for values of M.P. larger than 500 to 600msec. However, for the A-region the conclusion can be more definite and it does not corroborate the constancy of DT_{75} reported in expt 1. Finally, it is interesting to note that even though DT_{75} is a function of M.P. the DT_{75}/M.P. vs M.P. function does not show the Weber ratio as constant which, as we said in 1.4.1, is a common finding when T values approach absolute threshold.

2.5 General discussion.

The goal of Chap. 2 was to obtain basic information on the effect of non-temporal stimulus variables in inter-modal duration discrimination and, to determine the shape of the Weber function. Experiments 2 and 3 showed that certain non-temporal stimulus variables have a minimal effect on performance. Changing the duration of the first pulse produced no variation in performance level over a large range of first pulse durations. On the other hand, the sequence of markers T-L yielded an averaged $\bar{DT}_{75}$ of 73.73msec. 7msec. shorter than for the L-T sequence. However, in both the T-L an L-T conditions, the level of performance was much better than in expt 1 at comparable durations.

Different psychophysical methods gave quite different results. The clearest way to see the difference is in observing the functional relationship between DT_{75} and T under each method in expts 1 and 4. Actually, this is the most important part of the results since we are trying to establish the shape of the DT vs T function. The averaged DT_{75} are presented at all values of T used in the first four experiments in Fig. 7. From this figure a partial answer to a comment made in 2.4 can be given. It is likely that the function obtained in expt 4 is mainly due to the use of the M.-F. method and

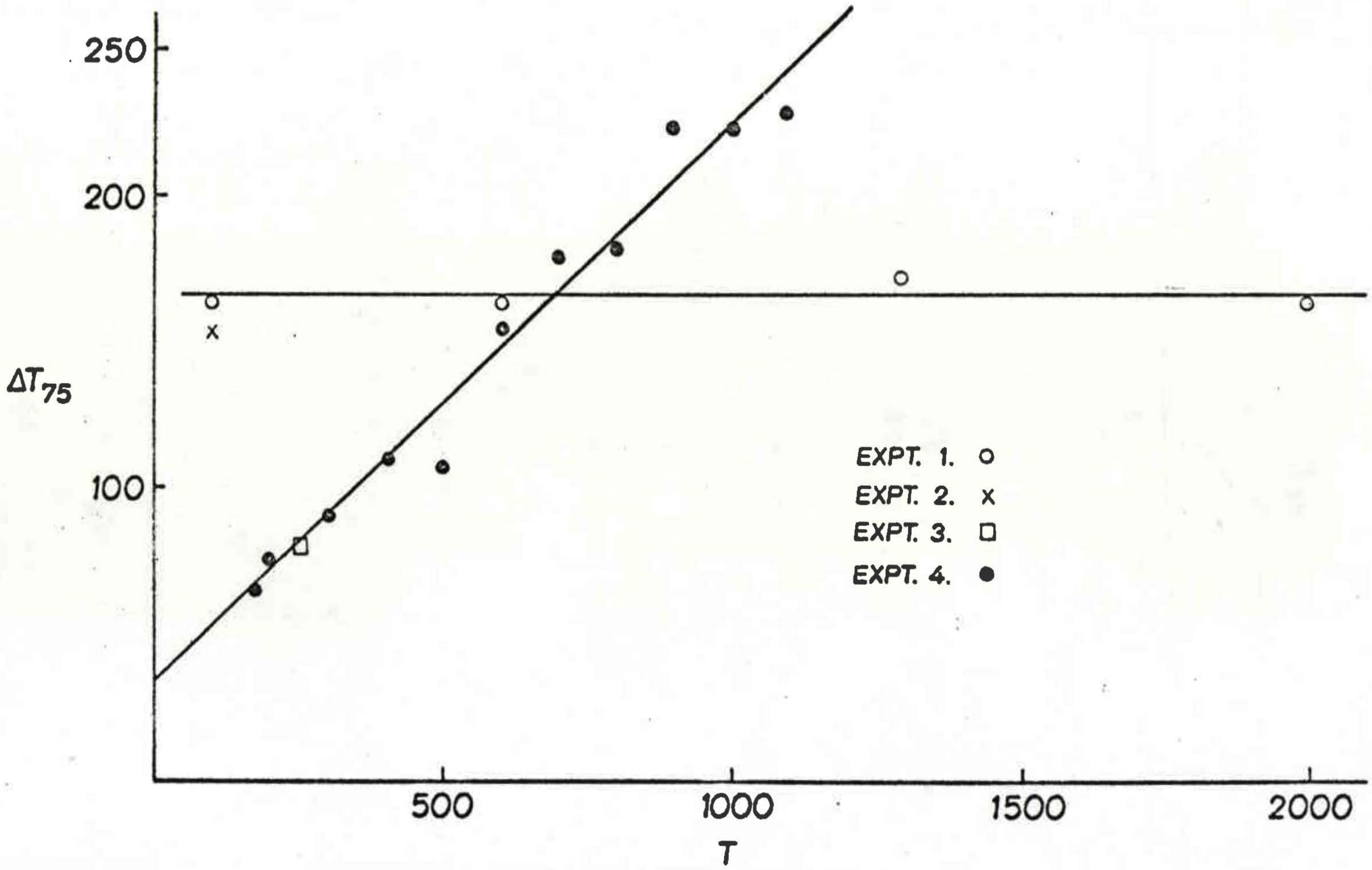


FIGURE 7. Estimates of DT_{75} obtained in the first four experiments as a function of T. In expt 1 and 2 T=0, in expt 3 and 4 T=M.P.

not to the within O design. This is supported by the fact that estimated DT_{75} for expt 3 where the Os ran in only one M.P. falls exactly over the function obtained in expt 4. However, with regard to expt 1 we do not know if it could be replicated within Os. Yet, it is very likely that the level of performance observed at short values of T would stand, on the average, since the results of expt 2 corroborate those of expt 1. So, we would like to propose that there is a strong possibility that different mechanisms are operating in the two methods used in Chap II, the M.-F. method and the method we will designate under the name SS (single-stimulus). The difference between the M.-F. method and SS method is further shown in the test of the generalisation reported in 2.1 for the SD/DT_{75} ratio. A two point psychometric function was obtained from expt 3 by taking $DT_o=d_3-d_o$ and $DT_1=d_2-d_1$ and defining $P(c)_o=[P(R_o|d_o)+P(R_1|d_3)]/2$ and $P(c)_1$ in a similar way from data averaged overall Os in condition L-T. The SD/DT_{75} ratio is at 3.1 a value quite different from those around 1.8 reported in section 2.1. Further visual inspection of Fig.7 shows the M.-F. performance as better than the SS for T values up to 700msec. Then as T increases the M.-F. becomes worse than the SS performance. However, in section 2.4 it was shown that the averaged data was much less representative of individual data for T values larger than 700msec. Actually we would like to propose that in as much as the present data are concerned, the performance with the M.-F. method deteriorates as T is increased to reach the level of the SS method around T=700msec. However, the specification of the functions at M.P.>700msec. would necessitate further experimentation both with the SS and M.-F. methods.

Thus, it can be argued that at least for shorter T values, different timing mechanisms might be available to an observer in intermodal duration discrimination. These mechanisms would have different operating characteristics. Since each mechanism appears to be related to a particular psychophysical method, one might get some information on these characteristics by analysing certain features of the methods.

Allan & Kristofferson (1974a) noted that all current models of duration discrimination assuned $d_i(I)$ to be the outcome of a timing operation performed over the total temporal extent of d_i. The discrimination would be made by comparing the value of I yielded on a trial with a variance free criterion K(I). They proposed an additional mechanism in which a real time criterion of mean duration approximately M.P. could be triggered at the onset of the interval. The discriminative judgement could be made on the relative order of occurence at a decision center of the termination of the criterion at t_c and the offset of the interval at m_2. If t_c is registered first an R_1 response is emitted. On the other hand R_o is given if m_2 occurs first. In that mechanism, there is no actual measurement of duration over d_i as in the models reviewed in section 1.4.

It is interesting to note that the M.-F. and SS method differ in the opportunity given to the O, to develop either type of processing. Indeed, it is very likely that the establishment of a real-time criterion requires practice (Kristofferson,1973). So, this would be best done in situations in which the real-time criterion is kept constant over long periods. More specifically, it has to be an efficient decision making device over many sessions. While that may be the case in the M.-F. method, it is unlikely to be so in the SS method. Indeed, in the latter, the distance between d_o and d_i is varied from one session to the next and it is very unlikely that the O, can form a stable real-time criterion that can be used for different d_o-d_i pairs. On the other hand, the use of a particular mechanism to perform the discrimination could be related to the structure of the stimulus-response mapping in a given method. Indeed, it could very well be that in the M.-F. method the identification of more than one stimulus with a given response favors a mechanism which is not linked to the measurement of the whole interval. Indeed, the real-time criterion as described before could very well be inefficient in an M.-F. situation if each d_i was associated with a different response.

Thus, it could be that in the M.-F. method a real-time criterion is operating and that it is more efficient at short d_o than an interval measurement. However, from the results in Fig.7, the interval measurement as used with the SS method, could be more efficient at longer values, or at least as efficient as the real-time criterion.

It becomes more and more apparent that more than one central mechanism could be available to an O, in a duration discrimination task. Indeed, in an intermodal situation, even if we have isolated the mechanism as probably central, we are still faced with the possibility that at least two central operating mechanisms can be used to perform the discrimination.

Finally, it is now evident that at d_o or M.-P. values shorter than 1,200msec. the level of performance obtained in intermodal situations is definitely worse than in comparable intramodal ones. Thus, the straightforward type of argument reported in section 1.2 where identical levels of performance supported the claims of a single central processor cannot be used in the present case. The nature of the stimuli bounding an interval are of importance even though within the intermodal situation the specific sequence under study is of little importance. With regard to the assumption that intermodal duration discrimination requires the operation of a central timing mechanism, the present results yield ambiguous evidence. While Allan et al (1971) received direct support from expt 1, expt 4 is more directly accounted for by Creelman's (1962) model.

Thus, in the next chapter we will seek more information on those lines. That is to say we will evaluate the capacity of models developed for intramodal discrimination, to account for performance in intermodal situations. However, one can expect all models to have difficulty in accounting for the totality of the results reported in Chap.II. Indeed, from the two Weber functions obtained in expts 1 and 4, very general predictions of the models can be evaluated. We have shown in section 1.4 that Allan et al (1971) and Kristofferson (1966) made the strong deduction of independence of sensitivity from the absolute values of the durations to be discriminated. On the other hand, Creelman (1962) and Kinchla (1972) predicted that a monotonic decreasing function would best describe the relationship between the performance index DT_{75} and T. Thus, the function reported in expt 1 is a strong support for Allan et al (1971). Indeed, the preformance remains stable over a large range of durations as predicted by the model. However, the linear increasing function obtained in expt 4 can be more readily explained by Creelman (1962) and Kinchla (1972) because of the clear dependence of the performance level on the absolute values of T. Unfortunately, one only has to recall the individual functions of expt 4 to see that quite likely these models would have some difficulty to account for the functions displayed by Os 304 and 301. So, even within the class of interval measurement models, different mechanisms could be operating in various conditions of intermodal discrimination.

III QUANTITATIVE MODELS IN INTERMODAL DURATION DISCRIMINATION: EXPERIMENTS 5 AND 6

3.1 Introduction

In the present chapter, we intend to obtain more information on the characteristics of a central duration processing device. It was concluded in section 2.5 that quite different mechanisms might be used in various duration discrimination situations. More precisely, the performance in an intermodal duration discrimination task was shown to be adequately described in some cases by a function of the form $DT_{75}=K$ and in other cases, $DT_{75}/T=K$. These two types of functions are consistent with different classes of models described in section 1.4, of which the onset-offset model (Allan et al, 1971) and the Poisson counter model (Creelman, 1962) are representative. Thus, experiments 5 and 6 were done in order to evaluate these two models in an intermodal duration discrimination situation. These models make their stronger predictions with regard to the variations in performance as a function of T. So, psychometric functions were obtained at different ranges of T with the M.-F. method. In a first step, two groups of Os were run one at M.P.=300msec. (expt 6) and the other at M.P.= 600msec. (expt 5). The next step consisted in within Os comparisons of the effects of shifting M.P. within the same set D symmetrical around 300msec. In such a set-up, the subsets D_s

and D_1 are modified without changing any of the intervals.

Before carrying on with the experimentation proper we will analyse in more detail the models that we intend to evaluate in this section. Although the basic structure of the models was given in section 1.4, it was then related to a type A partitioning and cannot readily be applied in the present case. Thus, we will proceed to describe the modifications that the use of a type B partitioning imposes on the models.

3.2 Modifications of duration discrimination models.

3.2.1 Onset-offset model

Kristofferson (1973), and Allan & Kristofferson (1974b) presented a modification of the onset-offset model which dealt with the problem of the non-linearity of the dq vs DT function for values of dq>.5; reported previously (e.g. Allan & Kristofferson,1971;McKee et al,1970). Within the context of a quantal model, where the O should reach perfect performance, they argued that the non-linearity was caused by the O emitting responses which were not stimulus-controlled on a certain constant proportion of the trials. Thus, they assumed that when a stimulus d_i is presented, the O will enter a "non-process" state $\bar{p}$ with a probability ε, in which case he will guess and give a response R_1 with probability α. Otherwise, the O will be in a process state and emit an R_1 response with a probability β_i as defined in the onset-offset model.Thus,

$$P(R_1|d_i)=\varepsilon\alpha+\beta_i(1-\varepsilon)$$

In such a situation, the observed $P(R_1|d_i)=\beta_i$ when $\varepsilon=0$. In general β_i is defined as follows:

$$\beta_i=\int_{d_c}^{d_i+q} f(I)dI$$

where d_c is a duration for which $P(R_o)=P(R_1)=.5$ and, d_i is a given interval in a set D of n intervals. Since we are dealing with a quantal model, it is possible to define stimulus values for which $\beta_i=0$ and 1. These values are reached, for a given d_i, where $d_c<d_i-q$ and $d_c>d_i+q$. Deviations from perfect performance for any d_i which generates internal distributions not overlapping the response criterion, could be assumed to be due to the non-processing of the stimulus.

The M.-F. method provides an efficient means to obtain such information. In the present case, we have a main set D=6 where d_o and d_5 were placed far enough apart so that both were at least q msec. away from the mid-point. Thus, from the values of $P(R_1|d_o)$ and $P(R_1|d_5)$ one can derive estimates of ε and α where:

$$\varepsilon=1+P(R_1|d_o)-P(R_1|d_5) \tag{3}$$

$$\alpha=P(R_1|d_o)/\varepsilon \tag{4}$$

Thus, the probability of an R_1 response being emitted in a process state following the presentation of a given d_i will be:

$$\beta_i=\frac{P(R_1|d_i)-P(R_1|d_o)}{1-\varepsilon} \tag{5}$$

We will designate such an estimate as the corrected probability of a response R_1 to a given d_i. A minimal psychometric function can be generated from the other four inside d_i values, with the observed $P(R_1|d_i)$ corrected from the estimates of ε and α in order to obtain a more accurate representation of the d_q vs DT function.

In the original model d_q was defined as the distance between d_o and d_i in units of q. It is actually a sum of absolute values of triangular deviates $\Delta_q(R_1|d_i)$ obtained from $P(R_1|d_i)$.

The use of dq is less appropriate in type B partitioning because there is no base duration. However, one can still obtain a bias free measure of discriminability by using the triangular deviate Δq itself since it is defined by reference to a decision criterion. Then, the psychometric function $\Delta q(R_1|d_i)$ vs d_i can be defined as follows:

$$\Delta q(R_1|d_i) = \frac{1}{q}(d_i - d_c) \tag{6}$$

Thus, Δq will be a linear function of d_i with slope $\frac{1}{q}$ and reaching zero at $d_i=d_c$, -1 at $d_i=d_c-q$ and +1 at $d_i=d_c+q$. Thus, the slope and span of the Δq function are identical to the one displayed by a d_q vs DT function. So, despite some modifications the model keeps its basic characteristics:the mapping of real-time into internal time is one-to-one and thus, each d_i (I) will have equal variance $\frac{q^2}{6}$. The data in the following experiments will be presented in terms of Δq vs d_i or Δq vs (d_i-M.P.) functions. These functions will be analysed mainly with regard to their linearity which is essential for the assumption of constancy of q in a given set D.

An even stronger test of this assumption will be performed in exp 6 by defining three different successive response criteria on a constant set D. In such a situation if q is indeed a constant, one should obtain three parallel Δq vs d_i function with slope $\frac{1}{q}$. That experimental manipulation avoids the usual concomittent change in the set of d_i and M.P. In fact, in the present case, the O is always assessing the same set of d_i and only M.P. is varied.

3.2.2 Poisson counter model

As we have stated in section 1.4, Creelman (1962) proposed his model to account for duration discrimination performance in a two-alternative forced-choice situation. Allan et al (1971) proposed a modification of the model applicable to a single stimulus task. However, the index of discriminability d'_c, like d_q, was based on a type A partitioning and cannot be directly applied in the M.-F. method. Indeed, d'_c represents the distance between the mean of the internal distributions of counts corresponding to d_o and d_i, $d_o(I)$ and $d_i(I)$, in units of the standard deviation of $d_o(I)$. However, in the present case, there is no such base duration as in type A partitioning and the performance is best described with reference to the decision criterion. Thus, d'_c as such cannot be used in a straight forward manner in the M.-F. method. So, a modification of Creelman's model will be presented where an index of discrimination Z_c will be derived. This index will represent, very much in the same manner as Δq, the distance from the mean of $d_i(I)$ to a zero-variance decision criterion $d_c(I)$. Thus, following Creelman (1961), $d_i(I)$ will be encoded as a number, n. corresponding to the number of pulses occurring during d_i from a large source of elements whose probability of emitting a pulse at any moment is a constant, λ, and where the inter-pulse interval is exponentially distributed. In such a system the probability of n pulses occurring over d_i is $P(n) = e^{-\lambda d_i}\frac{(\lambda d_i)^n}{n!}$. However, it can be shown that for large values of λ, the Poisson distribution can be approximated by a normal distribution. Thus $d_i(I)$ will be described as a Gaussian random variable with mean and variance λd_i.

In a duration discrimination task where the M.-F. method is used one can describe the decision problem as follows: each interval d_i in a set can be assumed to be represented internally as a normal random variable $d_i(I)$ with mean and variance $\lambda d_o, \lambda d_1, \ldots, \lambda d_i, \lambda d_n$. Furthermore over a set of n distributions, one can determine a zero variance decision criterion, λd_c. Such a criterion would enable an O to organise a response-to-stimulus mapping in accordance with the task requirements. The decision structure is represented in Fig.8 for a set of 4 intervals.

Given such a situation it is assumed that an R_1 response will be triggered for all values of $I>\lambda d_c$, and an R_o response for $I<\lambda d_c$. Thus, the probability of an R_1 response for the d_o interval will be defined as:

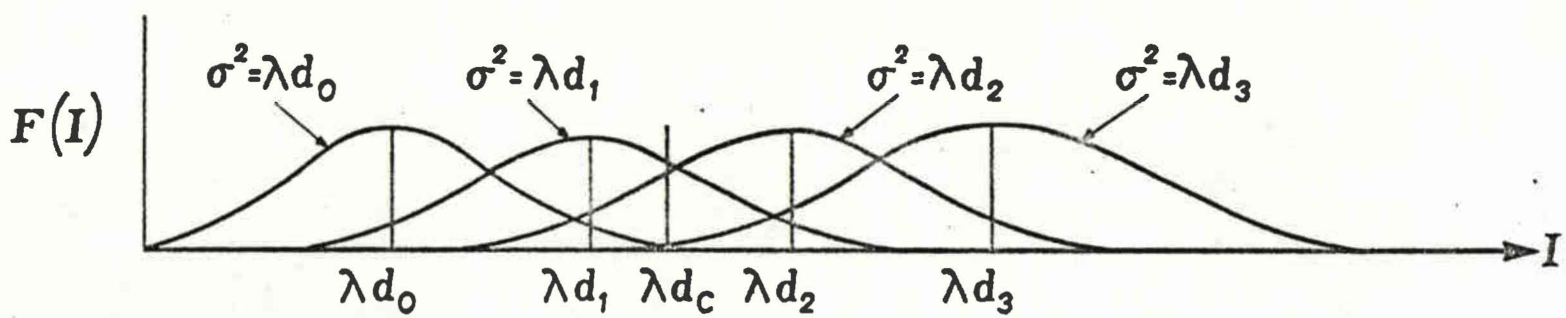


FIGURE 8. Internal mapping of four intervals in the Poisson counter model.

$$P(R_1|d_o)=\int_k^{+\infty} f(I|d_o)dI$$

then for any d_i,

$$P(R_1|d_i)=\int_k^{+\infty} f(I|d_i)dI$$

since $f(I|d_i)$ is $N\sim(\lambda d_i,\lambda d_i)$, it can be shown (Green & Swets, 1964) that

$$P(R_1|d_i)=\int_k^{+\infty} \Phi\left[\frac{\lambda d_i-k}{(\lambda d_i)^{\frac{1}{2}}}\right]dk$$

where all durations are expressed in sec.x10^{-3}, and $k=\lambda d_c$. So,

$$P(R_1|d_i)=\int_{\lambda d_c}^{+\infty} \Phi\left[\frac{\lambda^{\frac{1}{2}}(d_i-d_c)}{d_i^{\frac{1}{2}}}\right]dk \qquad (7)$$

conseqently, a normal deviate can be defined as:

$$Z_c(R_1|d_i)=\frac{\lambda^{\frac{1}{2}}(d_i-d_c)}{d_i^{\frac{1}{2}}} \qquad (8)$$

Then, one can use the normal deviate $Z_c(R_1|d_i)$ as an index of discrimination representing the distance between the mean of each $d_i(I)$ and the criterion λd_c in units of the standard deviation of $d_i(I)$. Since the distributions have unequal variance each $Z_c(R_1|d_i)$ will be obtained with reference to its respective variance λd_i i.e., $Z_c(R_1|d_o)$ will be estimated from $\frac{\lambda^{\frac{1}{2}}d_o-d_c}{d_1^{\frac{1}{2}}}$. Similarly, $Z_c(R_1|d_i)$ will be calculated from the equation $\frac{\lambda^{\frac{1}{2}}(d_1-d_c)}{d_1^{\frac{1}{2}}}$. Theoretical $Z_c(R_1|d_i)$ vs d_i functions were obtained for different values of λ. They are presented in Fig 9. It is readily apparent that the functions are non-linear. The non-linearity is more accentuated for the shorter d_i. Such functions show that for distributions whose mean is more than two standard deviations away from λd_c, a further

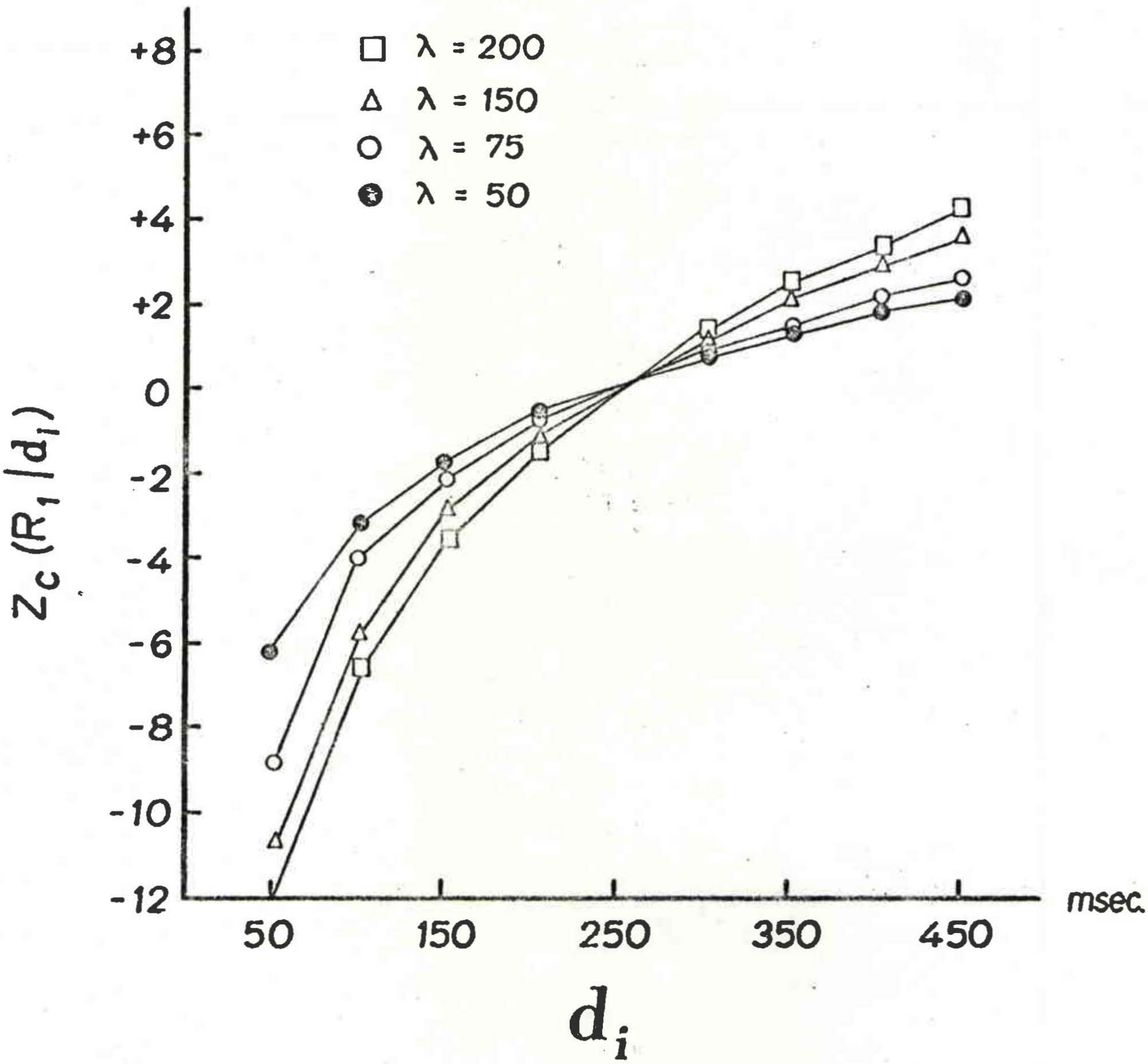


FIGURE 9. Theoretical $Z_c(R_1|d_i)$ vs d_i functions for a set of 8 d_i symmetrical around M.P.=250msec. at 4 values of λ.

diminution of the intervals will produce a faster improvement of the performance by comparison with an equal lengthening of the intervals. So a typical psychometric function as predicted by eq. 7 should show $P(R_1|d_i)$ vs d_i as a positively skewed sigmoid function. Furthermore, for a constant distance between λd_c and λd_i , $Z_c(R_1|d_i)$ is an increasing function of λ and the increase in Z_c is a function of the actual value d_i. By contrast with the onset-offset model, the discriminability will be a function of the actual set of d_i values used and not only of the absolute difference between any two d_i.

For classical psychophysics, the common way of expressing such a relationship between DT and the absolute value of the durations involved is given by the Weber function DT/T=K. If one assumed that a given set of data follows Weber's law, it would be interesting to observe how the Poisson counter model can account for the same set of data. In order to perform the analysis we allowed λ to vary between M.P. values. While maintaining the assumption that λ was constant, within a given set D we assumed that its value could be adjusted from one set D to another. Thus, in a way, this is not an integral part of a Poisson counter and can be considered as an empirical development. From an hypothetical set of data for which the Weber ratio was arbitrarily fixed at .10, λ was estimated for a number of M.P. values. The results presented in Fig.9 are quite interesting and show λt as a constant. Thus for data which can be represented by the Weber function, such a model

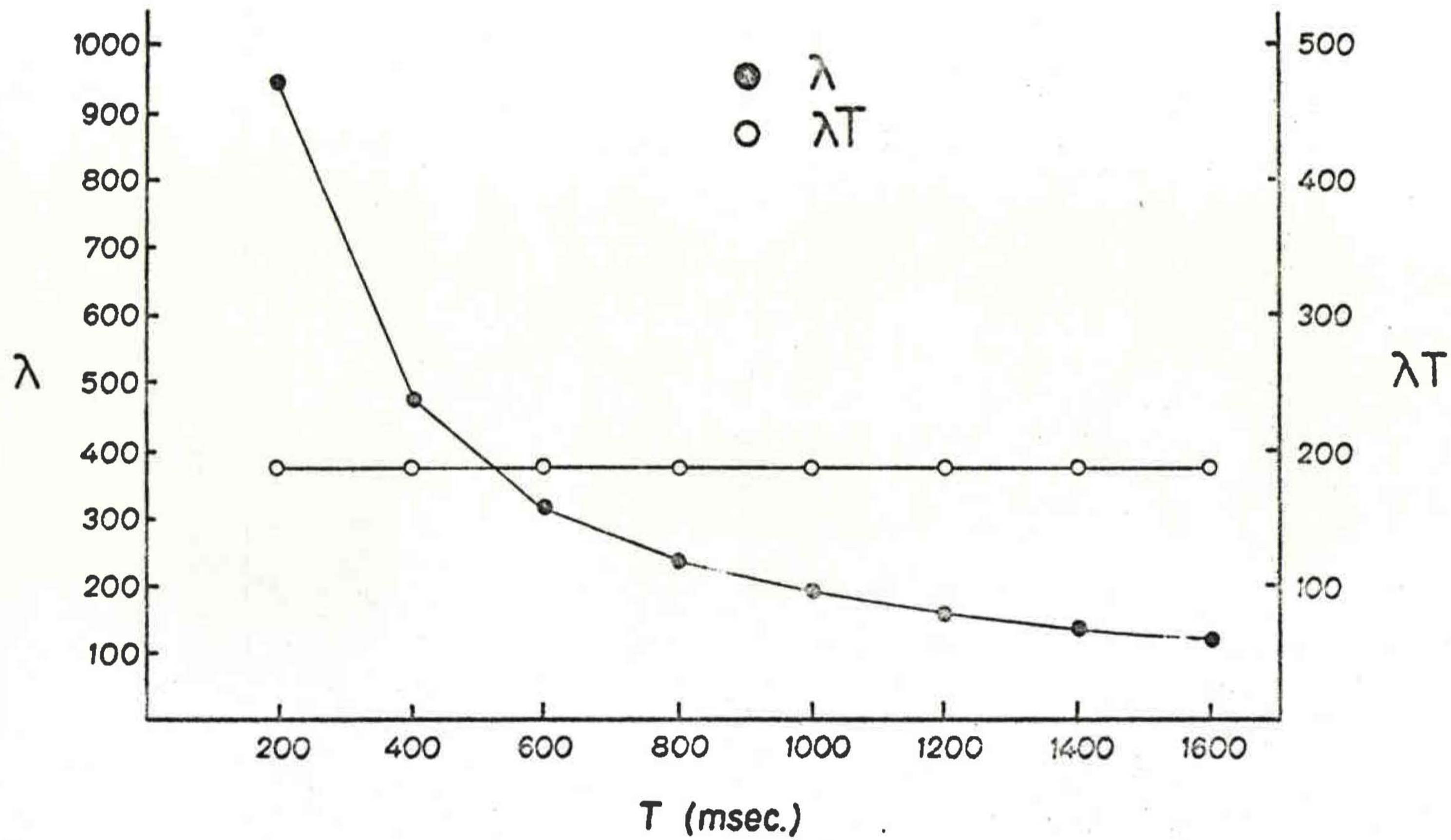


FIGURE 10. Theoretical estimates of λ and λT at values of T for which DT_{75} was calculated assuming $DT_{75}/T=.1$.

shows λT as being a constant. Since T is taken as M.P. and that M.P. is usually a good approximation of d_c it could be argued that λ would be modified in order to keep λd_c constant. Thus, internal distributions would be displaced in order to be set around a constant criterion value which could yield a better performance.

An interesting point is that, an increase in variance of the internal representation of a stimulus has been commonly associated with a decrement in performance (Treisman,1967). However, in the present case, since both the mean and the variance of $d_i(I)$ are equal to λd_i an increase in variance, e.g. by increasing d_i, is by definition linked to an equal increase in mean. $Z_c(R_1|d_i)$ is defined as the ratio of the distance between λd_i and λd_c, to the standard deviation, $(\lambda d_i)^{\frac{1}{2}}$. Then, for example, doubling d_i will increase the mean by a factor of 2 and the standard deviation by a factor of $\sqrt{2}$. So, while such a change in d_i does affect the variance, the overall effect on the performance in terms of Z_c will be an improvement since the variation in the mean will be larger.

Finally, it is important to note that, since in the M.-F. method the intervals are varied at random within a block, one has to assume λ to be constant for the entire set D. However, it is quite possible that λ could be varied over days or adjusted to different ranges of intervals when varied over a series of experiments.

3.3 Method

Three experienced Os were run in each experiment. They were Os 15, 6 and 1 in expt 5 and, Os 17, 2b and 201 in expt 6. Each O had previously participated in an intermodal duration discrimination task. They were all paid volunteers.

Because these two experiments were done at a one year interval, there are some differences in the characteristics of signals in a trial between the two situations. In expt 5, there was no warning signal and the duration of the markers was set at 500msec. There was a warning in expt 6 and the markers were at 10msec.

In both experiments the M.-F. method was used with a D of 6 intervals. For expt 5 all three Os ran through the same set: d_o=350, d_1=450, d_2=550, d_3=650, d_4=750, and d_5=850msec.

In expt 6 a series of 5 test sessions were run with only two intervals, one on each side of the M.P. 300, in order to obtain an estimate of the level of performance and thus, use a range of values which would be optimal for each O in the rest of the experimentation. There were 300 trials/session divided in three equal blocks in which each of the two intervals was presented an equal number of times in a random order. Following these test sessions, two Os, 201 and 17, performed with a similar set:150, 240, 290, 310, 330 and 450msec.;for O 2b, the set was:150, 240, 280, 320, 360 and 450msec. In all the experiments described previously, the M.P. was the reference point for stimulus-response mapping. However, in expt 6, other values were used which divided the set D non-symmetrically. So, the term "cut-off point" (C.P.) will be defined as the reference point which partitions D into the two response categories. With the main set D kept constant, three C.P. were successively used for each O. For Os 201 and 17 the C.P. were at 280, 300, 320msec. and they were at 260, 300 and 340msec. for O 2b. The reason for placing the inside four intervals closer together was to insure a reasonable error rate for the d_i further away from the assymetrical C.P. (e.g. d_4 when the C.P. in between d_1 and d_2). From these four inside d_i, three psychometric function were obtained successively, at an asymptotic level of performance. The outside values, d_o and d_5 were placed far enough from any C.P. so that they could be assumed to be outside the psychometric range. They were used only to obtain estimates of ε and β_i for the onset-offset model. In order to reach stable performance, each O was run for at least 16 sessions under each C.P. somewhat like in expt 3. However, in expt 5 each O was run for an identical number of 20 sessions. In all the cases, the data from the last 5 sessions were used as experimental data.

In expt 5 and for C.P.=300msec. in expt 6, there were 3 blocks of 90 trials per session. Each d_i was presented 15 times in a random order in a block. For the other two C.P. in expt 5, because of the assymetrical partition, the number of trials per d_i was determined in such a way that the O had, over a block, an equal probability of being presented with an element of the subset d_l and d_s. The were always four intervals in one subset and two in the other, and the intervals in the 2-element subset were presented 24 times each and those in the 4 element subset 12 times each. Thus, each session contained three blocks of 96 trials for a total number of 286 trials/ session.

3.4 Results and discussion

In the following section, for both models, we will first compare the estimates of the parameters q and λ for the different C.P. values. Then, we will proceed to the comparison of the predicted vs observed psychometric functions for the two models. Throughout the analysis of the results, the performance index P(c) and the discriminability indices Δq and Z_c will be estimated from the inside four d_i.

The stability of the experimental data is illustrated in Fig. 10 where overall P(c), averaged over all Os, is presented for each daily session. It is apparent that expt 6 shows no gain in performance over days, whereas in expt 5 the increase is of about .05 over the twenty sessions. This small effect of practice might be due to the fact that all Os had previously run in a similar experiment. The stability of the performance for each O in expt 6 was further assessed by fitting a straight line with the least square method to the daily values of P(c) for the last five sessions at each C.P. value. The parameters of the analysis (slope and y-intercept), and total number of sessions in a condition are presented in Table B_1, Appendix B. In all cases, the increase or decrease in P(c) over the experimental sessions was smaller than .05.

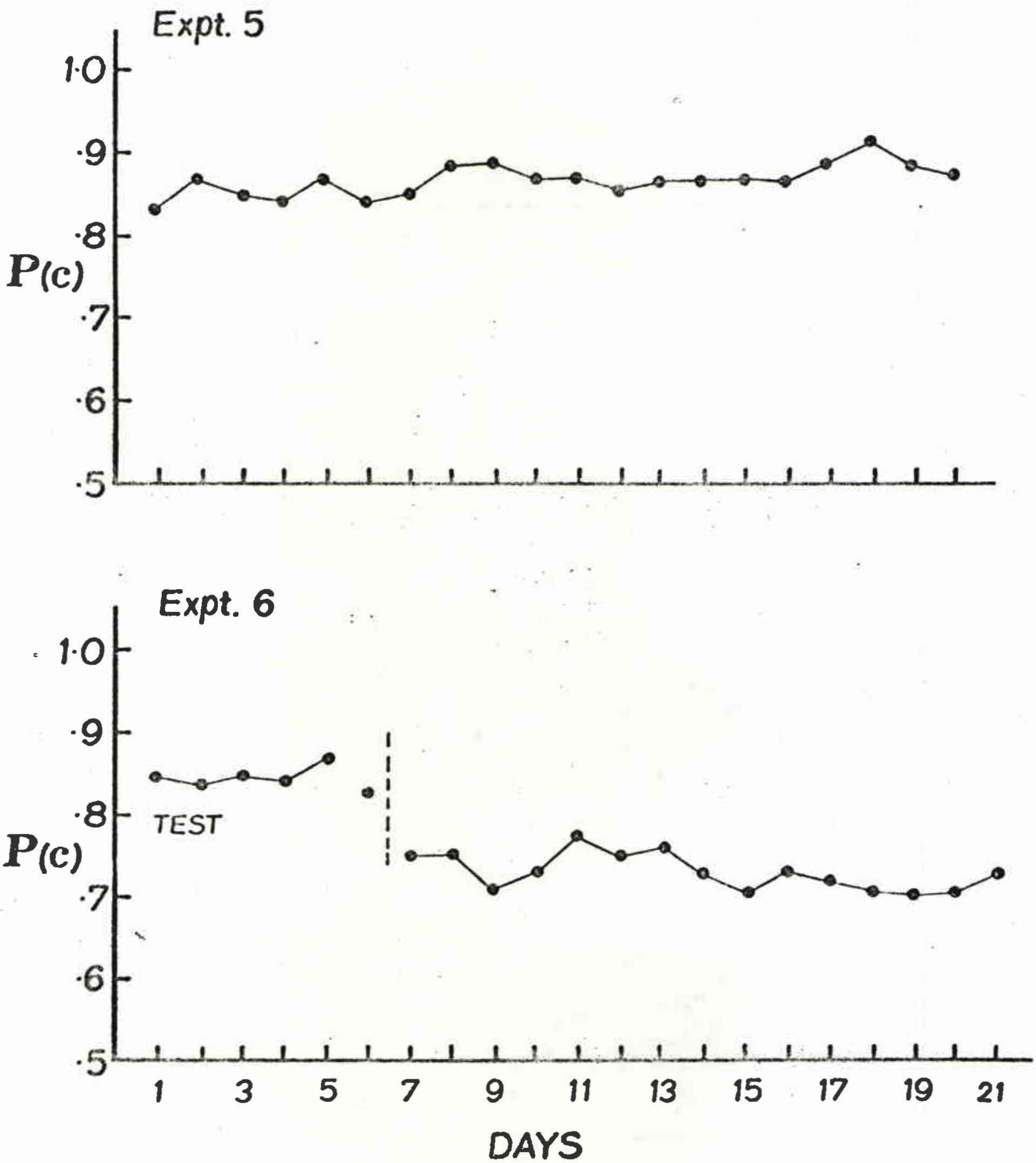


FIGURE 11. Overall P(c) at each session of experimentation estimated from data pooled over all Os in expts 5 and 6.

3.4.1 Parameter estimation

In the following section the parameters of the Poisson counting model and the onset-offset model will be estimated. The behaviour of these parameters as a function of C.P. will be evaluated in accordance with each model's predictions.

The Poisson counter model

We proposed in section 3.2.2 that with the M.-F. method the main parameter λ should be constant for a given C.P. value, but could be modified over various C.P. points. λ was estimated by using d_c and λ as free parameters and by iteration determining the combination of these two parameters which would minimise the following sum of squared deviations between $\hat{Z}_c(R_1|d_i)$ and $Z(R_1|d_i)$. Estimates of $P(R_1|d_i)$, $\hat{Z}(R_1|d_i)$, $Z(R_1|d_i)$ and the sum of squared deviations are reported in Tables B2, B3, B4, and B5 in Appendix B. The estimates of λ are reported in Table 9 for expt 5 and 6. It is readily evident that λ does vary over C.P. values. On the average, λ at 600 is less than half the value it is at C.P. 300. On the other hand, although C.P. was varied in expt 5, the shifts were rather small and make it practically impossible to use the variations in C.P. to further specify the λ vs C.P. relationship. Actually, the one feature evident from the estimates in expt 6 is the large variability in λ although the experimental data were gathered in conditions of assymptotic performance.

However, it could be interesting to examine the constancy of the expression λC.P. Indeed, since it was shown in section 2.4 that the M.-F. method yielded DT_{75} vs T functions close to Weber's law, λC.P. should be expected to be constant in the present experiment. The estimates of λ were multiplied by each C.P. and the outcome is presented in Table 9. Actually averaged λT at M.P.=600msec. is 43.2 while it is 50.4 at M.P.=300msec. These figures are quite close to each another given we are dealing with two independent groups of Os. That suggests that a timing mechanism might be operating with a constant absolute value decision criterion as proposed in section 3.2.2 Finally, it is interesting to note that in spite of small shifts in C.P. in expt 6, Os were able to displace their decision criterion, d_c, with remarkable accuracy. Furthermore, the accuracy does not appear to be a function of C.P. Estimates of d_c were no closer to C.P. in expt 5 than in expt 6.

The onset-offset model

In the onset-offset model, the estimation of q is made simpler by the prediction that the $\Delta q(R_1|d_i)$ vs d_i function is linear. However, estimates of the parameters ε and α will first be obtained in order to correct the $P(R_1|d_i)$.

Individual estimates of $P(R_1|d_i)$, β_i, $\Delta_q(R_1|d_i)$, ε, and

Table 9

Estimates of λ and d_c, and the sum of squared deviations for each O in experiments 5 and 6.

O	C.P. (msec)	λ	d_c (msec)	Σdev^2	$(\lambda C.P.)\times 10^{-3}$
6	600	87.5	604	.1034	52.5
15	600	86	592	.002	51.6
1	600	42.5	600	.0124	25.5
17	280	160	280	.0042	44.8
	300	235.5	307	.0088	70.65
	320	180	327	.0392	57.6
201	280	257.5	283	.0005	72.1
	300	203.5	298	.003	61.05
	320	134.5	324	.0998	43.
2b	260	94.5	263	.0163	24.57
	300	125	294	.0290	37.5
	340	120	336	.0249	40.8

α are reported in Tables B6, B7, B8 and B9 in Appendix B. It is interesting to note that for Os 6, 15, 201 and 17, ε is smaller than .02 while it is at .04 for O 2b and .09 for O 1. Thus, in most cases the correction is minimal. However, for 2b at C.P.=260msec. the correction was not applied because the uncorrected estimate of q shows that d_o is not outside the psychometric range. For O 2b at C.P.=340msec. a similar case occurs. However, because d_5 is at the limit of the psychometric range (4msec. away from the d_c+q point), the correction was made.

The estimates of d_c and q were obtained by fitting a straight line to the corrected $\Delta q(R_1|d_i)$ vs d_i function with a least square technique to the inside four d_i.

In the original onset-offset model q was defined as a constant. However, recently (Allan & Kristofferson,1974b) it appeared that q, while being constant over certain ranges of duration, varied between different regions. That is to say, the q vs M.P. function displayed a step-like shape;q would be constant over a given range and then increase abruptly to remain somewhat constant at this new larger value for a certain range of M.P. values. The results reported in Table 10 show that q is a function of the C.P. under study. Averaged q is 202.6 at C.P.=600msec. and falls to 93.54 at C.P.=300msec. From the results displayed by Os 17, 201 and 2b in expt 6 q does not appear as a systematic function of C.P. Although O 201 does show a regular increase in q as C.P. is varied.

Table 10

Estimates of q, d_c, r^2 for each O in experiments 5 and 6.

O	C.P. msec.	q(msec.)	d_c(msec.)	r^2
6	600	187.79	611.45	.9881
15	600	189.91	596.40	.9988
1	600	228.11	650.70	.9999
17	280	103.20	280.00	.9938
	300	81.14	307.00	.9721
	320	95.30	327.30	.9721
201	280	80.30	284.10	.9990
	300	86.90	299.30	.9936
	320	103.08	323.60	.9307
2b	260	140.40*	263.60	.9786
	300	112.59	297.50	.9991
	340	114.10	337.20	.9992

*This value is from uncorrected $P(R_1|d_i)$.

Actually, somewhat like for λ, q is variable as C.P. is varied but the small shifts in C.P. do not allow for a definite description of the q vs C.P. function

3.4.2 Psychometric functions

A direct comparison of the sum of squared deviations between observed and predicted $P(R_1|d_i)$ for each model is given in Table 11. The Σdev^2 was prefered to r^2 because in all the cases except C.P.=320 values for O 201, $r^2 > .98$. However, while Σdev^2 might render a discrimination of fitness easier, it becomes already apparent that both models account very well for the observed data. An examination of Table 11 corroborates the similitude between models. Indeed, the onset-offset model fits better 6 out of the 12 sets of data reported, while the Poisson model is better for the other 6. Similarly, for both models, the largest Σdev^2 are observed for the same psychometric functions mainly, C.P.=320 for O 201, O 6, and to a lesser extent C.P.=320 for O 17. Such a result makes it virtually impossible to identify either model as being representative of the operation of a central timekeeper. However the crux of the argumentation throughout that Chapter was that the models could be distinguished in terms of linearity vs non-linearity of the standardised scores vs d_i functions. In Fig. 9, the non-linearity of the Z_c vs d_i functions is apparent for large Z_c. But, in expts 5 and 6 $Z_c(R_1|d_i)$ lies between -2 and +2. Actually, in that region the

Table 11

Observed and Predicted $P(R_1|d_i)$ for the Poisson counting model and the onset-offset model for expts 5 and 6 with the sum of the squared differences Observed-Predicted.

O	C.P.	d_i	$\hat{P}(R_1\|d_i)$	Poisson $P(R_1\|d_i)$	Poisson $\Sigma dev^2 x10^2$	Onset-offset $P(R_1\|d_i)$	Onset-offset $\Sigma dev^2 x10^2$
2b	260	240	.3203	.3203		.3406	
		280	.6201	.6280		.8209	
		320	.8611	.8381		.8209	
		360	.9333	.9437	.07	.9508	.268
	300	240	.1245	.1062		.1197	
		280	.3511	.3795		.3566	
		320	.6667	.7008		.6798	
		360	.9067	.8900	.258	.9010	.025
	340	240	.021	.0159		.0171	
		280	.1111	.1216		.1288	
		320	.3556	.3795		.3444	
		360	.6435	.6724	.154	.6408	.046
17	280	270	.3921	.4025		.4086	
		290	.6145	.5974		.5925	
		310	.7528	.7538		.7483	
		330	.8603	.8658	.043	.8668	.081
	300	270	.1333	.1342		.1416	
		290	.3049	.3132		.3016	
		310	.5580	.5345		.5209	
		330	.7098	.7346	.123	.7303	.190
	320	270	.0674	.0723		.0787	
		290	.2235	.1770		.1833	
		310	.3017	.3348		.3314	
		330	.5265	.5186	.333	.5227	.267

Table 11 (continued)

O	C.P.	d_i	$\hat{P}(R_1 \mid d_i)$	Poisson $P(R_1 \mid d_i)$	Poisson $\Sigma dev^2 x10^2$	Onset-offset $P(R_1 \mid d_i)$	Onset-offset $\Sigma dev^2 x10^2$
201	280	270	.3472	.3421		.3501	
		290	.5778	.5818		.5791	
		310	.7833	.7842		.7743	
		330	.9056	.9076	.004	.9092	.01
	300	270	.2267	.2216		.2287	
		290	.4178	.4103		.4074	
		310	.6089	.6204		.6207	
		330	.7956	.7900	.24	.7922	.026
	320	270	.1447	.1137		.1146	
		290	.1900	.2276		.2265	
		310	.3240	.3795		.3762	
		330	.6148	.5503	.972	.5598	.798
6	600	450	.0222	.0159		.01472	
		550	.1688	.2461		.2302	
		650	.7288	.7077		.6683	
		750	.9466	.9437	.647	.9527	.752
15	600	450	.0266	.0246		.0323	
		550	.2888	.2992		.2804	
		650	.7496	.7475		.7138	
		750	.9555	.9560	.012	.9556	.148
1	600	450	.08	.0712		.0814	
		550	.2977	.3275		.3005	
		650	.6517	.6578		.6362	
		750	.8789	.8700	.108	.8842	.027

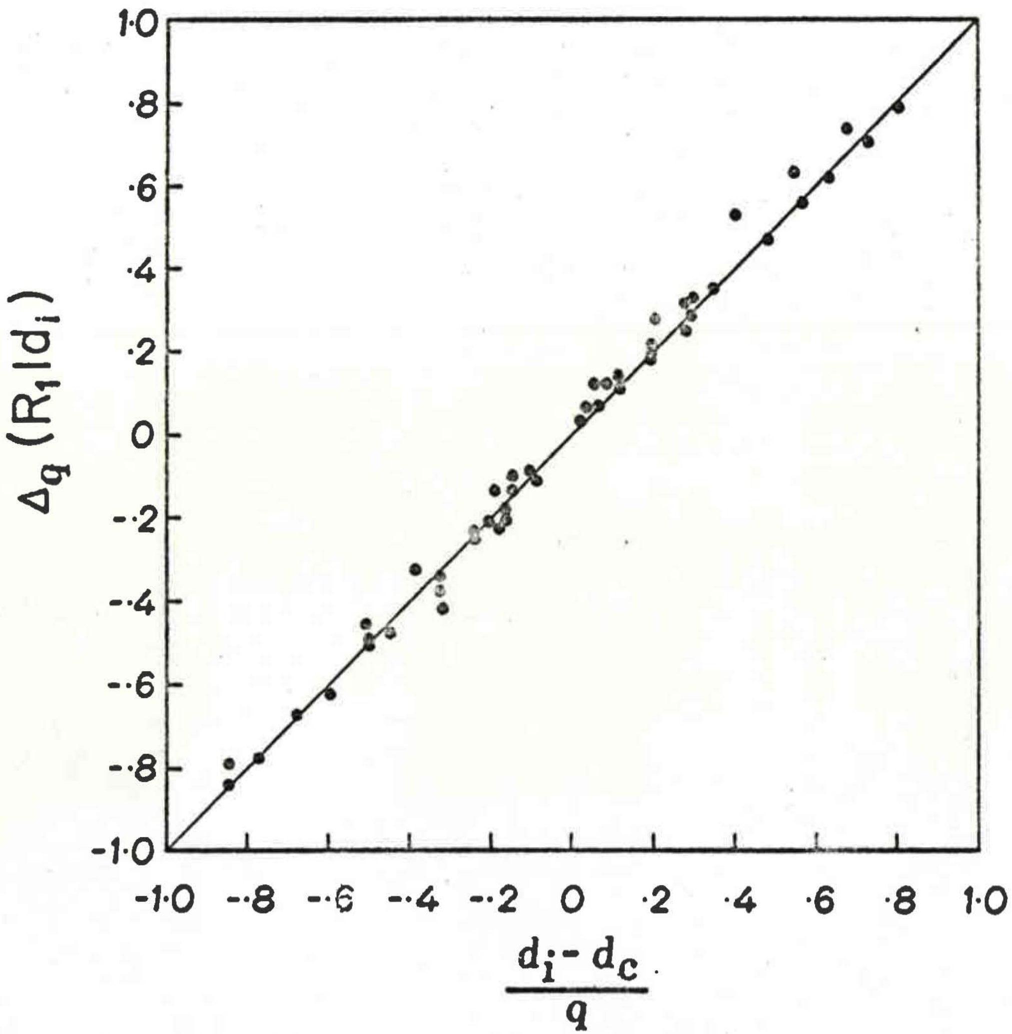


FIGURE 12. Composite figure of the twelve psychometric functions from expts 5 and 6 standardized to their respective estimates of q.

function is almost linear thus reducing the possibility of discriminating between models. Precise comparison of the models will be hard to run because values of $Z_c>2$ corresponds to $P(c)>.97$ values difficult to stabilise experimentally. So, the results on the $\hat{P}(R_1|d_i)$ vs $P(R_1|d_i)$ comparison are not totally unexpected.

The linearity of the standardized scores psychometric functions can be further appreciated by an analysis of the data following the onset-offset model which does predict a linear Δq vs d_i function. A further test of linearity was carried on a composite function where each individual function is represented in a standardized form. The distance d_i-d_c was transformed in units of q for each individual function using the values of the parameters q and d_c as given in Table 10. Thus, when $\dot{\Delta}_q(R_1|d_i)$ is presented as a function of $(d_i-d_c)/q$ the function should be perfectly linear, i.e. slope 1.0 and intercept 0. The result is shown in Fig.12. The diagonal is a straight line of slope 1 and intercept 0 and it represents the data very well. Actually, the best fitting straight line obtained with a least-square technique shows a slope of 1.015 and intercept of .00514. The goodness of fit of the linearity is excellent since $r^2=.9921$; a very good fit since we had 48 points in the function.

3.5 General discussion

The analysis of the results from expts 5 and 6 has mainly displayed the difficulty to differentiate between the two quantitative models under study. That difficulty is due to the fact that both models predict linear relationship between a standardized index of discrimination and d_i over a very large range of $P(R_1|d_i)$ values $(.04<P(R_1|d_i)<.99)$. On the other hand, it was demonstrated clearly that standardized scores were in general a linear function of d_i. That implies that in a set D, the $d_i(I)$, unless very far from d_c have equal variance distributions. Thus, in the present conditions the internal representation of duration, for the most part of a set D, is not an increasing function of T. Very low error data points would be needed in order to check the non-linearity in the Z_c vs d_i predicted function. It is for such points that the Poisson counting model could best be checked against the modified onset-offset model which would very likely consider these errors as non-process errors. It is doubtful that such an enterprise would be very useful in view of the agreement between both models over most of the psychometric function at least for the conditions of the present experiments. Furthermore the whole process of comparing the two models is complicated by the fact that the modified onset-offset model is a four parameter model whereas the Poisson counter is a two-parameter model.

Within the scope of the onset-offset model, Kristofferson (1973) has proposed an empirical rule, the "doubling" hypothesis, which states that for every C.P. value, double that value should double the magnitude of q. While we did not carry an extensive test of that rule, the results reported in Table 10 do show the mean q at M.P. 300 as 101.9msec. and as 202.6msec. at M.P. 600msec. This ratio of 2, as predicted, is surprising if one considers that we are dealing with groups of Os. Although the doubling hypothesis is not part of the model, it is logically related to it and is presently a useful generalisation for representing the q vs C.P. function in auditory and visual duration discrimination (Kristofferson, 1973). The fact, that in the present case the results might follow the same rule is further indication that similar timing mechanisms would be operation in inter and intramodal duration discrimination. However, it is important to note that in the present intermodal situations the values of q are three to four times larger than the ones reported for auditory duration discrimination with similar methodology. Thus, even though the timing device might be the same in inter and intramodal cases, it is less accurate in the intramodal situation when values of C.P. less than 600msec. are considered. On the other hand, values of λ are very much comparable to those reported by Abel (1972a,b). Actually, that precise feature plus the relative constancy of the λ(C.P.) values make the Poisson

Table 12

Estimates of DT_{75} averaged over 5 experimental sessions for each O at C.P. of 300 and 600msec.

C.P.			
300		600	
O	DT_{75}	O	DT_{75}
201	51.75	15	106.84
17	48.35	6	104.26
2b	65.38	1	149.56
$\bar{X}$	55.10	$\bar{X}$	120.22
S.D.	9.00	S.D.	25.00
DT/M.P.	0.1833	DT/M.P.	0.2003

counting model an interesting alternative. However, the remarkable linearity of the composite figure (Fig.11) is a strong support for the onset-offset model.

In the previous part, section 2.5, we had mentioned that in the M.-F. method the differential sensitivity function could be described as a straight line of the form DT_{75}=.1904 M.P.+34.03. If one considers the two groups that were run independently at M.P.=300msec. and 600msec. in the present chapter, a minimal function, with two points, can be obtained. Values of DT_{75} were calculated for each O for the last 5 sessions. These values are reported in Table 12. A comparison with the results of expt 4 shows the present performance as superior, each DT_{75} being lower by 15 to 20msec. Furthermore, if a line is fitted to the two point function, it yields the following result: DT_{75}=.217M.P.-10.02. Thus while the slopes are very similar in both experiments, there is a drop in the intercept in expts 5 and 6. Such a result supports the findings reported in expt 4 with the sliding M.P. method:the performance index DT_{75} is a linear function of M.P. It is also interesting to note that in expts 5 and 6 experienced Os with extensive practice showed a decrement in performance as a function of an increase in M.P. that is similar to that of less practiced Os in expt 4. Thus, while there is a definite effect in absolute terms, the differential discriminability functions are very similar in shape. Furthermore, it is interesting to point out that like in expt 1 the present one is a between group design and suggests that that feature cannot explain the results of expt 1. A final comparison of the present results with those obtained in Chap. I was made by calculating an SD/DT_{75} ratio at C.P. 600 and 300 using the data pooled over the three Os with the same technique as in expt 4, we obtained at each C.P. a two-point psychometric function from which SD and DT_{75} were estimated. The SD/DT_{75} ratio was of 1.84 at C.P. 300 and 1.75 at C.P. 600. This is very close to the values reported in Table 2 which were around 1.8 for the intermodal experiment run in a comparable range. Thus although the present set of data and that of expt 1 behave very differently with regards to Weber's law, the constancy of the ratio seems to hold for both situations. This is further indication that similar mechanisms are responsible for the performance in different situations of duration discrimination. So, it appears that models developed to account for intramodal duration discrimination, can fit reasonnably well the performance in an intermodal situation. Thus, the assumption of a central timekeeper is upheld at least for intervals shorter than 1 sec.

IV RESPONSE LATENCIES IN DURATION DISCRIMINATION: EXPERIMENT 7

4.1 Introduction.

In general, the theoretical analysis of duration discrimination through quantitative modeling shows two major processes as being in operation in the task:

1) transduction process: the transformation of the temporal extent of the stimulus d_i into some internal representation $d_i(I)$

2) decision process: the determination of the appropriate response through some operation on $d_i(I)$.

A crucial aspect of such a description is that $d_i(I)$ is the result of the transduction process operating over the total temporal extent of d_i. More specifically, $d_i(I)$ is the outcome of a measurement being performed from the offset of m_1 to the onset of m_2. However, we mentioned in section 2.2 that with the M.-F. method the discrimination could be done in quite a different way. The O could trigger at the offset of m_1 an internal real-time criterion of duration d_c. A decision could be taken concerning the relative extent of d_i by judging the order of occurrence at a decision center of the termination of d_i at t_2, and of the termination of d_c at t_c. In such a system, there is no measurement proper made over the temporal extent of d_i. The duration discrimination task is reduced to a temporal order judgement between an internal event, t_c, and an external one t_2. Then, a general decision making strategy can be defined: when t_2 occurs before t_c ($t_2<t_c$) an R_o response is triggered and, when t_2 is registered after t_c ($t_2>t_c$) an R_1 response is emitted. Under the assumption that t_2 and t_c are random variables with some distribution function, the probability that t_2 is registered before t_c can be defined as $P(t_2<t_c)$ and similarly $P(t_2>t_c)$ the probability that t_c occurs before t_2. Then, $P(R_o)=P(t_2<t_c)$ and $P(R_1)=P(t_2>t_c)$; and given a set D, $P(R_1)$ will be an increasing function of d_i. However, the exact shape of the psychometric function will depend on the precise form of the distribution functions associated with t_2 and t_c.

In general an R_o is triggered by the occurrence of an external event t_2, and R_1 is linked to an internal event, t_c. Then, if one were to measure the latency of these responses, RL, under conditions where the O is required to respond as quickly as possible, general predictions can be made concerning the variations in RL as a function of d_i[1].

It is assumed first that the observed RL is the result of a movement component, K, and a discrimination component, I. Furthermore, I and K are assumed to be random variables where

---

[1] The following analysis of response latencies in duration discrimination is inspired from a theoretical expose by A.B. Kristofferson in a grant proposal to the National Research Council of Canada, 1974.

$\bar{I}$ and VAR(I) are the first two moments of the distribution of I, and $\bar{K}$ and VAR(K) those of the random variable K. For values of d_i associated with low error level, K and I can be assumed to be independent. Then,

$$VAR(RL)=VAR(I)+VAR(K)$$

and,

$$\overline{RL}=\bar{I}+\bar{K}$$

The discrimination is a function of t_2 and t_c and, given a low error level the mean and variance of I, when $t_2<t_c$ will be totally controlled by t_2, and similarly t_c will define I when $t_2>t_c$. Since the occurrence of $t_2<t_c$ yields an R_o and that of $t_2>t_c$ an R_1, the following relationships can be defined:

$$VAR(RL)_o=VAR(t_2)+VAR(K_o)$$

$$\overline{RL_o}=\overline{t_2}+\overline{K_o}$$

Similarly,

$$VAR(RL)_1=VAR(t_c)+VAR(K_1)$$

$$\overline{RL_1}=\overline{t_c}+\overline{K_1}$$

For the sake of simplicity the random variable K is assumed to have constant mean and variance for a given type of response. Thus, variations in $\overline{RL}$ and VAR(RL) can be ascribed to variations in the discrimination component, I.

RL_1, since it is triggered by the occurrence of t_c, is independent of t_2 and should not display any synchronisation with the actual termination of the interval at t_2. More precisely, $\overline{RL_1}$ and $VAR(RL)_1$ should be the same for different values of d_i at least for all d_i for which $P(R_1|d_i)=1$. A consequence of that prediction is that an R_1 could be triggered before the occurrence of t_2, which means that some RL_1 could be shorter than d_i. On the other hand, since R_o is time locked to t_2, RL_o will be directly proportional to d_i. Predictions concerning $VAR(RL)_o$ are less straightforward because they depend on specific assumptions relating $VAR(t_2)$ to d_i. However, we can at least predict that $VAR(RL)_o$ should be a non-decreasing function of d_i. Thus, the general predictions concerning the $\overline{RL}$ vs d_i functions define two very different functions. The $\overline{RL}_o$ vs d_i function will be an increasing function of d_i, the A-function. If for simplification it is assumed that $\overline{t}_2=d_i$, the A-function will be linear with slope 1. The $\overline{RL}_1$ vs d_i function will be linear with slope 0 and called the B-function. However, for these predictions to hold one has to be able to maintain that variations in RL originate in the discrimination component as assumed. But, as d_i is brought closer to d_c, t_2 and t_c occur in close temporal contiguity. Then, as $P(t_2<t_c)$ and $P(t_2>t_c)$ converge towards .5 there is a definite possibility that response competition could blur the relationship between t_c and RL_1, and t_2 and RL_o by delaying some responses on certain trials thus probably increasing VAR(RL) and displacing $\overline{RL}$. Consequently we will simplify the situation by mainly considering d_i values far enough from d_c so that the probability of an erroneous judgement of order between t_c and t_2 is very low.

One problem with the preceding line of reasoning resides in the quantitative determination of the psychometric range; we have previously faced the same problem in section 2.1. However, it was shown in section 3.2 that within the onset-offset model the psychometric range would cover a span of qmsec. on each side of d_c. Since both Os to be used in the next experiment had previously run at an M.P. of 250msec. in expt 3, the value of q estimated in that experiment was used to determine the range. Evidently, there was no way of knowing if that estimate obtained under "accuracy" (no speeding of the responses) would be valid in a speed condition. Still, it was the best estimate available at the moment.

Before carrying on to the experiment proper, we would like to note the similarity between the present work and that of Kornblum (1973), and Ollman & Billington (1972). In their studies these authors try to differentiate signal detection triggered responses and temporal estimation responses in simple reaction time. They address themselves to the problem of so-called "anticipation" responses in a simple reaction time task. The instructions to their Os are to respond as quickly as possible to the presentation of a signal and, if no signal is given to emit a response x milliseconds after the warning signal. The major difference between these studies and ours is first that an external signal is an unequivocal signal to respond and, second that the situation is not one of discrimination of relative temporal occurrence of the external signal and the internal temporal criterion. Indeed, in our situation the external signal can occur before or after the assumed termination of the real-time criterion thus forcing the O to perform a complete discrimination of temporal order on every trial. Actually, that basic difference is even clearer when one considers that in the reaction time studies the task is one of simple reaction time, the response is always the same whichever trigger originates the response. The use of two different responses corresponding to the two possible orders of occurrence of the signals makes the present study a choice reaction time task. Thus, for the time present we will not draw any relationship between their results and ours since both situations are very different.

We would like to stress the point that the present thesis is basically exploratory because of the absence of data against which ours could be compared. In this last experiment it is even more true and, for that reason we intend to keep the discussion at the level of general trends. Since we lack the knowledge to make valid predictions about precise features of the data mainly concerning the shape of the latency distributions, the analysis of the data will be mainly concerned with orderly variations of $\overline{RL}$ and VAR(RL) for d_i values outside the psychometric range. Furthermore, since we possess information on the level of performance of both Os in an accuracy condition, we will look for an effect of the speeding requirement on the precision of their discrimination.

4.2 Method.

Two Os were run in the experiment, O 605 and 503. Both Os had previously participated in expt 3. Since the stimulus conditions were almost identical both Os can be considered as having had extended practice at discriminating intermodal intervals in the present range.

The experimental situation was similar to the L-T condition in expt 3. The warning signal (cue light) was followed 1 sec. later by the 10msec. light marker and feedback (cue light) was given 2.4 sec. after the offset of the 10msec. tone marker. The Os were required to answer as quickly as possible after the offset of the first marker. The response was made by depressing a push button with the right hand index for an R_o and the middle finger for an R_1 response. Both fingers were resting on the buttons throughout the experimental session.

The main set D contained 4 elements partitioned symmetrically by an M.P. set at 250msec. Each element was presented an equal number of times in a random order during a block of 140 trials; there were two such blocks in a session. So, 70 trials/d_i were collected in a session. The experimentation was divided into two sections, training and experiment proper. In the training sessions the Os were presented with various intervals around M.P.=250msec., the 4 elements of D being changed from session to session. However, the set D was always symmetrical. O 605 ran through 10 training sessions and O 503 had 20.

In the experiment proper, our interest was related to values of d_i outside the psychometric range. Thus, response latencies were obtained for three pairs of outside values: 400-100, 375-125, and 360-140msec.; the inside values were constant at 310 and 190msec. The outside pair was changed from session to session from the extreme to the inside and the opposite, i.e. over six sessions d_3 would take values of 400, 375, 360, 360, 375, 400msec. These six sessions represented a cycle. There were 6 cycles for O 605 and 5 for O 503. The last two cycles were used as experimental data. Thus, 280 responses/d_i were obtained for each outside value and 840 responses/d_i for each inside value. There were 24 practice sessions for O 605 and 18 sessions for O 503. The raw response latencies were measured to the nearest millisecond from the offset of the first marker through a small computer system (PDP-8E). The latencies had a maximum around 3 sec. determined by the presentation of the feedback signal 2.5 sec. after the offset of m_2.

4.3 Results and Discussion.

The results will be discussed in terms of $\overline{RL}$ and VAR(RL) averaged over estimates from each session rather than from pooled results. Furthermore, unless otherwise indicated, these estimates come from distributions where RL's>750msec. have been eliminated. For O 605 there were 13 such long RL's out of a grand total of 3360 responses whereas for O 503 there were 27 responses eliminated out of the same total. Although our analysis will bear only on R_o to d_o and R_1 to d_3 we will also report RL_o to d_1 and RL_1 to d_2.

Values of $\overline{RL}$ and VAR(RL) over all experimental cycles for the three outside d_i are reported in Fig. 13 for O 605 and Fig. 14 for O 503. In Fig 13 it is readily apparent that both $\overline{RL}_o$ and $VAR(RL)_o$, and RL_1 and $VAR(RL)_1$ decrease steadily from cycle to cycle. However, the last two cycles are very comparable for both $\overline{RL}$ and VAR(RL). O 503 does not display a similar trend; neither $VAR(RL)_o$ nor $VAR(RL)_1$ show any improvement over cycles. The $\overline{RL}_1$ does increase over cycles whereas $\overline{RL}_o$ does not move in any direction except at d_o=100msec. where it increases over the first two cycles. As was the case for discrimination data, it appears as though practice affects differently various Os.

In section 4.1 the strongest predictions from the real-time hypothesis concerned the difference between the

FIGURE 13. Mean and variance of response latencies at each experimental cycle for O 605 (140 trials/point)

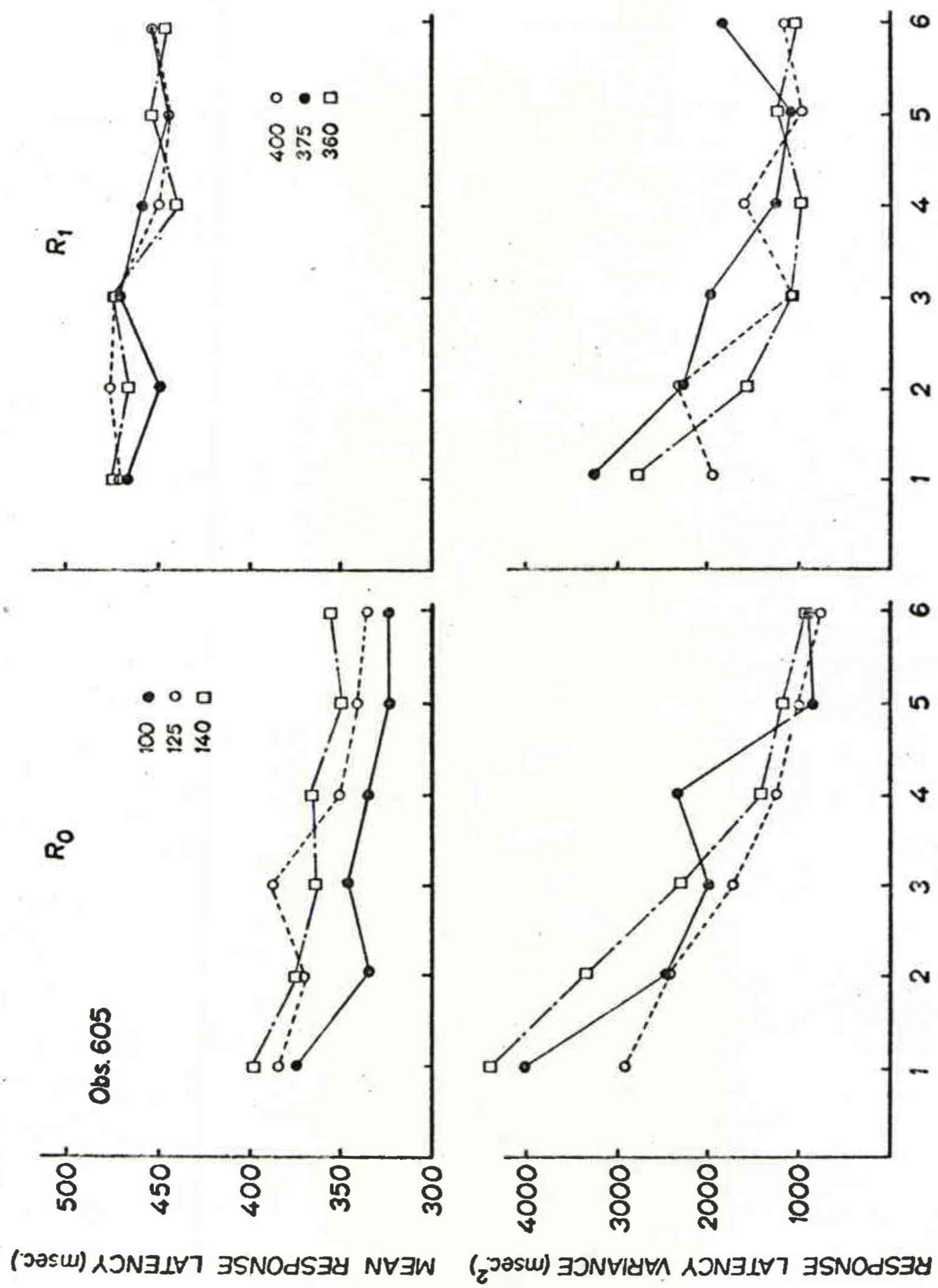
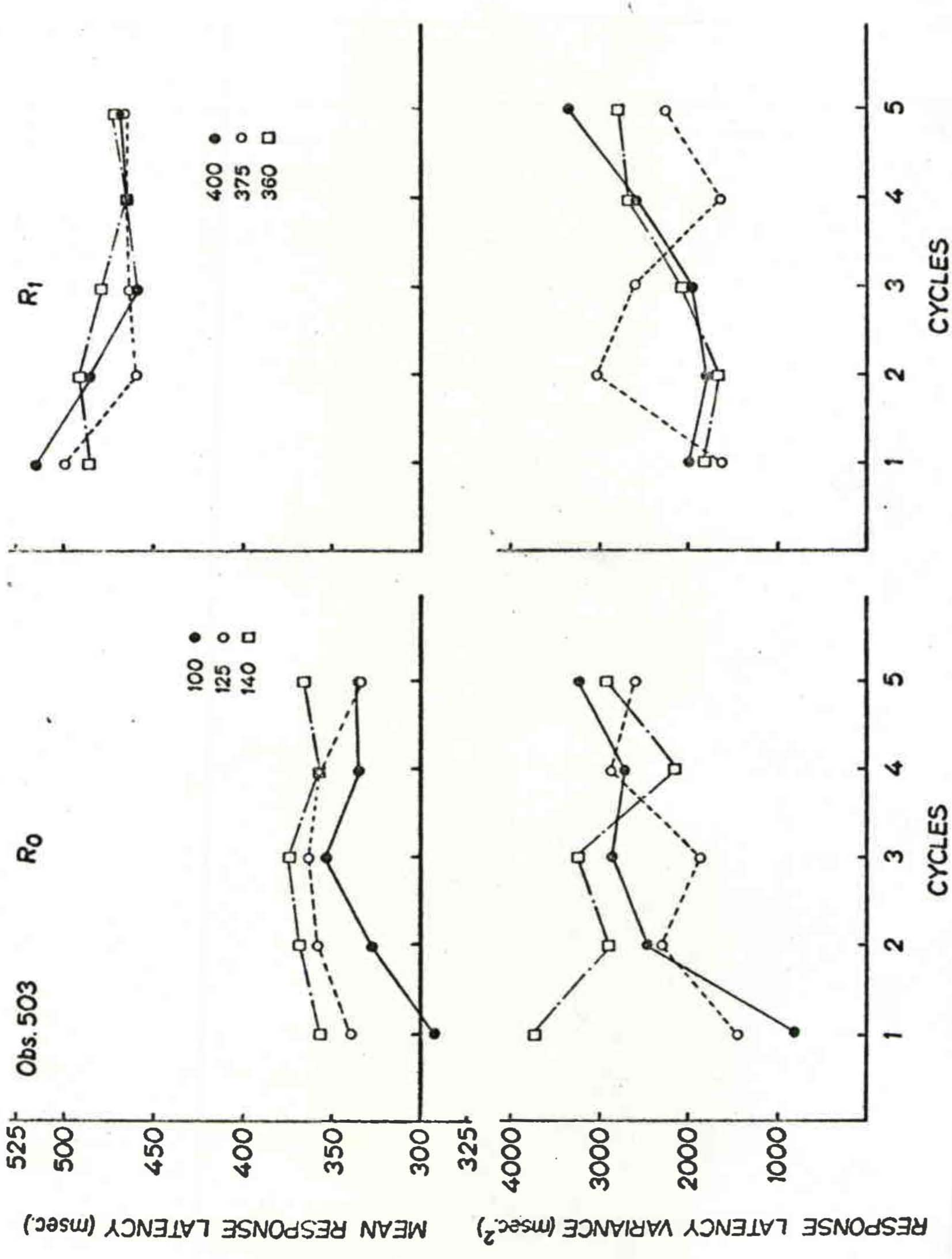

Obs. 605
R0
R1
100
125
140
400
375
360
MEAN RESPONSE LATENCY (msec.)
RESPONSE LATENCY VARIANCE (msec.2)
500
450
400
350
300
4000
3000
2000
1000
1
2
3
4
5
6
CYCLES
CYCLES

FIGURE 14. Mean and variance of response latencies at each experimental cycle for O 503 (140 trials/point)



Obs. 503
R_0
R_1
100 ●
125 ○
140 □
400 ●
375 ○
360 □
MEAN RESPONSE LATENCY (msec.)
RESPONSE LATENCY VARIANCE (msec.²)
525
500
450
400
350
300
325
4000
3000
2000
1000
1
2
3
4
5
CYCLES
CYCLES

A-function and the B-function. The $\overline{RL}_o$ and $\overline{RL}_1$ are reported in Fig. 15 for O 605 and Fig. 16 for O 503 as a function of d_i. A visual inspection of both Figures shows readily that the predictions are substantiated for both Os. Indeed, the B-functions display a remarkable stability over d_i values. It is a very strong support for the hypothesis that these responses are time-locked to a single event in time, independent of d_i. Furthermore, the A-functions are clearly increasing functions of d_i which supports the assumption that their trigger is dependent on the termination of d_i. However, the stronger prediction describing the A-function as a linear slope 1 function is not quite corroborated. A linear least square curve fitting shows both A-functions as having a slope of .68 which falls short of the predicted value. However the linear fit accounts for 85% of the variance for O 503 and 96% for O 605 which can be seen from the slope 1 line that has been fitted by eye to each A-function.

The VAR(RL) as a function of d_i are presented in Fig. 17 for O 605 , and in Fig. 18 for O 503. It had been predicted that $VAR(RL)_1$ should be constant over all values of d_i, whereas $VAR(RL)_o$ should not be a decreasing function of d_i. An examination of these Figures shows $VAR(RL)_1$ as being indeed quite stable, even though it is somewhat lower at d_3=375msec. in Fig. 18. Similarly. $VAR(RL)_o$ displays little variation which suggests that $VAR(t_2)$ is not a function of d_o. Finally, $VAR(RL)_o$ and $VAR(RL)_1$ are very close to each another, in

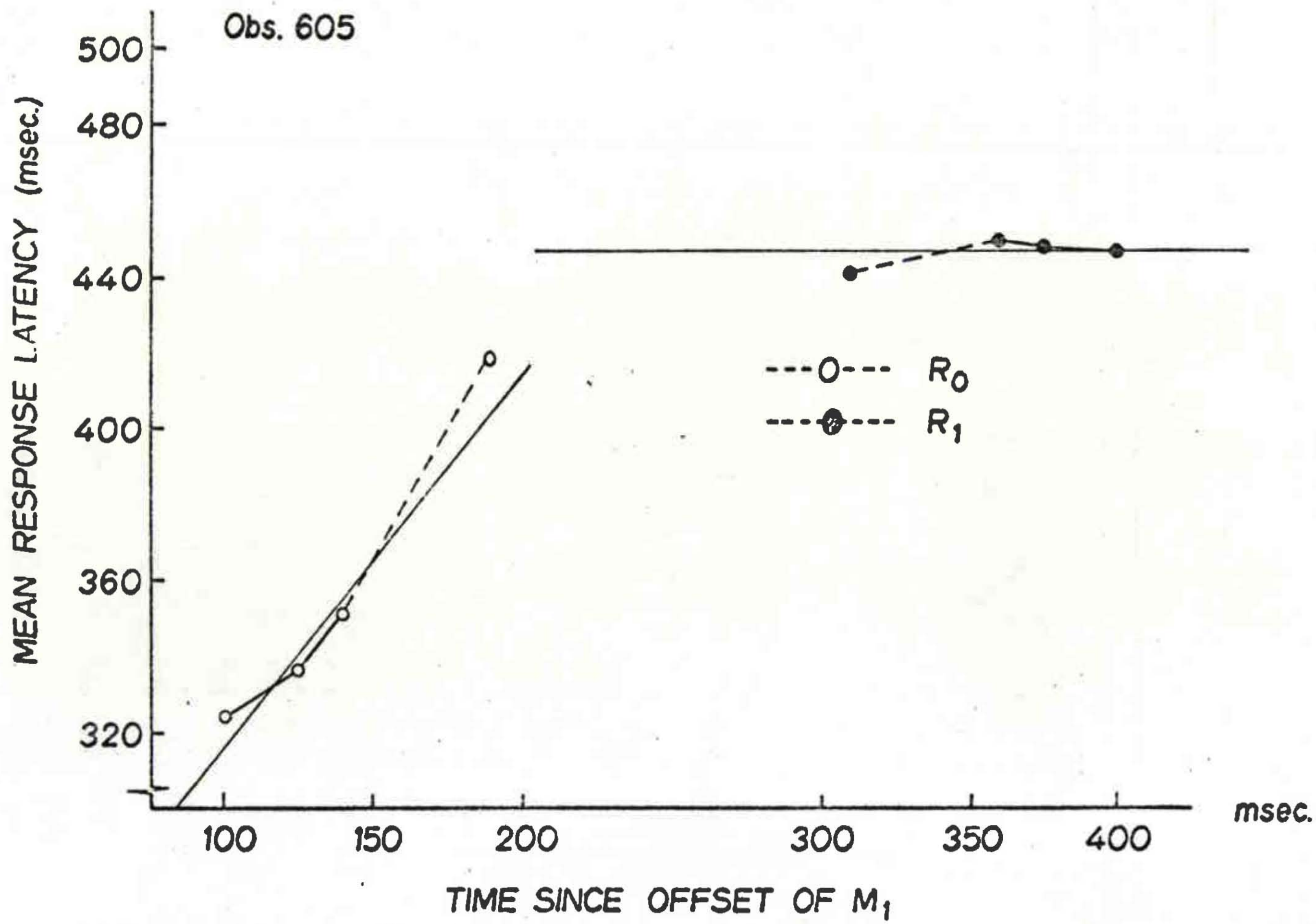


FIGURE 15. Mean response latency for correct responses to each d_i for O 605.

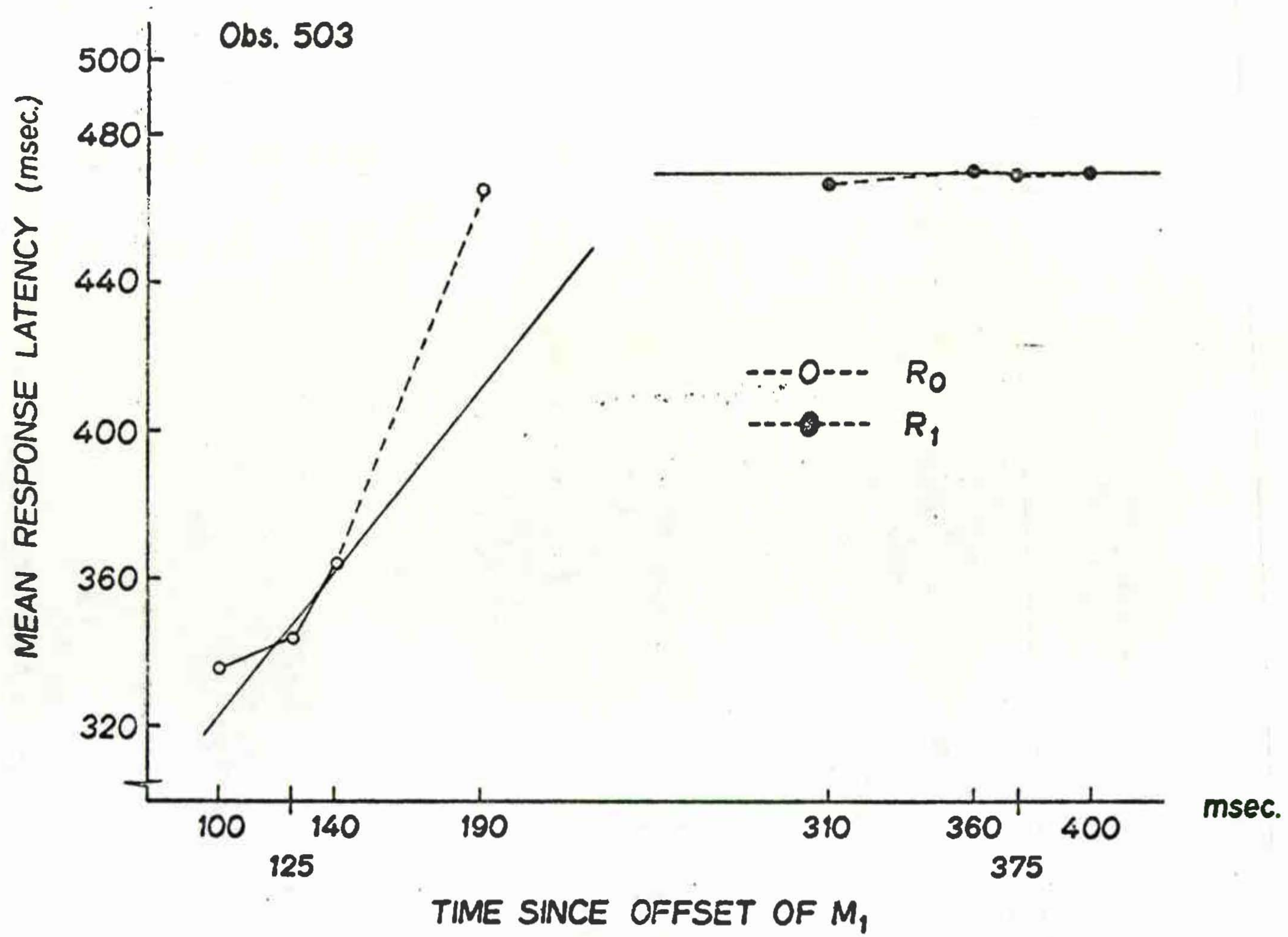


FIGURE 16. Mean response latency for correct responses to each d_i for O 503.

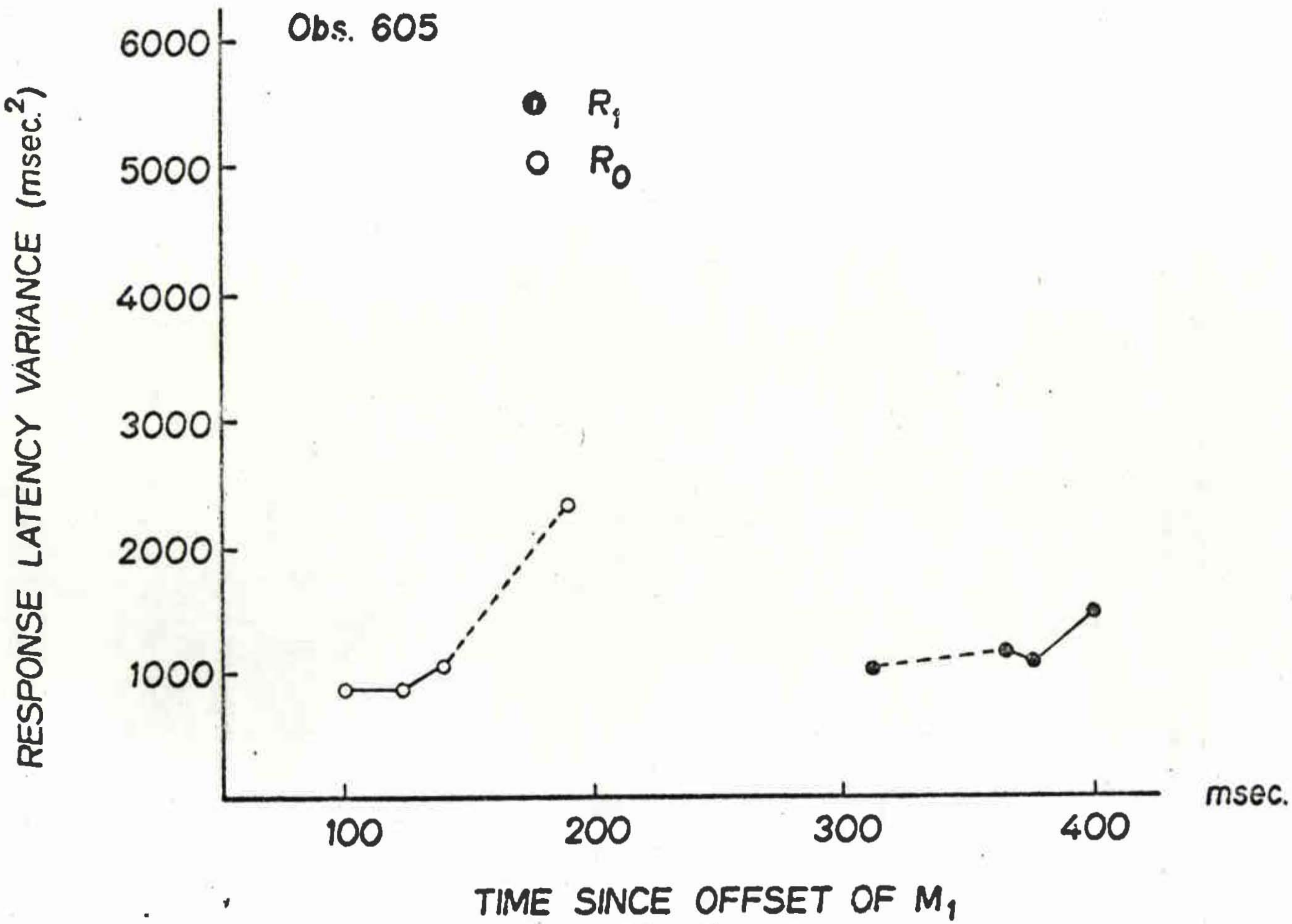


FIGURE 17. Correct responses latency variance as a function of d_i for O 605.

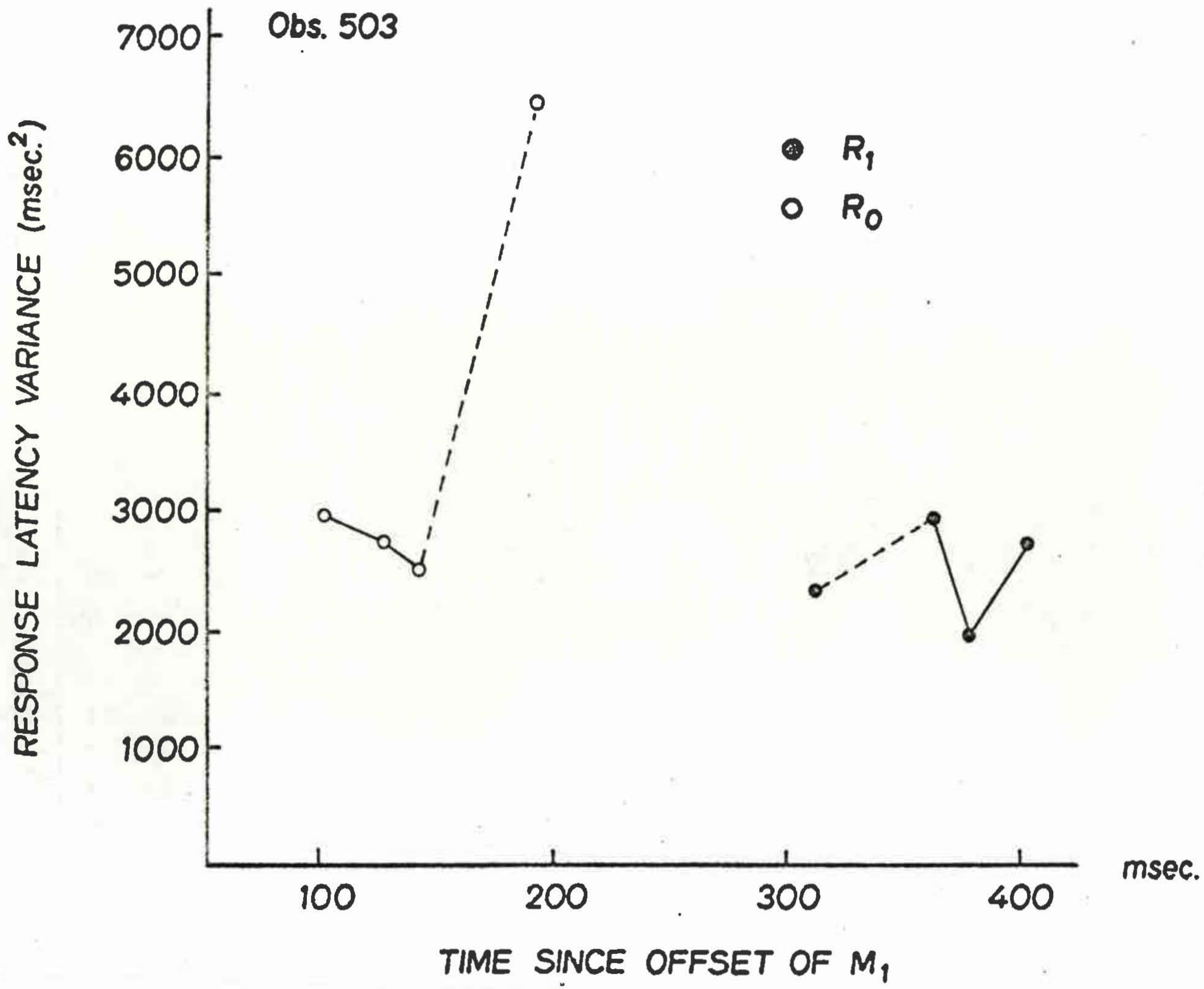


FIGURE 18 Correct responses latency variance as a function of d_i for O 503.

general, leading one to consider the possibility that in the present situation t_2 and t_c have equal variance distributions and moreover that these variances are independent of d_i.

The real-time criterion predictions can be further tested by a detailed analysis of the $\overline{RL}$ and VAR(RL) in Table 13 and 14. For both Os, $\overline{RL}_1$ are within 1 msec. of the mean $\overline{RL}_1$ for the three values of d_3. However, O 605 shows a $\overline{RL}_1$ 22msec. faster than that of O 503, on the average. Moreover, $VAR(RL)_1$ is at 1210msec.^{2} for O 605 and at 2537msec.^{2} for O 503, when $VAR(RL)_1$ is averaged over the three d_3 values. The difference is even larger for average $VAR(RL)_o$ and it is three times larger at 2736msec.^{2} for O 503 than the estimate of 934msec.^{2} for O 605. Finally, O 605 shows an average $\overline{RL}_o$ 10msec. faster than O 503. Thus, O 605 displays faster and more stable RL's by comparison with O 503. However both Os are definitely showing results typical of the real-time criterion hypothesis.

The response latency distributions are reported in Fig. 19,20,21, and 22. The similarity between the three d_3 distributions is striking in Fig. 19 and is also very good in Fig. 21. In Fig. 19, the occurrence of a good proportion of responses before the actual value of d_i in the d_3=400msec. function does support the predictions of the real-time criterion hypothesis concerning responses not only being triggered but also registered before t_2. On the other hand, the three d_o distributions, in Fig. 20 and 22, are clearly separated

Table 13

Mean and variance of response latencies for the outside members of the set D for O 605.

d_i	$\overline{RL}$(msec.)	VAR(RL)(msec.^{2})	$\overline{RL}-d_i$	$\overline{RL}-d_c$	d_c
100	323	889	223		
125	336	873	211		
140	351	1039	211		
$\hat{X}$		934	218		
360	449	1109	89	204	245
375	448	1070	73	204	244
400	447	1451	47	195	252
$\bar{X}$	448	1210		201	

Table 14

Mean and variance of response latencies for the outside members of the set D for O 503.

d_i	$\overline{RL}$(msec.)	VAR(RL)(msec^2)	$\overline{RL}-d_i$	$\overline{RL}-d_c$	d_c
100	335	2961	235		
125	343	2729	222		
140	364	2519	224		
$\bar{X}$		2736	227		
360	471	2926	111	247	224
375	469	1969	94	238	231
400	470	2717	70	241	229
$\bar{X}$	470	2537		242	

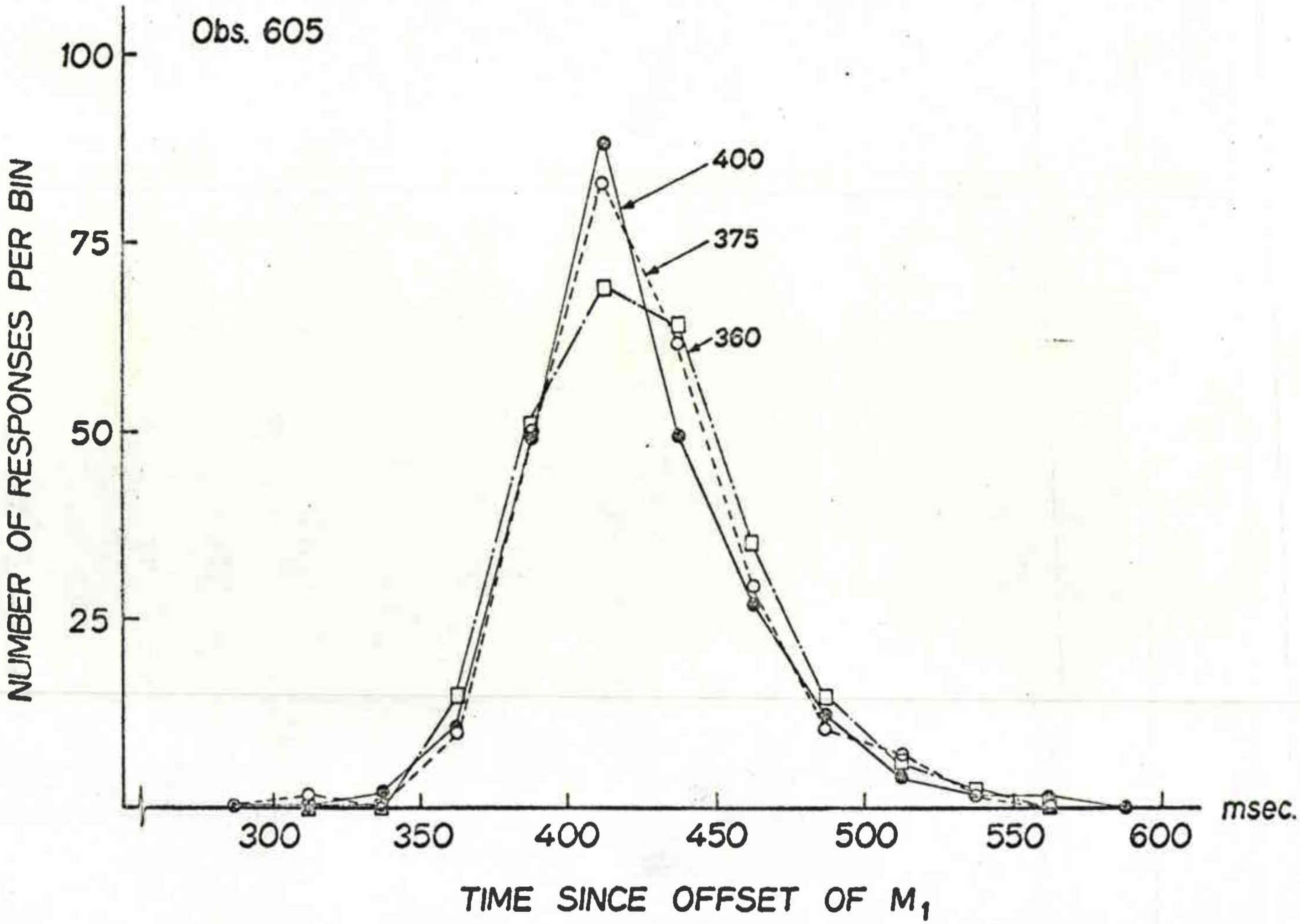


FIGURE 19. Number of responses per 25msec. bin for RL_1 to each d_3 value for O 605 (280 responses/d_3).

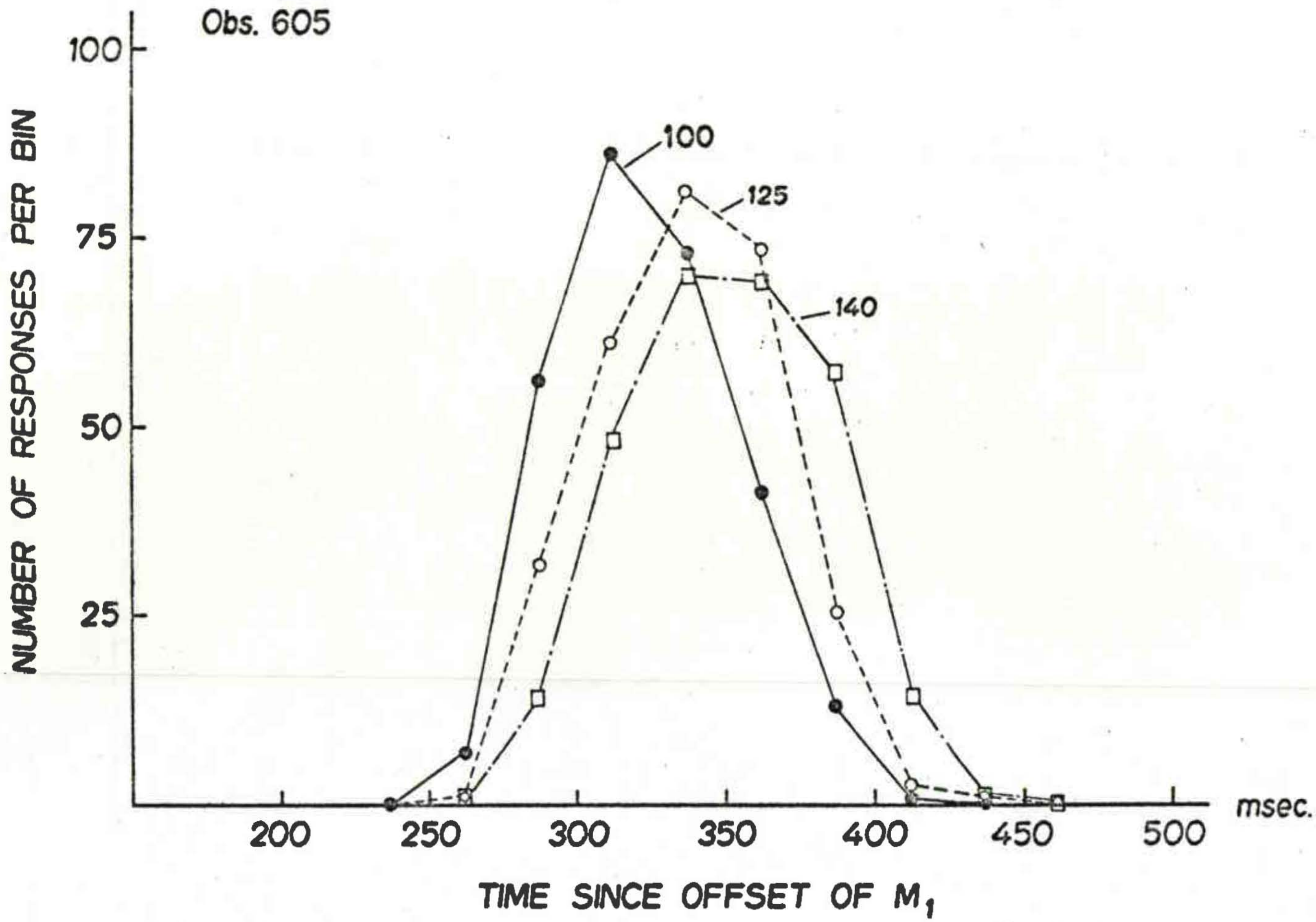


FIGURE 20. Number of responses per 25msec. bin for RL_o to each d_o for O 605 (280 responses/d_o).

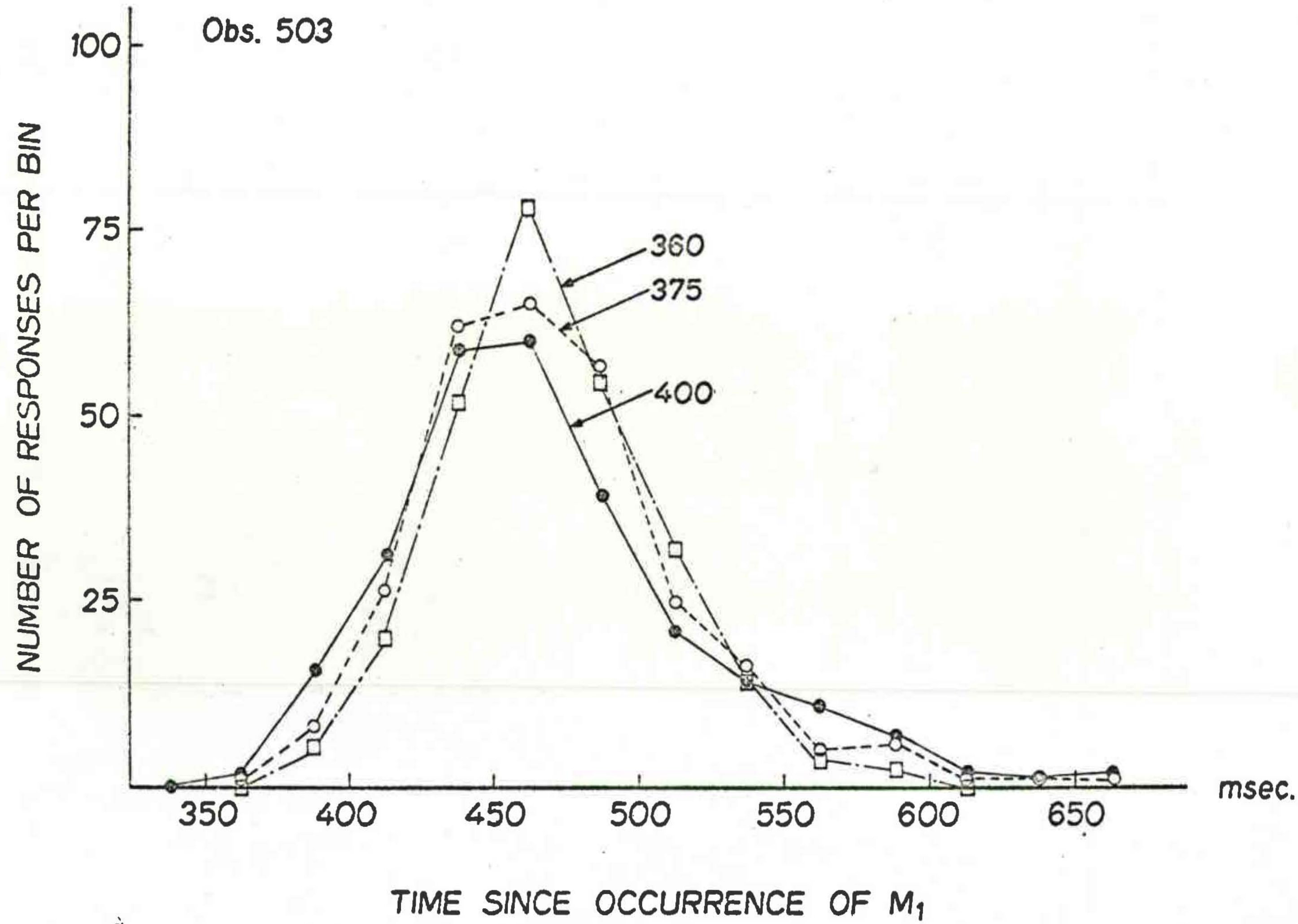


FIGURE 21. Number of responses per 25msec. bin for RL_1 to each d_3 value for O 503 (280 responses/d_3).

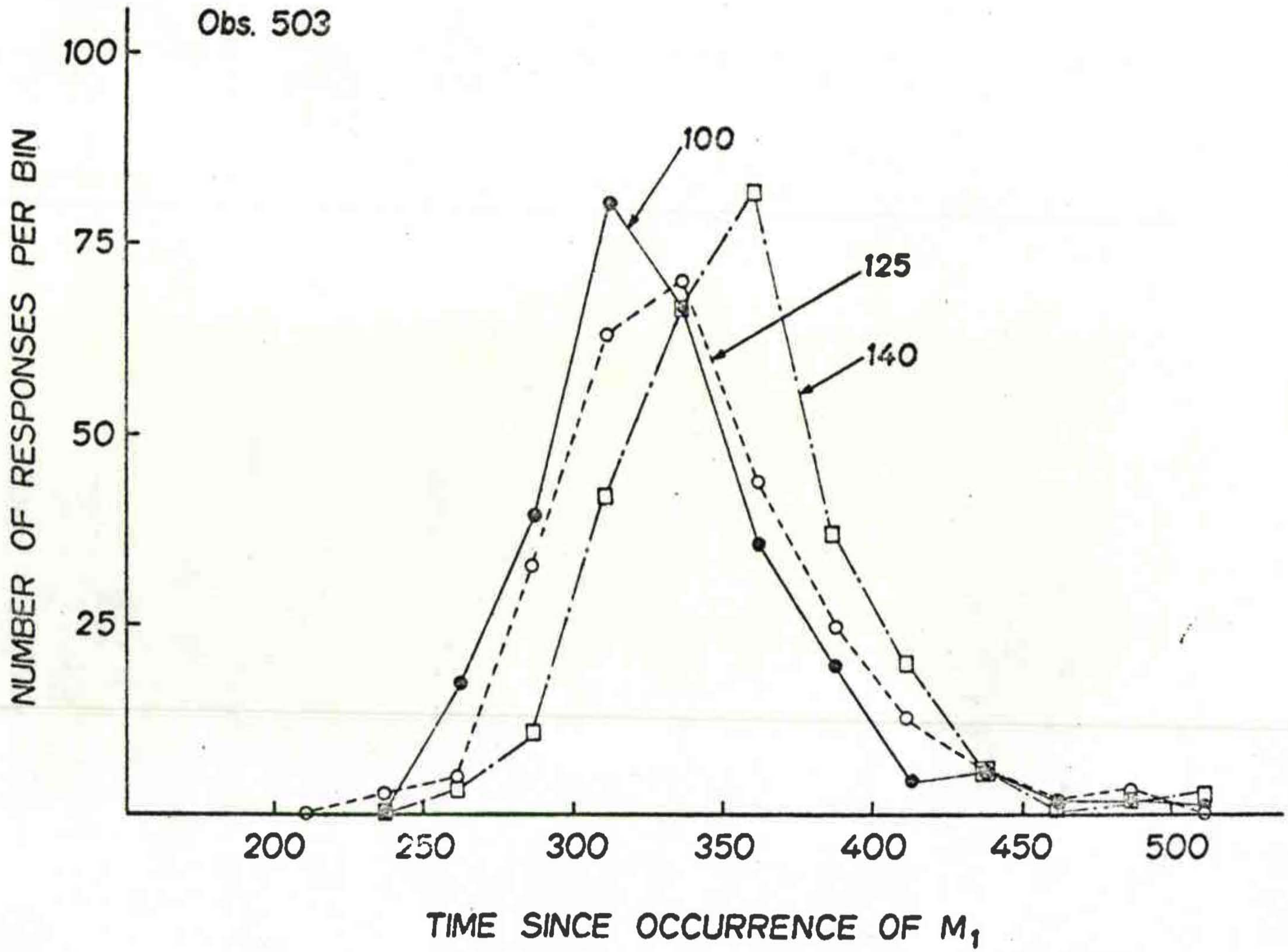


FIGURE 22. Number of responses per 25msec. bin for RL_o to each d_o value for O 503 (280 responses/d_o).

from each another while being similar in shape. Thus, in general, the examination of latency distributions corroborates the previous argumentation in terms of mean and variance. However, because of the small number of responses in each distribution (max. 280 responses) we do not wish to carry on the discussion on the definition of the general function best representing these distributions.

In order to have a better idea of the speed at which the responses were made after t_2 or t_c one has to remember that RL's are measured from the offset of m_1. Thus $RL_o=RT_o+d_i$ and $RL_1=RT_1+d_c$, where RT represents the actual reaction time as measured from the time of occurrence of the appropriate trigger. The transformation is readily done for RT_o; and $\overline{RT}_o$ averaged over the three d_o values is 218msec. for O 605 and 227msec. for O 503. However, the estimation of RT_1 is complicated by the lack of objective means of determining $\overline{t_c}$ which would then give the duration of d_c. An estimate of d_c could be obtained indirectly by the use of the discrimination data. Indeed, it can be argued that an O would discriminate at chance level if $\overline{t_2}=\overline{t_c}$ and if t_2 and t_c have symmetrical distribution functions. Then, by definition $P(t_2<t_c)=P(t_2>t_c)$ and $P(R_o)=P(R_1)=.5$. Thus, for each of the three D-sets, $P(R_1|d_1)$ and $P(R_1|d_2)$ were used to estimate the point d_c where $P(R_1)=.5$. The estimation was done by linear interpolation. The discrimination data are reported in Table 15 and the outcome of the estimation procedure appears in Tables 13 and 14. The

Table 15

Estimates of $P(R_1)$ at all d_i and overall P(c) for O 503 and O 605.

O	d_o	$P(R_1 \mid d_o)$	d_1	$P(R_1 \mid d_1)$	d_2	$P(R_1 \mid d_2)$	d_3	$P(R_1 \mid d_3)$
503	100	.0107	190	.3031	310	.9713	400	.9778
	125	.0285	190	.2459	310	.9710	375	.9856
	140	.0212	190	.2686	310	.9724	360	.9793
$\bar{X}$		.0201		.2725		.9715		.9809
P(c)	.9155							
605	100	.0035	190	.1296	310	.9207	400	.9107
	125	.0142	190	.1399	310	.9249	375	.9105
	140	.0142	190	.1192	310	.9021	360	.9142
$\bar{X}$		.0105		.1282		.9159		.9118
P(c)	.9222							

estimate of d_c is 228msec. for O 503 and 247msec. for O 605 which yields an $\overline{RT}_1$ of 201msec. for O 605 and one of 243msec. for O 503. These are relatively fast RT,s since we are dealing with choice reaction time. It is interesting to note that the difference between $\overline{RT}_1$ and $\overline{RT}_o$ is around 15msec. for both Os. That difference could originate in the use of two different fingers for the two responses.

It could be assumed that a large proportion of VAR(RL) is linked to variability in discrimination stage rather than in the motor response production stage of the total time taken to output a response. In such a case, there should exist a direct relationship between VAR(RL) and accuracy as given by the discrimination data. An examination of Table 15 shows both Os as having a similar performance in terms of P(c) averaged over all d_i. However, a closer analysis indicates a difference in accuracy between the Os when the outside members of the set D are considered. Indeed, the index ε as defined in eq. 3 is at .0419 for O 503 and .0987 for O 605. It could very well be that the larger ε reflects the effect of faster RT's for O 605. Indeed, it is a commonly accepted fact that faster RT's are likely to be linked to a larger proportion of erroneous responses (Audley, 1974).

As we mentioned in section 4.1 we have, for both Os, information on their level of performance under conditions that can be described as accuracy conditions. They ran in expt 3, and since no mention was then made about speeding of responses it can be assumed that response time was not an active variable in determining performance. Unfortunately, we do not possess any response latency data to substantiate that claim. Yet, performance from expt 3 can be readily compared with the present one since it was obtained with a set D of 100,200,300, and 400msec. after extended practice. Psychometric functions for speed (expt 7), S-function, and accuracy (expt 3), A-function, conditions are presented in Fig. 23. A visual inspection of the Figure does not reveal any striking difference between them. The main feature is a break in the upper segment of the S-function. Indeed, while the A-function is a monotonic increasing function of d_i, the S-function is non-monotonic for d_i>310msec. This flat portion in the S-functions could be linked to the use of a real-time criterion in the speed condition. A better analysis of the speed-accuracy relationship could be performed by comparing estimates of discrimination indices under both conditions. Estimates of q and ε were calculated for each O under both conditions and are reported in Table 16. The major difference between speed and accuracy appears for O 605 in the index of non-process error ε. Indeed, ε increases from .004 in the A condition to .0987 in the S condition. Thus, it is likely that the stress placed on quick responding induced a higher rate of non-process error. The interesting point is that if the increase in error

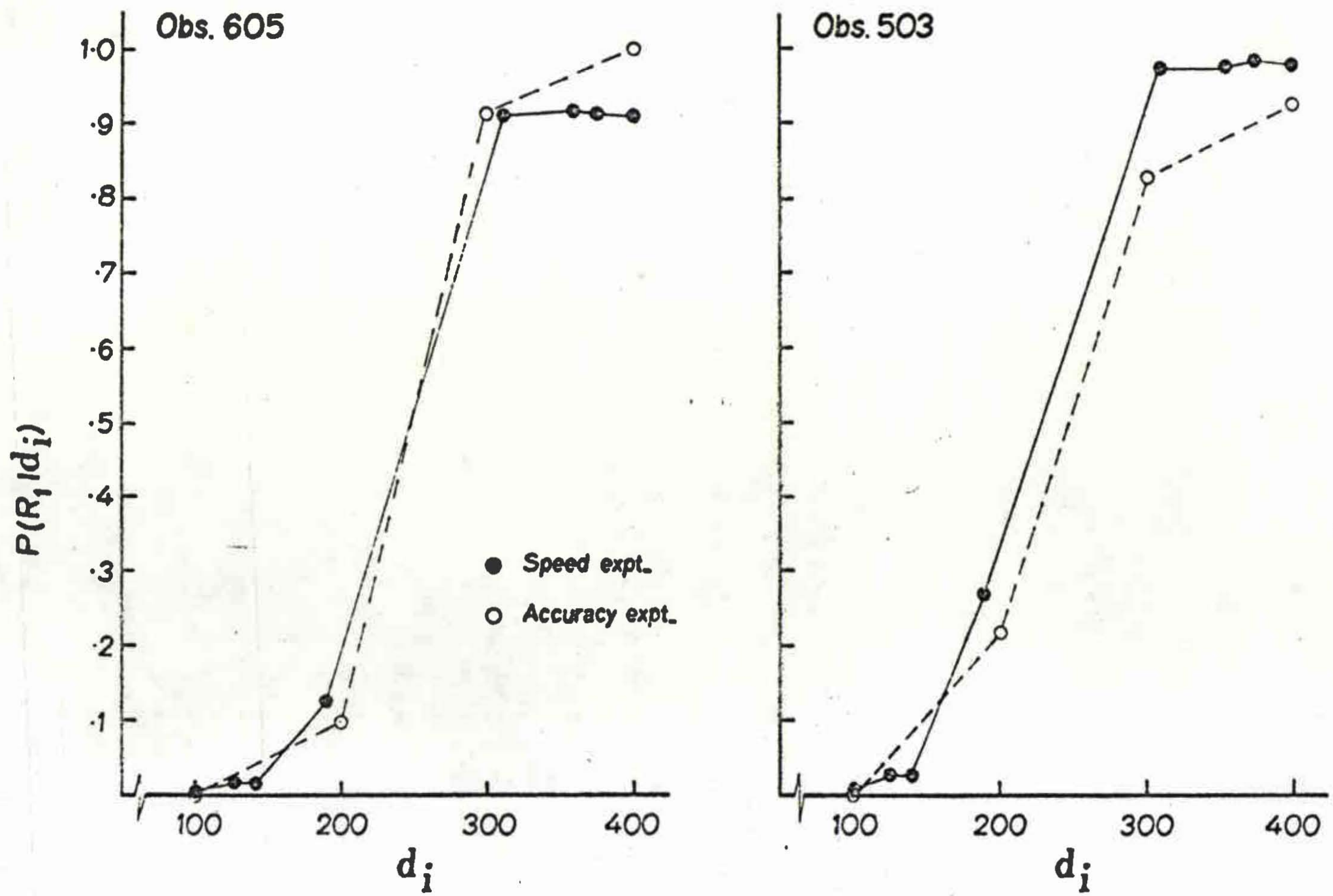


FIGURE 23. Individual psychometric functions under speed and accuracy conditions.

Table 16

Estimates of q and ε under speed and accuracy conditions for Os 605 and 503.

Condition	Index	Observer 605	Observer 503
Accuracy	q	82.54 (msec.)	115.46
	ε	.004	.0566
Speed	q	80.64	116.27
	ε	.0987	.0419
	$q^2/6$	1083.9 (msec.^{2})	2253
	$VAR(RL_1)$	1210	2537

is only related to non-process errors, the index of discriminability q, when corrected for errors, should remain unchanged. The results show a negligible difference of 1.9msec. between the estimates of q in speed and accuracy condition for O 605. The results are even clearer for O 503 with a difference of .08msec. However, in the case of that O the level of ε decreases by .015 in the speed condition. Thus, it does appear that the speeding of responses did not produce a deterioration of discriminative power.

However, the present analysis implies the acceptance of an interval measurement model that is not supported by the response latency data. So, it is useful only in as much as it describes quantitatively the variability of the Os' responses as a function of d_i. Yet, it could be interesting to consider the index q in relation to the variance of the response latencies. More precisely, if we assume following the onset-offset model that the density distribution of t_c is triangular with variance $q^2/6$, that variance could be compared to $VAR(RL)_1$. Indeed, since the onset-offset model proved to accurately describe the variability of a timing system, and d_c is the only variable involved in time-keeping in the present situation, RL_1 only will be considered. There is evidence (Kristofferson, 1973) that the major source of variability in response timing originates in the time-keeper itself. Thus, we should expect $q^2/6$ to approach $VAR(RL)_1$. The results are quite interesting; the real-time criterion variance estimated from $q^2/6$, as shown in Table 16, accounts for 89% and 88% of the total response variance for O 605 and O 503 respectively. It appears that increasing our comprehension of the mechanism underlying duration discrimination, the present experimental situation could provide a powerful means of relating directly response time to psychometric performance. In view of such a relationship, it becomes important to obtain response latencies at larger M.P. values. Since q has been shown to increase with M.P., for large shifts in M.P., one should observe an increase in $VAR(RL)_1$ proportional to the increase in q if the present relationship holds.

It has become evident that the measurement of response latency can be crucial to determine the operational characteristics of a central timing device. In that line of thought it could be useful in checking an hypothesis put forward in section 2.5. Indeed, it was argued that the SS method might not enable an O to use a real-time criterion mechanism. The present results undoubtedly show that even with the M.-F. method the O has at least two different classes of mechanisms he can use to perform a duration discrimination. Furthermore, the evidence suggests that the onset-offset model could be modified to account for the behavior of both response latency and probability data.

V SUMMARY AND CONCLUSION

The basic goal of the present work was to obtain a better understanding of the functional characteristics of timing devices operating in human duration discrimination. The usefulness of intermodal signals to study central temporal processors was demonstrated through an analysis of the literature on temporal order judgement and successiveness discrimination tasks. The absence of information on intermodal duration discrimination forced us to engage in a double investigation: first, determining the discrimination function of Os, and second evaluating quantitative models of duration discrimination in an intermodal situation. Most of the experimentation was done with intervals of less than 1sec. This decision to concentrate on shorter intervals followed from the discrepancy observed in that range between the discrimination function obtained in expt 1 (reported in Rousseau & Kristofferson, 1974) and the classical function mentionned by most authors.

In the second Chapter we evaluated the importance of some stimulus variables in the intermodal situation of expt 1 In expt 2 large variations in the duration of m_1 did not yield any change in overall P(c) averaged over four Os. Thus, the possibility that the use of brief markers would have produced temporal uncertainty is largely reduced. Similarly, in expt 3 minimal differences in overall P(c), averaged over six Os, was reported when a tone-light sequence was compared to a light-tone sequence. The light offset used in expt 1 appeared as reliable a signal as a tone offset. Thus, the intermodal feature of the intervals can be considered as the operating variable in these two experiments.

We observed a drastic effect of the psychophysical method used in a given experiment. Indeed, Fig.7 displays two discrimination functions each one associated with a particular method. The M.-F. method gave a function characterised by $DT_{75}=KT$, and the SS method's function is best described by $DT_{75}=K$. It is important to note that the difference in DT_{75} observed at short durations has been corroborated in expts 2 and 3, and again in expts 5 and 6. Thus, such a result is not likely to be accidental. If DT_{75} is considered as a measure of internal variability, the use of the M.-F. method seems to enable the operation of a timekeeper whose variability decreases when the duration of intervals to be assessed is reduced below a critical value of 700msec.However, the SS method suggests the existence of a timing device whose variability is constant at a relatively high level. Thus, in intermodal conditions more than one timekeeper is available to the O and the structure of the set D enables one or the other.

Although no direct comparison of intra and intermodal duration discrimination was done in the present work DT_{75}/T have been compared. Refering to Table 1, we can see that in intramodal conditions the ratios are around .10 in most cases. As far as the intermodal intervals are concerned, the M.-F. method yielded ratios of approximately .20 around M.P.=500 msec. increasing up to .4 at the lower bound. Even though the SS method does not give a constant ratio, performance at different T values can be expressed in terms of a Weber ratio. It is at 1.6 for T=100 and decreases to .27 at T=600msec. which is close to the M.-F. method results. Then, as T is further increased the ratio is reduced reaching the level of intramodal tasks at T=2000msec. Thus, in general, intra and intermodal intervals at the same time as M.-F. and SS methods yield definite differences in performance for durations below 700msec. In that range, the timing mechanisms are more sensitive to certain features of discrimination tasks.

However in that very same region, the psychometric functions of intra and intermodal duration discrimination showed an orderly relationship in the SD/DT_{75} ratio. In Table 2 the ratio was somewhat constant at 1.8. The constancy of the ratio will be further evaluated by comparing ratios from average psychometric functions of expt 1 (four d_o values), expt 5 (C.P.=300msec.), expt 6, and the three intramodal experiments reported in Table 2. The ratios are presented in Fig. 24; the linear relationship is striking. A least square linear curve fitting was performed on the function which yielded a slope of .48 and an intercept of 6.1. Furthermore, 98.6% of the variance in the function is accounted for by the

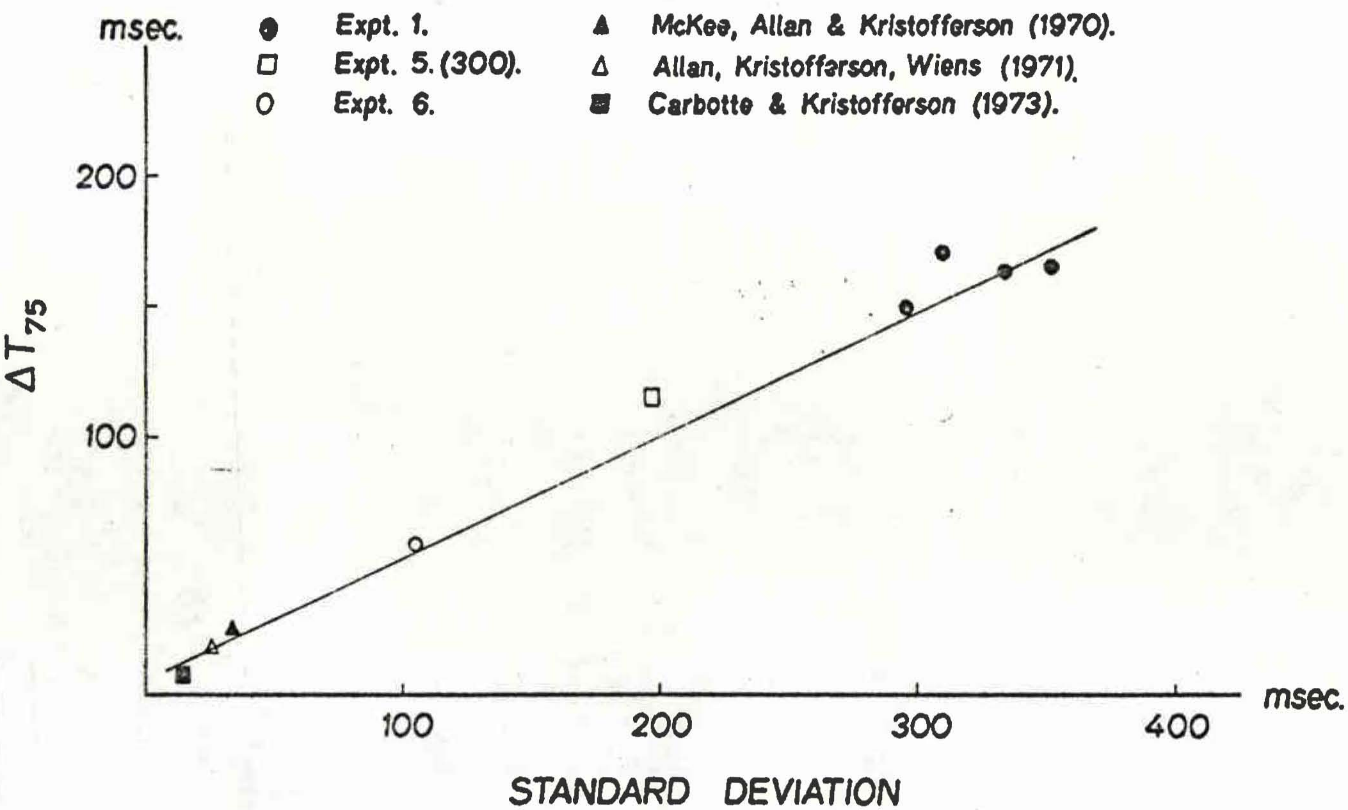


FIGURE 24. Estimates of DT_{75} as a function of the standard deviation for averaged psychometric functions from 6 different experiments.

linear fit. So, the relationship is clear and representative of intra and intermodal psychometric functions. In general, DT_{75} is half the value of the standard deviation which is a strong indication that a common timing mechanism is operating in all these situations.

The accuracy of the Os being proportional to the SD it is interesting to recall that in section 1.4.2.3 Kinchla's model predicted that $SD=\frac{DT}{d'}$. Since we have shown that SD/DT=.48 the model predicts that value to be equal to the inverse of the d' corresponding to a P(c)=.75 which is $1/2Z(c)_{75}$=.74. This is somewhat larger than the observed value.

It was not possible to determine the specific characteristics of the central timekeeper. However, $d_i(I)$ was shown to have a symmetrical distribution and a variance which is an increasing function of M.P.While both models fit well the data obtained with the M.-F. method, the constant DT_{75} function of expt 1 is more readily amenable to the onset-offset model since it simply requires q to be constant over T. However, while λ was shown to increase over M.P. with the M.-F. method, it would have to decrease over T in order to fit the SS method's results, which makes the Poisson counter model somewhat awkward to apply generally. The adequacy of the onset-offset model to account for intermodal duration discrimination increases the power of the model. Indeed, many authors (Allan & Kristofferson,1974a) have shown that model to fit intramodal duration discrimination. However, intermodal estimates of q when compared to those for auditory empty intervals (Kristofferson, 1973) are roughly three times larger on the average. At M.P.=300msec. intermodal q is at 93msec. and auditory q is around 30msec.; similarly they are at 200msec. and 65msec. respectively for M.P.=600msec.

The measurement of response latencies in duration discrimination has brought us one step forward in the understanding of timing mechanisms. Indeed, we have definitely shown that an O does not necessarily perform an interval measurement in duration discrimination. The reduction of duration discrimination to temporal order discrimination is of definite interest for future modeling. Also of interest is the finding that response latency variance is directly related to psychometric variance. The similarity between $q^2/6$ and $VAR(RL)_1$ allows one to consider the existence of a timekeeper which can be used as an interval timer or as an "alarm clock". That is to say, the timer can be controlled by external events m_1 and m_2 or set to a specific value, d_c. In that way, it would be a counter-timer whose characteristics would originate in a common timekeeper.

REFERENCES

Abel, S.M. Discrimination of temporal gaps. Journal of the Acoustical Society of America, 1972, 52, 519-524, a.

Abel, S.M. Duration discrimination of noise and tone bursts. Journal of the Acoustical Society of America, 1972, 51 1219-1223, b.

Allan, L.G. & Kristofferson, A.B. Judgements about the duration of brief stimuli. Perception & Psychophysics, 1974, 15 434-440, a.

Allan, L.G. & Kristofferson, A.B. Psychophysical theories of duration discrimination. Perception & Psychophysics, 1974, 16, 26-34.

Allan, L.G., Kristofferson, A.B. & Wiens, E.W. Duration discrimination of brief light flashes. Perception & Psychophysics, 1971, 9, 327-334.

Audley, R.J. Some observations on theories of choice reaction time: Tutorial review. In S. Kornblum (Ed.) Attention and Performance IV, New-York: Academic Press, 1973, 509-545.

Babkoff, H. & Sutton, S. Perception of temporal order and loudness judgements for dichotic clicks. Journal of the Acoustical Society of America, 1963, 35, 574-577.

Behar, I. & Bevan, W. The perceived duration of auditory and visual intervals: cross-modal comparison and interaction. American Journal of Psychology, 1961, 74, 17-26.

Blakely, W.A. The discrimination of short empty time intervals. Unpublished doctoral dissertation, University of Illinois, 1933.

Carbotte, R.M. Discrimination of brief empty time intervals. Unpublished doctoral dissertation, McMaster University, 1972.

Carbotte, R.M. & Kristofferson, A.B. On energy dependent cues in duration discrimination. Perception & Psychophysics 1973, 14, 501-505.

Collyer, C.E. Frequency selectivity in successiveness discrimination. Unpublished B.A. Thesis, McMaster University, 1971.

Collyer, C.E. The detection of a temporal gap between two disparate stimuli. Perception & Psychophysics, 1974, 16(1), 96-100.

Creelman, C.D. Human discrimination of auditory duration. Journal of the Acoustical Society of America, 1961, 34, 582-593.

Efron, R. An invariant characteristic of perceptual systems in the time domain. In S.Kornblum (Ed.), Attention and Performance IV, New-York: Academic Press, 1973, 713-736.

Efron, R. Effect of stimulus duration on perceptual onset and offset latencies. Perception & Psychophysics, 1970, 8 251-254.

Eijkman, E. & Vendrik, A.J.H. Can a sensory system be specified by its internal noise? Journal of the Acoustical Society of America, 1965, 37, 1102-1109.

Fraisse, P. Psychologie du temps. Paris: Presses Universitaires de France, 1967.

Gengel, R.W. & Hirsh, I.J. Temporal order: The effect of single versus repeated presentation, practice, and verbal feedback. Perception & Psychophysics, 1970, 7, 209-211.

Goldstone, S., Boardman, W.K. & Lhamon, W.T. Intersensory comparisons of temporal judgements. Journal of Experimental Psychology, 1959, 57, 243-248.

Goodfellow, L.D. An empirical comparison of audition,vision, and touch in the discrimination of short intervals of time. American Journal of Psychology, 1934, 46,243-248.

Green, D.M. & Swets, J.A. Signal detection theory and psychophysics. New-York: Wiley, 1966.

Green, D.M. Temporal auditory acuity. Psychological Review, 1971, 78, 540-551.

Guilford, H.P. Psychometric methods (2nd edition). New-York: McGraw-Hill, 1954.

Henry, F.M. Discrimination of the duration of sound. Journal of Experimental Psychology, 1948, 38, 734-743.

Hirsh, I.J. & Sherrick, C.E.Jr. Perceived order in different sense modalities. Journal of Experimental Psychology, 1961, 62, 423-432.

Hirsh, I.J. & Fraisse, P. Simultanéité et succession de stimuli hétérogènes. L'année psychologique, 1964, 64, 1-19.

Kinchla, J. Duration discrimination of acoustically defined intervals in the 1 to 8 sec. range. Perception & Psychophysics, 1972, 12, 318-320.

Kornblum, S. Simple reaction time as a race between signal detection and time estimation: A paradigm and model. Perception & Psychophysics, 1973, 13, 108-112.

Kristofferson, A.B. Successiveness discrimination as a two-state quantal process. Science, 1967, 158, 1337-1339.

Kristofferson, A.B. Psychological timing mechanisms. A paper presented at the Fourth Annual Meeting of Lake Ontario Vision Establishment, Niagara Falls, Ontario, 1973.

McKee, M.E., Allan, L.G. & Kristofferson, A.B. Duration discrimination of brief visual off-flashes. Technical Report No. 42, McMaster University, 1970.

Michon, J.A. Processing of temporal information and the cognitive theory of time experience. Studium Generale, 1970, 23, 249-265.

Nichols, H. The psychology of time. American Journal of Psychology, 1891, 3, 453-539.

Nilsson, T.H. Two-pulse-interval vision thresholds. Journal of the Optical Society of America, 1969, 59, 753-757.

Oatley, K., Robertson,A. & Scanlan, P.M. Judging the order of visual stimuli. Quarterly Journal of Experimental Psychology, 1969, 21, 172-175.

Ollman, R.T. & Billington, M.J. The deadline model for simple reaction time. Cognitive Psychology, 1972, 3, 311-336.

Ornstein, R.E. On the experience of time. Middlesex: Penguin Books, 1970.

Robinson, D.N. Visual discrimination of temporal order. Science, 1967, 156, 1263-1264.

Rutschmann, J. & Link, R. Perception of temporal order of stimuli differing in sense mode and simple reaction time. Perceptual and Motor Skills, 1964, 18, 345-352.

Small, A.M. & Campbell, R.A. Temporal differential sensitivity for auditory stimuli. American Journal of Psychology, 1962, 75, 401-410.

Sternberg, S & Knoll, R.L. The perception of temporal order: Fundamental issues and a general model. In S. Kornblum (Ed.), Attention and Performance IV, New-York: Academic Press, 1973, 629-685.

Stott, L.H. The discrimination of short tonal durations. Unpublished doctoral dissertation, University of Illinois, 1933.

Tanner, T.A., Patton, R.M. & Atkinson, R.C. Intermodality judgements of signal duration. Psychonomic Science, 1965, 2, 271-272.

Treisman, M. Temporal discrimination and the indifference interval: Implications for a model of the "internal clock". Psychological Monographs, 1963, 77(13), Whole 576.

Treisman, M. Noise and Weber's law: The discrimination of brightness and other dimensions. Psychological Review, 1964, 71, 314-330.

Woodrow, H. Time perception. In S.S. Stevens (Ed.), Handbook of experimental psychology, New-York: Wiley, 1951, Chap. 53.

APPENDIX A

INDIVIDUAL ESTIMATES IN EXPERIMENTS 1,2,3, and 4.

Table A1

Individual $P(R_1|d_i)$, P(c) and d' at d_o=100msec.

O	$P(R_1\|d_i)$	$P(R_1\|d_o)$	P(c)	d'
		d_1=150		
30	.4536	.4036	.5250	.12
31	.2975	.2724	.5126	.08
32	.4286	.2250	.6018	.43
33	.5572	.4286	.5643	.33
		d_2=250		
30	.6714	.1357	.7679	1.52
31	.5857	.1630	.7091	1.19
32	.7607	.0857	.8375	2.10
33	.7429	.2643	.7393	1.28
		d_3=350		
30	.8286	.1072	.8607	2.14
31	.7000	.1936	.7531	1.36
32	.8786	.0357	.9214	3.06
33	.9000	.1036	.8982	2.56
		d_4=450		
30	.9929	.0107	.9911	4.64
31	.8500	.1179	.8661	2.22
32	.9786	.0107	.9839	4.37
33	.9714	.0107	.9804	4.20
		d_5=700		
30	.9928	.0036	.9946	4.64
31	.9570	.0714	.9428	3.22
32	.9679	.0250	.9714	3.93
33	.9964	0.	.9982	4.64

Table A2

Individual $P(R_1|d_i)$, P(c) and d' at d_o=600msec.

O	$P(R_1\|d_i)$	$P(R_1\|d_o)$	P(c)	d'
		d_1=650		
12	.6714	.3108	.6803	0.94
13	.5848	.4400	.5724	0.35
14	.5053	.3656	.5698	0.36
15	.4358	.4008	.5174	-0.08
16	.4821	.3929	.5392	0.23
17	.5719	.3827	.5945	0.48
		d_2=750		
12	.8884	.1179	.8850	2.35
13	.6870	.2350	.7261	1.21
14	.7678	.2179	.7750	1.51
15	.5923	.1723	.7115	1.18
16	.6428	.2286	.7071	1.10
17	.7810	.1770	.8010	1.68
		d_3=850		
12	.9467	.0684	.9389	2.95
13	.7970	.1637	.8168	1.48
14	.9458	.2179	.8635	2.32
15	.7706	.0646	.8530	2.21
16	.6250	.2010	.7119	1.14
17	.9285	.0932	.0120	2.74
		d_4=950		
12	.9856	.0180	.9840	4.10
13	.8029	.1268	.8376	1.97
14	.8750	.0965	.8897	2.41
15	.8230	.0330	.8962	2.80
16	.7785	.0790	.8500	2.17
17	.9175	.0466	.9388	3.04
		d_5=1050		
12	.9960	.0000	.9980	4.64
13	.9138	.0480	.9330	2.98
14	.9640	.0608	.9517	3.30
15	.9298	.0111	.9594	3.79
16	.7850	.0825	.8512	2.17
17	.9784	.0286	.9740	3.93

Table A3

Individual $P(R_1|d_i)$, P(c) and d' at d_o=1200msec.

O	$P(R_1\|d_i)$	$P(R_1\|d_o)$	P(c)	d'
		d_1=1250		
20	.5536	.3118	.6208	.64
21	.5143	.3835	.5653	.33
22	.6533	.3880	.6318	.64
23	.5214	.4143	.5536	.26
24	.5153	.4982	.5081	.02
25	.6357	.4107	.6125	.56
		d_2=1350		
20	.6895	.1322	.7792	1.64
21	.7645	.2079	.7784	1.50
22	.7428	.2509	.7460	1.32
23	.6464	.3000	.6732	.88
24	.6714	.3477	.6619	.80
25	.8322	.1536	.3893	1.99
		d_3=1450		
20	.9464	.0286	.9589	3.43
21	.9322	.0786	.9268	2.87
22	.8346	.1455	.8446	2.03
23	.7885	.2313	.7746	1.48
24	.7266	.2679	.7294	1.22
25	.9478	.0679	.9398	3.11
		d_4=1550		
20	.9921	.0000	.9960	
21	.9679	.0572	.9554	3.43
22	.9134	.1223	.8955	2.52
23	.8786	.1770	.8518	2.12
24	.8602	.1964	.8319	1.96
25	.9711	.0107	.9803	4.20
		d_5=1800		
20	.9970	.0030	.9970	4.64
21	1.0000	.9921	.9960	
22	.9491	.0609	.9441	3.19
23	.9536	.0357	.9589	3.52
24	.9322	.0857	.9232	2.87
25	.9964	.0179	.9893	4.37

Table A4

Individual $P(R_1|d_i)$, P(c) and d' at d_o=2000msec.

O	$P(R_1\|d_i)$	$P(R_1\|d_o)$	P(c)	d'
		d_1=2100		
5	.6762	.3719	.652	.77
6	.5666	.4782	.544	.23
9	.6654	.3063	.680	.92
10	.7598	.2786	.741	1.28
11	.7383	.3786	.680	.94
		d_2=2200		
5	.8136	.1589	.827	1.87
6	.6535	.2929	.680	.94
9	.8654	.2322	.816	1.82
10	.8714	.1470	.862	2.17
11	.8561	.2858	.785	1.64
		d_3=2300		
5	.9535	.0968	.929	2.92
6	.7464	.1786	.784	1.59
9	.8953	.1782	.859	2.14
10	.8964	.0500	.923	2.92
11	.8678	.1112	.878	2.36
		d_4=2400		
5	.9749	.0322	.971	3.76
6	.7977	.1358	.832	1.92
9	.9250	.0572	.934	3.11
10	.9464	.0643	.936	3.11
11	.8996	.1750	.862	2.20
		d_5=2600		
5	.9781	.0288	.975	3.93
6	.9780	.0210	.944	4.10
9	.9714	.0472	.964	3.69
10	.9783	.0179	.980	4.10
11	.9821	.0286	.977	3.93

Table A5

Linear least square fit individual slope + intercept.

Obs	Slope	Intercept	r^2
	Base duration		
	100		
30	.0101	-.2550	.9527
31	.0055	.0852	.9572
32	.0132	-.1092	.9928
33	.0112	-.2825	.9763
$\bar{X}$	.0100	-.1403	
	600		
12	.0101	.5725	.9487
13	.0060	.0930	.9612
14	.0070	.2580	.8937
15	.0092	-.2705	.9833
16	.0050	.1245	.9058
17	.0087	.2370	.9451
$\bar{X}$	.0076	.1690	
	1200		
20	.0140	-.1892	.9740
21	.0127	-.3383	.9979
22	.0064	.3575	.9940
23	.0062	-.0510	.9999
24	.0051	-.0581	.9766
25	.0128	-.0258	.9951
$\bar{X}$	.0095	-.0508	
	2000		
5	.0108	-.2967	.9998
6	.0057	-.2600	.9764
9	.0064	.3550	.9720
10	.0082	.4833	.9976
11	.0056	.4289	.9363
$\bar{X}$	.00734	.1421	

Table A6

Individual estimated of P(c) for each cycle in expt 2 at three durations of the light marker.

Observer	Cycle	Duration of the light Marker (msec.) 10	500	4000
100	1	.85	.96	.95
	2	.90	.94	.97
	3	.81	.91	.95
	4	.80	.96	.91
	5	.89	.94	.89
	6	.92	.93	.97
102	1	.77	.68	.73
	2	.65	.70	.65
	3	.71	.70	.73
103	1	.57	.74	.63
	2	.60	.67	.50
	3	.57	.49	.61
	4	.57	.55	.51
	5	.51	.66	.65
	6	.55	.55	.44
1	1	.77	.81	.73
	2	.79	.83	.80
	3	.73	.81	.84
	4	.77	.80	.80
	5	.79	.77	.74
	6	.73	.73	.78

Table A7

Estimates of $P(R_1|d_i)$ averaged over two sessions at M.P. values in the range of 175-1200msec. for 4 Os.

Obs	d_i	$P(R_1\|d_i)$	d_i	$P(R_1\|d_i)$	d_i	$P(R_1\|d_i)$	d_i	$P(R_1\|d_i)$
304	100	.113	100	.039	200	.053	275	.039
	150	.325	150	.146	250	.173	325	.140
	200	.646	250	.874	350	.853	475	.859
	250	.946	300	.986	400	.939	525	.846
	350	.013	450	.113	500	.046	600	.126
	425	.160	525	.299	625	.266	725	.259
	575	.906	675	.660	775	.770	875	.670
	650	.986	750	.770	900	.863	1000	.799
	650	.065	750	.019	850	.080	8850	.040
	825	.253	925	.253	1025	.319	1100	.160
	975	.619	1075	.766	1175	.739	1300	.733
	1150	.886	1250	.926	1350	.946	1550	.973
1	100	.066	100	.060	200	.054	275	.053
	150	.262	150	.146	250	.293	325	.162
	200	.646	250	.783	350	.876	475	.902
	250	.898	300	.939	400	.946	525	.946
	350	.053	450	.106	500	.060	600	.053
	425	.194	525	.300	625	.237	725	.189
	575	.907	675	.816	775	.695	875	.623
	650	.973	750	.857	900	.866	1000	.892
	650	.041	750	.128	850	.100		
	850	.294	925	.336	1085	.410		
	975	.641	1075	.687	1175	.746		
	1150	.917	1250	.906	1350	.837		

Table A7 (continued)

Obs	d_i	$P(R_1\|d_i)$	d_i	$P(R_1\|d_i)$	d_i	$P(R_1\|d_i)$	d_i	$P(R_1\|d_i)$
302	100	.093	100	.000	200	.039	275	.026
	150	.253	150	.273	250	.219	325	.099
	200	.706	250	.893	350	.906	475	.926
	250	.933	300	.966	400	.979	525	.973
	350	.000	450	.013	500	.000	600	.006
	425	.055	525	.106	625	.080	725	.080
	575	.933	675	.886	775	.839	875	.853
	650	1.000	750	.993	900	1.000	1000	.986
	650	.000						
	825	.120						
	975	.706						
	1150	.933						
301	100	.013						
	200	.130						
	400	.885						
	500	.980						
	200	.026	300	.026	375	.033	475	.048
	300	.185	400	.155	500	.176	575	.183
	500	.972	600	.872	700	.767	825	.650
	600	.973	700	.945	825	.861	925	.783
	500	.073	600	.074	700	.074	800	.067
	650	.299	750	.156	850	.206	950	.194
	950	.838	1050	.610	1150	.686	1250	.723
	1100	.945	1200	.779	1300	.823	1400	.841

APPENDIX B

INDIVIDUAL ESTIMATES IN EXPERIMENTS 5 AND 6.

Table B1

Parameters of the least square linear fit to the last five sessions, coefficient of determination and total number of sessions, N, at each C.P. for three Os in expt 6.

O	C.P. (msec.)	Slope	intercept	r^2	N
201	280	.0017	.6849	.0292	19
	300	-.0055	.7465	.0064	23
	320	.0104	.7076	.0886	17
2b	260	-.0112	.7401	.2787	19
	300	.0009	.7886	.0467	21
	340	.0022	.7802	.0126	16
17	280	-.0078	.7310	.1230	23
	300	-.0031	.7181	.1390	21
	320	-.0090	.7604	.2460	16

Table B2

Observed $P(R_1|d_i)$ and $Z_c(R_1|d_i)$ and Predicted $Z_c(R_1|d_i)$ estimated with minimum sum of squared deviations for each O in expt 5

O	d_i	$P(R_1\|d_i)$	$Z_c(R_1\|d_i)$	$Z_c(R_1\|d_i)$	Σdev^2
6	450	.0222	-2.0115	-2.1474	
	550	.1688	-.9588	-.6811	
	650	.7288	.6093	.5337	
	750	.9466	1.6130	1.5767	.1026
15	450	.0266	-1.9344	-1.9630	
	550	.2888	-.5570	-.5252	
	650	.7496	.6732	.6671	
	750	.9555	1.7011	1.6919	.00195
1	450	.08	-1.4053	-1.4577	
	550	.2977	-.5312	-.4395	
	650	.6517	.3902	.4043	
	750	.8789	1.1696	1.1292	.0129

Table B3

Observed $\hat{P}(R_1|d_i)$ and $\hat{Z}_c(R_1|d_i)$ and Predected $Z_c(R_1|d_i)$ estimates with minimum sum of squared deviations for O 2b.

C.P.	d_i	$\hat{P}(R_1\|d_i)$	$\hat{Z}_c(R_1\|d_i)$	$Z_c(R_1\|d_i)$	Σdev^2
260	240	.3203	-.4671	-.4552	
	280	.6201	.3060	.3115	
	320	.8611	1.0853	.9769	.01631
300	240	.1245	-1.1529	-1.2374	
	280	.3511	-.3826	-.2958	
	320	.6667	.4311	.5139	
	360	.9067	1.3210	1.2298	.0290
340	240	.0210	-2.0340	-2.1466	
	280	.1111	-1.2210	-1.1593	
	320	.3556	-.3705	-.3098	
	360	.6435	.3681	.4382	.0249

Table B4

Observed $\hat{P}(R_1|d_i)$ and $\hat{Z}_c(R_1|d_i)$ and Predicted $Z_cR_1|d_i)$ estimates with minimum sum of squared deviations for O 17.

C.P.	d_i	$\hat{P}(R_1\|d_i)$	$\hat{Z}_c(R_1\|d_i)$	$Z_c(R_1\|d_i)$	Σdev^2
280	270	.3921	-.2741	-.2434	
	290	.6145	.2913	.2348	
	310	.7528	.6833	.6815	
	330	.8603	1.0817	1.1010	.0045
300	270	.1333	-1.1110	-1.0927	
	290	.3049	-.5105	-.4844	
	310	.5580	.1461	.0827	
	330	.7098	.5529	.6144	.0088
320	270	.0674	-1.4957	-1.4553	
	290	.2235	-.7604	-0.9200	
	310	.3017	-.5197	-0.4215	
	330	.5265	.0666	.0454	.0372

Table B5

Observed $\hat{P}(R_1|d_i)$ and $\hat{Z}_c(R_1|d_i)$ and Predicted $Z_c(R_1|d_i)$ estimates with minimum sum of squared deviations for O 201.

C.P.	d_i	$\hat{P}(R_1\|d_i)$	$\hat{Z}_c(R_1\|d_i)$	$Z_c(R_1\|d_i)$	Σdev^2
280	270	.3472	-.3932	-.4015	
	290	.5778	.1965	.2086	
	310	.7833	.7833	.7782	
	330	.9056	1.3144	1.3129	.00024
300	270	.2267	-.7497	-.7687	
	290	.4178	-.2077	.2116	
	310	.6089	.2767	.3071	
	330	.7956	.8259	.7937	.0023
320	270	.1445	-1.0603	-1.2052	
	290	.1900	-.8778	-.7322	
	310	.3240	-.4568	-.2916	
	330	.6158	.2947	.1211	.0996

Table B6

Estimates of β_i, $\Delta_q(R_1\ d_i)$, ε and α for three Os at C.P. of 600msec.

O	d_i	$P(R_1\|d_i)$	β_i	$\Delta_q(R_1\|d_i)$	ε	α
6	350	.0044	.0000	-1.0000	.0178	.2471
	450	.0222	.0181	-0.8096		
	550	.1688	.1673	-0.4213		
	650	.7288	.7375	0.2754		
	750	.9466	.9592	0.7143		
	850	.9866	1.0	1.0		
15	350	.0044	.0000	-1.0000	.0267	.1647
	450	.0266	.0228	-0.7864		
	550	.2888	.2922	-0.2355		
	650	.7496	.7692	0.3108		
	750	.9555	.9772	0.7864		
	850	.9777	1.0	1.0		
1	350	.0359	.0000	-1.0000	.0939	.3817
	450	.0800	.0487	-0.6878		
	550	.2977	.2889	-0.2397		
	650	.6516	.6797	0.1997		
	750	.8789	.9300	0.6270		
	850	.9419	1.0	1.0		

Table B7

Estimates of β_i, $\Delta_q(R_1|d_i)$, ε and α for O 2b at three C.P. values.

C.P. (msec.)	d_i	$P(R_1\|d_i)$	β_i	$\Delta_q(R_1\|d_i)$	ε	α
260	150	.0195	.0000	-1.0000	.0528	.3684
	240	.3203	.3176	-0.2030		
	280	.6201	.6341	0.1446		
	320	.8611	.8886	0.5279		
	360	.9333	.9648	0.7347		
	450	.9667	1.0	1.0		
300	150	.0445	.0000	-1.0000	.0311	.1429
	240	.1245	.1239	-0.5023		
	280	.3511	.3578	-0.1541		
	320	.6667	.6835	0.2044		
	360	.9067	.9315	0.6290		
	450	.9733	1.0	1.0		
340	150	.0000	.0000	-1.0	.0472	.0000
	240	.0111	.0117	-0.8473		
	280	.1111	.1166	-0.5171		
	320	.3556	.3732	-0.1361		
	360	.6435	.6754	0.1992		
	450	.9528	1.0	1.0		

Table B8

Estimates of β_i, $\Delta_q(R_1|d_i)$, ε and α for O 17 at three C.P. values.

C.P. (msec.)	d_i	$P(R_1\|d_i)$	β_i	$\Delta_q(R_1\ d_i)$	ε	α
280	150	.0027	.0000	-1.0	.0027	1.0000
	270	.3921	.3904	-0.1163		
	290	.6145	.6134	0.1207		
	310	.7528	.7521	0.2958		
	330	.8603	.8599	0.4707		
	450	1.0	1.0	1.0		
300	150	.0000	.0000	-1.0	.0090	.0000
	270	.1333	.1346	-0.4813		
	290	.3049	.3049	-0.2155		
	310	.5580	.5631	0.0652		
	330	.7098	.7163	0.2467		
	450	.9910	1.0	1.0		
320	150	.0000	.0000	-1.0	.0084	.0000
	270	.0674	.0680	-0.6313		
	290	.2235	.2259	-0.3286		
	310	.3017	.3042	-0.2200		
	330	.5265	.5310	0.0315		
	450	.9916	1.0	1.0		

Table B9

Estimates of β_i, $\Delta_q(R_1|d_i)$, ε and α for O 201 at three C.P. values.

C.P. (msec.)	d_i	$P(R_1\|d_i)$	β_i	$\Delta_q(R_1\|d_i)$	ε	α
280	150	.0167	.0000	-1.0	.0167	1.0000
	270	.3472	.3362	-0.1801		
	290	.5778	.5706	0.0733		
	310	.7833	.7797	0.3362		
	330	.9056	.9040	0.5617		
	450	1.0	1.0	1.0		
300	150	.0134	.0000	-1.0	.0134	1.0000
	270	.2267	.2161	-0.3425		
	290	.4178	.4098	-0.0858		
	310	.6089	.6045	0.1106		
	330	.7956	.7928	0.3562		
	450	1.0	1.0	1.0		
320	150	.0000	.0000	-1.0000	.0022	.0000
	270	.1445	.1449	-0.4618		
	290	.1900	.1905	-0.3828		
	310	.3240	.3249	-0.1939		
	330	.6128	.6146	0.1220		
	450	.9972	1.0000	1.0000		