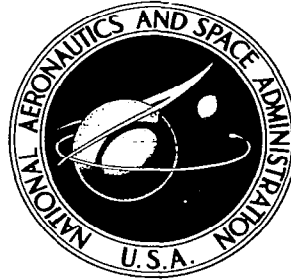


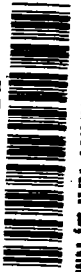
**NASA CONTRACTOR  
REPORT**

**NASA CR-427**



**NASA CR**

0099574



TECH LIBRARY KAFB, NM

LOCAL COPY: RETURN TO  
AFWL (WLIL-2)  
KIRTLAND AFB, N MEX

**A TIME CONSTANT INVOLVED  
IN ATTENTION AND  
NEURAL INFORMATION PROCESSING**

*by Alfred B. Kristofferson*

Prepared under Contract No. NAS 2-2486 by  
BOLT BERANEK AND NEWMAN, INC.  
Cambridge, Mass.  
*for Ames Research Center*



A TIME CONSTANT INVOLVED IN ATTENTION  
AND NEURAL INFORMATION PROCESSING

By Alfred B. Kristofferson

Distribution of this report is provided in the interest of information exchange. Responsibility for the contents resides in the author or organization that prepared it.

Prepared under Contract No. NAS 2-2486 by  
BOLT BERANEK AND NEWMAN, INC.  
Cambridge, Mass.

for Ames Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

---

For sale by the Clearinghouse for Federal Scientific and Technical Information  
Springfield, Virginia 22151 - Price \$0.70



## Abstract

Evidence is presented which indicates that it is reasonable to entertain the hypothesis that the human brain functions like a time-shared information processing system having a cycle time of 50 msec. A central periodic process is postulated which generates a series of equally-spaced points in time. These points, in turn, are the instants when the central processor can switch from one input channel to another and they also determine when information can be transferred from one stage within the processor to another.

Three behavioral time parameters are defined and experiments have been done which allow them to be estimated independently for single individuals. The three parameters are equal in magnitude, about 50 msec., for the group of subjects. They are highly correlated over individuals. They are independent of sensory modality. And they vary over individuals in the same way and to the same extent in relation to another variable. It is concluded that they are identical. Further, a simple theory provides an integrated interpretation of the three.

In one small experiment it is shown that the behavioral cycle time is approximately equal to the interval between zero-crossings of the alpha rhythm of the electroencephalogram and that there are significant correlations over individuals between this neurophysiological quantity and the behavioral parameters. However, there is a discrepancy between behavioral and EEG measurements for individuals at the upper end of the scale which is sufficiently large to preclude a conclusion of identity.



## CONTENTS

Abstract . . . . .	iii
Foreword . . . . .	vii
A TIME CONSTANT INVOLVED IN ATTENTION AND NEURAL INFORMATION PROCESSING . . . . .	1
Experiment 1. Successiveness Discrimination . . . . .	1
Experiment 2. Influence of Channel Uncertainty Upon Reaction Time . . . . .	6
Method of Data Analysis . . . . .	9
Results . . . . .	13
The Form of Reaction Time Distributions . . . . .	15
Theoretical Interpretation . . . . .	25
Interpretation of M . . . . .	26
Interpretation of K . . . . .	28
Interpretation of Q . . . . .	29
General Conclusion . . . . .	29
Experiment 3. An Electroencephalographic Measurement . . . . .	31
Conclusion . . . . .	36
REFERENCES . . . . .	40



## Foreword

This is a report of part of the research performed under Contract NAS 2-2486, "Research on Human Attention," between the National Aeronautics and Space Administration and Bolt Beranek and Newman, Inc. The contract is administered by the NASA Ames Research Center, Moffett Field, California. Dr. Trieve Tanner is the technical monitor.

I would like to express my gratitude to Mrs. Linda McElroy, Jonathan Headley, and Joshua Coran, each of whom spent many months in the collection and analysis of these data.



## A TIME CONSTANT INVOLVED IN ATTENTION AND NEURAL INFORMATION PROCESSING

The main purpose of this paper is to present the results of some recently-completed experiments and then to interpret those results in terms of the theory which initiated the experiments. Since the theory has been set forth in some detail in a recent report (1), it will be repeated here only insofar as the interpretation of the data requires.

### Experiment 1. Successiveness Discrimination

In this experiment we are concerned with measuring the time interval which must separate two independent sensory events in order for them to be discriminated as successive rather than simultaneous. If the sensory events are independent in the sense that they cannot be attended simultaneously, then the discrimination of them as successive may be limited by the time required to switch attention from one to the other, at least under ideal conditions. And by measuring this time interval we may be able to infer the time required to switch attention.

The two signals which are used in all of these experiments are a uniform spot of light and a pure tone. The light is directly fixated and large enough to fill the fovea. The tone is a 2000-cps sinusoid. Both stimuli are of a moderate intensity well above threshold.

When we first did experiments of this kind several years ago we used a direct, phenomenal report method which consisted

of presenting a light-sound pair to the subject and asking him to judge whether they were simultaneous or successive. It soon became obvious that such a procedure is inadequate, at least for making precise measurements of the performance of single individuals. The data suggested that a subject's criterion of simultaneity is not an absolute one; indeed, from one day to the next the experimental subject is very likely to shift his criterion by a substantial amount.

For this reason we decided to use a forced-choice psychophysical method in which two pairs of signals are presented on each trial, as shown in Figure 1, and the subject is asked to indicate which pair seems more likely to be successive. The critical events which must be judged are the terminations of the signals so that the signals both will be present prior to the time of judgment and can define the relevant channels for the subject.

Thus, on each trial a standard light-sound pair and a variable pair are presented. The terminations of the light and sound are objectively simultaneous for the standard and they are separated by some interval,  $t$  in Figure 1, in the variable. The subject must try to indicate which of the two pairs, the first or the second, is the "successive" pair. When he indicates the variable, he is said to be correct and we measure the probability of being correct,  $P(C)$ , for each of several values of the variable interval.

$P(C)$  increases monotonically as the variable interval is made longer, of course, and the data typically look like the data points which are plotted in Figure 2. In this figure the point of objective simultaneity is at the center of the baseline with positive intervals to the right and negative

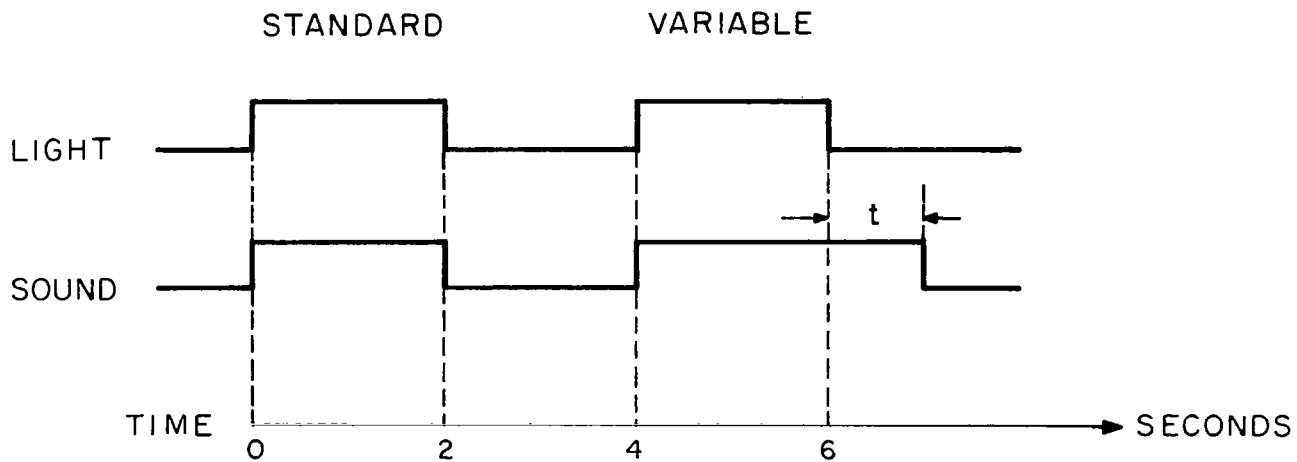
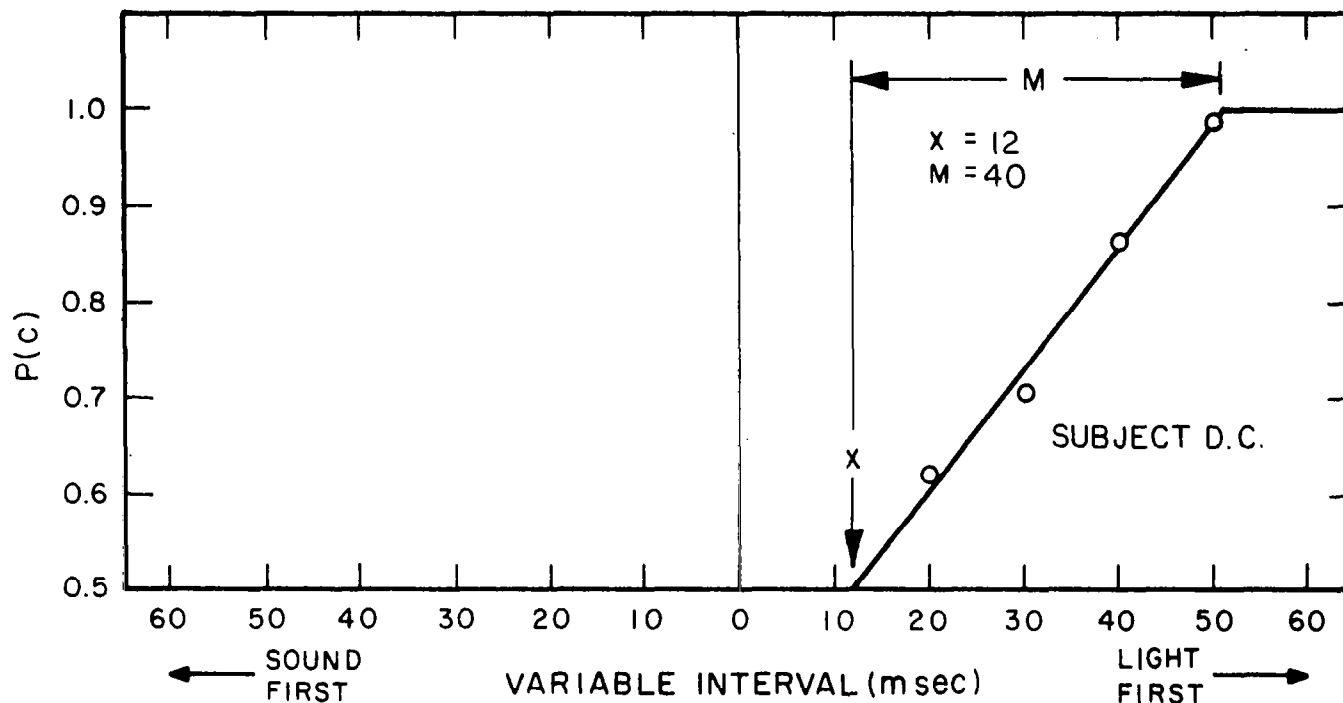


DIAGRAM OF STIMULUS EVENTS IN ONE FORCED-CHOICE TRIAL. ON ONE-HALF OF THE TRIALS, SELECTED RANDOMLY, THE STANDARD FOLLOWS THE VARIABLE.

FIG. 1



A TYPICAL SET OF SUCCESSIVENESS DISCRIMINATION DATA FOR THE LIGHT-FIRST, CHANNEL CERTAINTY CASE USING A TWO-CHOICE, FORCED-CHOICE METHOD. THE STANDARD INTERVAL IS ZERO

FIG. 2

ones to the left. The algebraic sign indicates which of the two signals occurs first. Positive intervals mean that the light termination precedes the sound by the indicated amount while negative intervals mean that the sound precedes the light. The data in Figure 2 were obtained in an experiment in which only light-first variables were presented and the subject was informed of that fact ahead of time. This procedure is the one we usually use because it makes it possible for the subject to attend to the channel which contains the first signal at the moment the first signal occurs.

There are several other procedural details which are important in making these measurements. Several practice sessions are usually required before the final data are taken, and these are necessary not only at the beginning of an experiment but also every time there is any change in the procedure such as a change in the range of variable intervals. The length of a single session is also important; if it exceeds more than about 100 trials without a substantial rest break, performance is likely to deteriorate.

The method of analyzing these data is also illustrated in Figure 2. A straight line is calculated which minimizes the squared-error in  $P(C)$ . Data points which have a theoretical  $P(C)$  greater than .98 or less than .52 when they are included in the calculation of the line are excluded and the line is recalculated.

Two parameters are estimated from each function. One of these is  $x$ , the value of the variable interval at which the line intersects the  $P(C) = .50$  axis and the other is  $M$ , the number of msec. which must be added to  $x$  for  $P(C)$  to reach 1.0.

These parameters are given a specific theoretical meaning. The first one,  $x$ , is interpreted as the objective interval between the light and sound which must exist in order for the visual and auditory neural signals to be simultaneous. The second,  $M$ , is the minimum interval by which the neural signals must be separated in order for them to be discriminated as successive 100% of the time.

Whether one is justified in describing these data with linear functions is a difficult question which has been discussed at length in an earlier report (1). Data were presented for sixteen subjects in that report and the linear hypothesis was compared to the traditional ogival hypothesis. There is a slight edge in favor of the latter function but it is contributed entirely by two or three subjects. For most subjects the linear hypothesis is as acceptable as the ogival and, since the linear hypothesis is amenable to simple and powerful theoretical interpretation, it will be used here.

The results of applying this procedure to eight young, male subjects are shown in Table I. The values of  $x$  are all positive and small, averaging about 8 msec. The major parameter,  $M$ , ranges from 39 to 77 msec. and its mean value is 54.

## Experiment 2. The Influence of Channel Uncertainty Upon Reaction Time

This very different set of operations was designed in an attempt to obtain an independent measurement of the time required to switch attention from one sensory channel to

<u>SUBJECT</u>	<u>x</u>	<u>M</u>
DC	11.8	39.4
NC	5.6	61.3
NG	22.3	47.2
GK	1.9	46.2
JH	7.5	42.2
PM	6.7	62.7
JC	7.3	76.7
KQ	<u>0.0</u>	<u>58.9</u>
mean	7.9	54.3

TABLE I  
OBTAINED VALUES OF x AND M IN MSEC.  
LIGHT-FIRST, CHANNEL CERTAINTY

another. Simple reaction times to a particular signal are measured (a) for trials on which the subject knows the relevant channel ahead of time (certainty) and (b) for trials on which he knows in advance only that the signal will be in one of two clearly-defined channels (uncertainty). There is a single response which is the same under all conditions.

Since the proportion of trials on which the subject fails to pay attention to the relevant channel at the critical moment should be larger for the uncertainty condition, it should be possible to make inferences about the switching time by comparing data for the certainty condition with that for the uncertainty condition. For this to work, however, it is necessary that uncertainty have no effects upon reaction time other than the effect of adding increments due to switching time.

It would be most convenient if subjects could behave ideally in this kind of experiment in the sense of always attending to the relevant channel when they are certain and always attending to one or the other of the two channels when they are uncertain. If they were able to do this, the calculation of switching times would be a simple matter. However, our experiments indicate that such a set of assumptions is violated almost without fail and a more indirect method is needed to extract precise information from the data.

The procedures for this experiment were developed out of a long series of experiments which have been described before (1). These experiments culminated in the selection of a three-signal discrimination task as the best one for the present purposes. The reasons for this selection are discussed in detail in (1).



There are three signals, the same light and tone as in Experiment 1, and a second light identical to the first and located adjacent to it. The three signals appear simultaneously at the beginning of the foreperiod, and at the end of the foreperiod one and only one of them terminates. The subject is instructed to respond as rapidly as possible if either the tone or the right light terminates, whereas if the left light terminates he is to withhold the response. He must, therefore, discriminate among the signals before initiating his response.

Before each trial a cueing signal is presented which conveys the information that the relevant channel for that trial is visual or that it is auditory or that it may be either. This cueing signal differentiates the certainty and uncertainty conditions. However, the subject knows that the negative signal, i.e. the left light, may occur on any trial and that the cueing signal merely tells him something about the positive signals. As a result, the experimental task is not symmetrical with respect to the relative "importance" of the visual and auditory channels, and one might expect the existence of a strong tendency to attend to the visual channel when uncertain. The data bear out this expectation in that uncertainty has a larger effect upon the auditory reaction times. However, a symmetrical division of attention between the channels is not required by the method of analysis of the data which is used and this factor is of no significance.

Method of Data Analysis.--The method of analyzing data for the effect of channel uncertainty and its rationale are summarized in Figure 3. This derivation has been discussed in detail elsewhere (1,2).

Figure 3 explains the analysis for a single channel. The measurements consist of reaction time means and variances for the channel under consideration for the certainty condition and for the uncertainty condition. The analysis is completely general. It is assumed that on some proportion,  $P$ , of the uncertainty trials an additional time increment,  $\delta$ , will be added to the value the reaction time would have had in the absence of uncertainty.  $P$  may have any positive value, although if it is zero a measurement cannot be made, and  $\delta$  is unrestricted in that it may assume any value and may be different on different trials. The distribution of  $\delta$ -values, which is hypothetical, has a mean of  $\Delta$  and a variance of  $\sigma_{\delta}^2$ .

Equation (1) shows the effect of adding  $\delta$  upon the mean of the obtained distribution. The increment by which uncertainty increases the mean reaction time is  $P\Delta$ .

Equation (2) shows the effect upon the variance of a distribution of adding a variable to some proportion of the instances. Note that when  $P = 1$ , equation (2) reduces to the well-known equation for the variance of the sum of two variables.

There is a pair of equations of this kind for each channel, four equations in all. If one assumes the  $\delta$ -distribution to be the same for the two channels, then there are four unknowns. However, the four equations are not independent and cannot be solved.

Each pair of equations can be combined to eliminate  $P$  with the result shown at the bottom of Figure 3. The equation in the box expresses a relationship between the mean and the

## INFLUENCE OF CHANNEL UNCERTAINTY UPON REACTION TIME

Measurements:

<u>Condition</u>	<u>Mean</u>	<u>Variance</u>
Certain (t)	$\bar{t}$	$\sigma_t^2$
Uncertain (T)	$\bar{T}$	$\sigma_T^2$

P = probability that uncertainty will add  $\delta$  to t.

$\delta$  - distribution (hypothetical) has mean =  $\Delta$  and variance =  $\sigma_\delta^2$

then,

$$\bar{T} = \bar{t} + P\Delta \quad (1)$$

$$\sigma^2 = \sigma_t^2 + P \sigma_\delta^2 + \left[ \frac{1-P}{P} \right] (\bar{T} - \bar{t})^2 \quad (2)$$

From (1) and (2),

$$\sigma_\delta^2 = K\Delta - \Delta^2$$

With

$$K = \frac{\sigma_T^2 - \sigma_t^2}{\bar{T} - \bar{t}} + (\bar{T} - \bar{t})$$

variance of the hypothetical  $\delta$ -distribution and this relationship depends only upon a coefficient called K. An estimate of the latter, in turn, can be calculated from the data as indicated below the box. It is the sum of a ratio and a number. The ratio is the effect of uncertainty upon the obtained variance divided by the effect of uncertainty upon the mean and the number is the effect upon the mean. The dimensionality of K is msec.

The theoretical meaning of K is given by the equation within the box and its empirical meaning by the equation at the bottom.

The coefficient K relates the mean and the variance of the hypothetical distribution of increments which are added to reaction time on some trials by uncertainty. It is not immediately obvious that it would be a valuable quantity to know but it will be shown that K admits of a very simple interpretation.

If the  $\delta$ -distribution is generated by a mechanism which is central to the sensory channels, the value of K should be independent of channel. Obviously, a  $K_l$  and a  $K_s$  can be calculated and they can be compared.

Empirical values of K depend to a great extent upon the difference in variance between the two experimental conditions. Consequently, they may be severely biased by extraneous sources of variance. It is very important to eliminate such sources insofar as possible. For this reason a single value of K is calculated for each short experimental session. This eliminates long-term sources of variation and the shortness

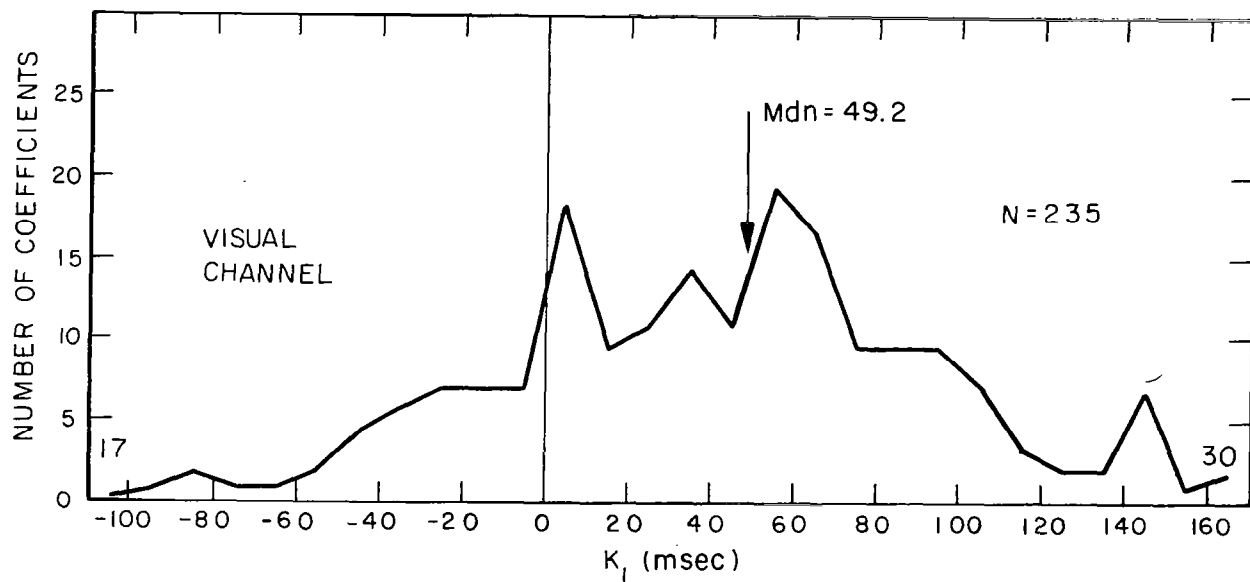
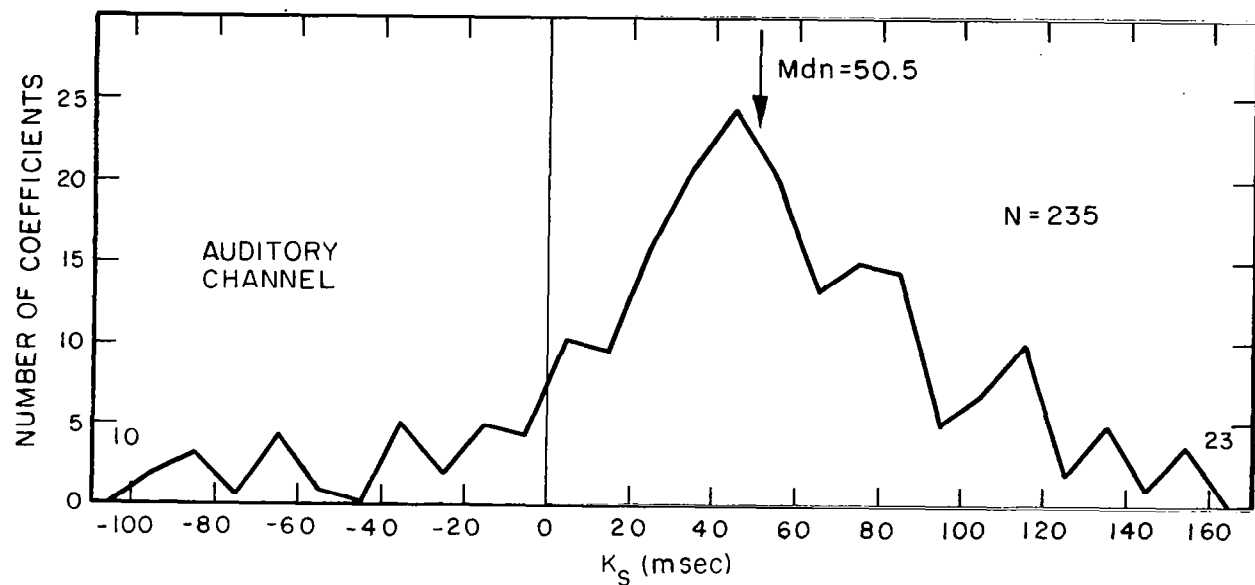
of the session minimizes within session sources. Each session consists of 80 trials, of which 20 are catch trials. The  $K$  for each channel is determined by 30 responses, 15 with certainty and 15 with uncertainty.

Since reaction time variance is large and the number of responses for each  $K$  is small, the values of  $K$  will vary over a wide range. Also, since the denominator of the calculation equation for  $K$  may be very close to zero for some sessions, a few very extreme values of  $K$  are to be expected. Accordingly,  $K$  is estimated by the median of its single session values.

Results.--The same eight subjects took part in this experiment. Each was thoroughly practiced before the data shown in Figure 4 were obtained. Figure 4 consists of a frequency distribution of single-session values of  $K$  for each channel. There is a total of 470 such values, about equally divided among the eight subjects.

Figure 4 demonstrates several points. The over-all median value of  $K$  is 49.8 msec. Furthermore,  $K_l$  and  $K_s$  are within a single instance of being identical. The variance of  $K$  is very large and there are some extreme values which fall off the graphs in both directions. The number of extreme values is indicated at the right and left of each distribution.

Finally, the variance of  $K_l$  is larger than that of  $K_s$ . This was expected because of the asymmetrical nature of the task. Since there is a tendency to attend to the visual channel more than to the auditory channel when uncertain, the sample of  $\delta$ -values obtained will be smaller, on the average, for the visual channel and the variance of  $K$  will be correspondingly larger.



DISTRIBUTIONS OF K. COMBINED DATA FOR EIGHT SUBJECTS. EACH K BASED ON 60 RESPONSES OBTAINED IN ONE SESSION.

FIG. 4

The medians of the single-session values of K have been calculated for each channel and for the two channels combined for each of the eight subjects. These are shown in Table II.

K ranges from 32 to 78 msec. and has a mean of 52.6 for these individuals. The rank-order coefficient of correlation (Spearman) of .73 between the two channels is statistically significant as it should be if the same mechanism generates both  $K_\ell$  and  $K_s$ .

### The Form of Reaction Time Distributions

Reaction times are long and they are highly variable from trial to trial when viewed in relation to microscopic neurophysiological events. No adequate explanation of these facts exists but it has frequently been suggested that they are due to delays which occur in the processing of information within the central nervous system. Stroud (3) believed that under certain ideal conditions reaction times form rectangular frequency distributions, and that their variance and duration can be attributed to a single-stage processing system in which the message is delayed in the single stage for some duration equally-likely to be any value from zero to D msec.

However, such distributions are rarely seen and when they are they are based upon so few responses that their shape and bounds are only poorly determined.

A model of the time course of information processing in reaction time has been developed which will be discussed here

<u>SUBJECT</u>	<u>K<sub>L</sub></u>	<u>K<sub>S</sub></u>	<u>K</u>
NC	86	49	73.0
NG	59	82	78.0
DC	40	39	39.5
KQ	14	37	32.5
JH	51	52	51.5
JC	52	72	61.5
GK	58	46	49.0
PM	<u>23</u>	<u>37</u>	<u>36.0</u>
mean	47.9	51.8	52.6

$$\rho = .73$$

TABLE II

MEDIANS OF SINGLE-SESSION VALUES  
OF K FOR VISUAL AND AUDITORY  
CHANNELS SEPARATELY AND COMBINED.  
THREE-SIGNAL DISCRIMINATION  
REACTION TIME



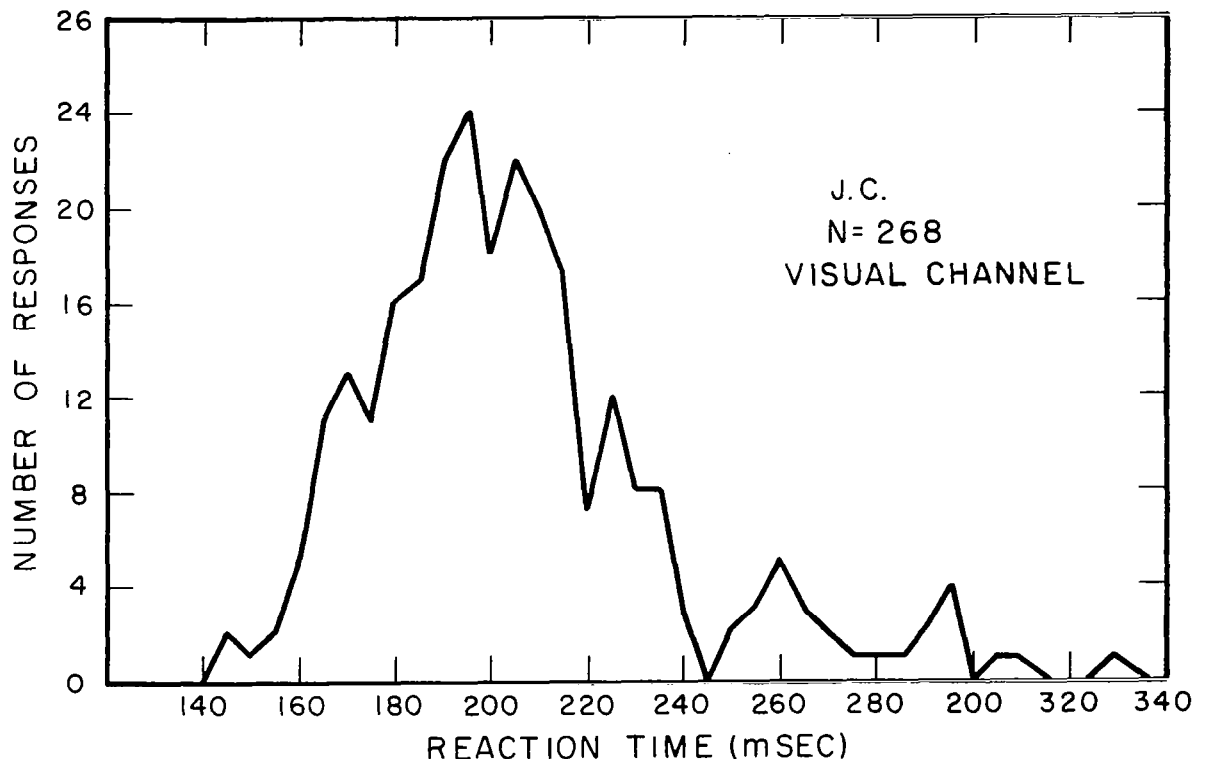
with respect to part of the data of Experiment 2. For most of the subjects in that experiment there were slow, systematic changes over the many experimental sessions. To minimize the effects of these, the sessions were divided into an early half and a later half. Only the data obtained under the certainty condition were used. This resulted in a total of 32 distributions (2 channels x early-later x eight subjects). These were plotted and one of them is shown in Figure 5.

Many of the distributions showed certain features in common. These were abstracted by visual inspection of the distributions and the distribution in Figure 5 illustrates the common features rather well.

There are three main segments, one which ascends rapidly on the left, one which descends rapidly in the middle, and the third which descends slowly on the right to form a prominent high tail. Each of these segments appears to be linear in many of the distributions and they seem to span intervals on the abscissa which are approximately equal. Note in Figure 5 that the first segment extends from about 150 to 200, the second from 200 to 250, and the third from 250 to roughly 300 or slightly more.

The dip in the distribution, which in Figure 5 goes entirely to zero at 245 msec., is probably real since it is clearly present in three-fourths of the distributions which have been inspected.

If this abstraction is valid, it implies a time-quantal mechanism consisting of three stages as a model for the process



A DISTRIBUTION OF VISUAL REACTION  
TIMES OBTAINED USING A THREE-SIGNAL  
DISCRIMINATION PROCEDURE

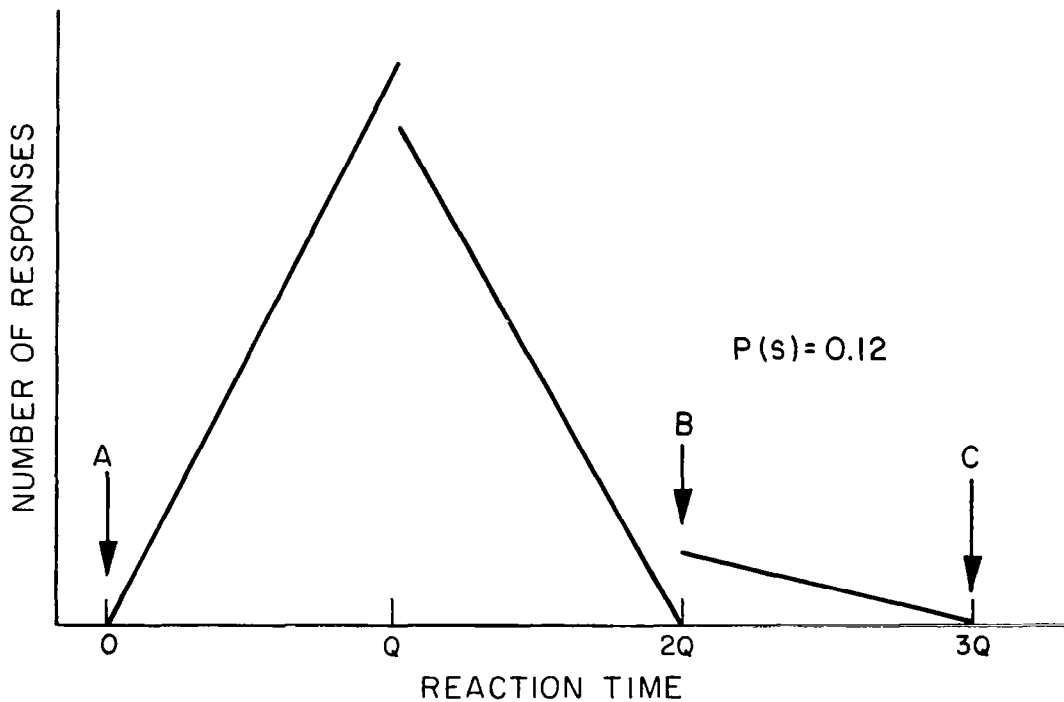
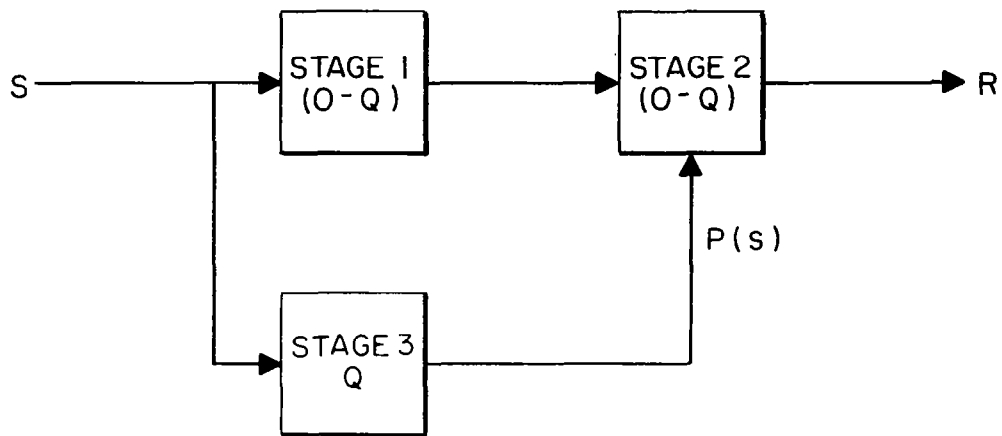
FIG. 5

of information transmission in discrimination reaction time. The main problem for present purposes is to estimate the size of the time quantum. Several methods have been tried. One of these involved fitting line segments to the three main regions of each distribution. This, of course, requires certain decisions about the data which are not entirely objective. However, it is a procedure which produces meaningful results (2,4).

In an attempt to improve the method of analysis, a specific model has been constructed which incorporates all of the features abstracted from the obtained distributions. This model, which is highly empirical in nature, is portrayed in Figure 6.

There are two stages (stage 1 and stage 2 in the diagram) which are involved in the processing of all messages and a third stage which sometimes influences the process. All of the stages are controlled by the same time constant which is called  $Q$ . A message enters stage 1 and it must remain there for some duration equally-likely to be any value from zero to  $Q$  msec. whence it is transmitted immediately into stage 2. It is delayed in stage 2 in the same way as stage 1. This implies a time mechanism which permits information to be transmitted from one stage to the next only at points in time which are separated by  $Q$  msec. It also implies independence between stage 1 and stage 2.

Stage 1 and 2 produce a distribution of total delays which form an isosceles triangle. Stage 3 is required to produce the tail or third segment. Stage 3 is activated by the input at the moment it enters stage 1 and, starting at



EMPIRICAL QUANTAL MODEL OF INFORMATION  
 PROCESSING IN DISCRIMINATION REACTION  
 TIME AND A DISTRIBUTION GENERATED BY IT

that instant, stage 3 counts exactly one  $Q$  of time and then it may or may not operate on stage 2. The probability that it will operate on stage 2 is  $P(S)$ . When it operates on stage 2 it does so by adding exactly one  $Q$  extra delay, providing that the message has not already passed through stage 2.

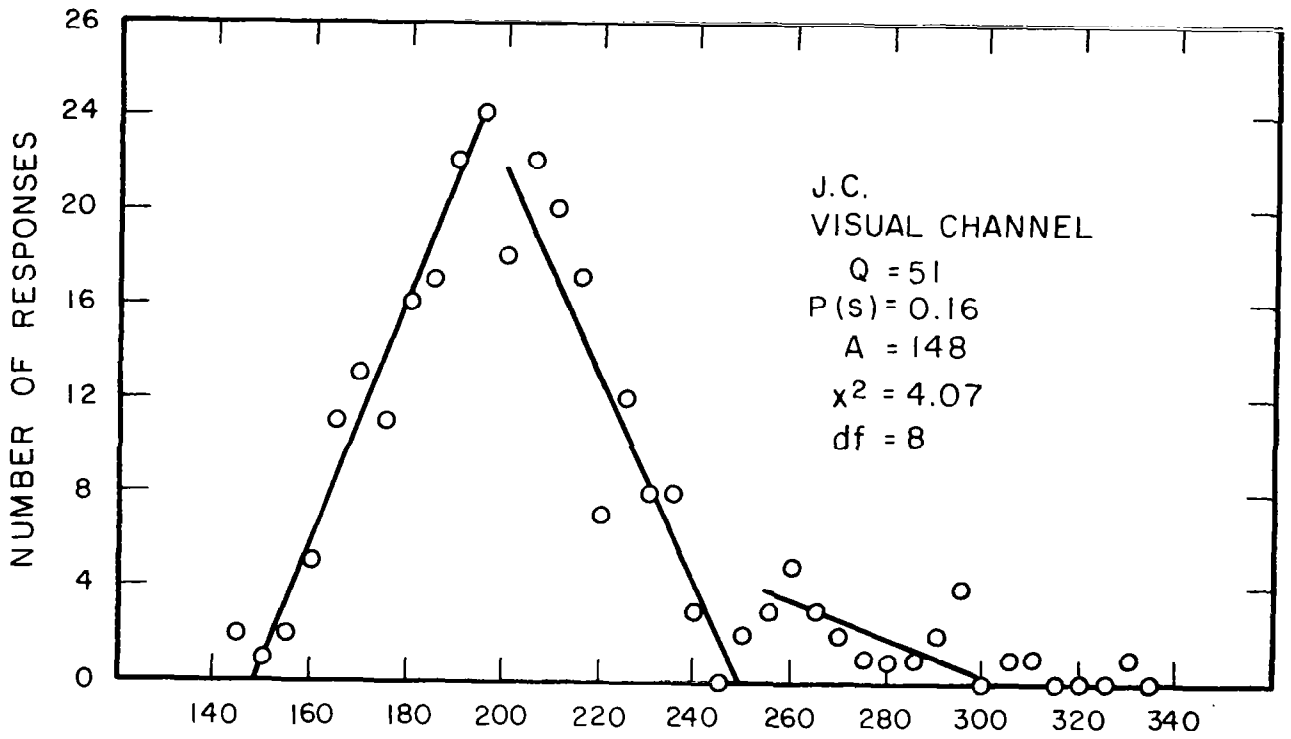
The existence of the high tail places severe restrictions on the set of possible models. Something like stage 3 is clearly required.

The form of the distribution of total delays which is predicted by this model is also shown in Figure 6. There are two parameters,  $Q$  and  $P(S)$ . The latter has been assigned the value .12 in the example.

In the application of this model to data there are three parameters. Since we cannot know the moment the input arrives at stage 1, a third parameter,  $A$ , is required which is a constant delay between the occurrence of the stimulus and the moment of arrival at stage 1.

Figure 7 shows this model fitted to the data of Figure 5 to a least-squared error criterion. The fit was obtained with the help of a computer which was programmed to calculate the squared-error for trial values of the three parameters. That set of the three parameters which minimizes the error is listed in the figure. It was determined to within 0.5 msec. for  $Q$  and  $A$  and to the nearest 0.005 for  $P(S)$ . The fit, as evaluated by chi-squared, is good in this case.

Twenty-eight of the 32 distributions have been analyzed in this manner and the fit of the model is acceptable in 18



THE QUANTAL MODEL FIT TO DATA TO LEAST-SQUARED ERROR CRITERION. Q AND A TO NEAREST 0.5 MSEC. AND P(s) TO NEAREST 0.005

FIG. 7

instances. In ten cases it is inadequate at or below the .05 level.

For the 18 cases in which the model is an adequate account of the data, the mean value of  $Q$  is 56 msec.

This particular model is not an adequate solution of the problem. It is promising but it needs to be revised and generalized and an attempt will be made to do that in the future. Therefore, the details of the model, viz. the specific interactions among the stages, are not to be taken seriously. It is discussed here because it points in a promising direction and, more importantly, because it is a critical element in the theoretical integration of all of these experiments.

For present purposes a weaker analysis of the data will be used. It involves assuming that the total span of the distribution is  $3Q$ . By determining the upper and lower bounds of the distribution and dividing their difference by three, an estimate of  $Q$  can be obtained.

Since there are a few scattered extreme scores, the bounds cannot be determined unequivocally. They are defined arbitrarily but objectively here in terms of an error-minimizing criterion. The data are grouped into five-msec. intervals. An interval containing no responses is an error if it falls within the bounds and an interval containing responses is an error if it falls outside the bounds. It is a simple matter to locate the upper and lower bounds which minimize the sum of all of the errors so defined.

Table III contains the results of this analysis for each channel for each subject. The two channels are nearly equal

<u>SUBJECT</u>	<u>AUDITORY (Q<sub>s</sub>)</u>	<u>VISUAL (Q<sub>L</sub>)</u>
DC	39.2	50.8
NG	60.0	71.7
NC	50.8	55.0
JC	53.3	56.7
KQ	41.7	50.0
GK	47.5	39.2
JH	52.5	52.5
PM	<u>58.3</u>	<u>72.5</u>
mean =	50.4	56.1

$$\rho = .85$$

TABLE III

PARAMETER Q ESTIMATED BY ONE-THIRD OF SPAN OF DISCRIMINATION REACTION TIME DISTRIBUTIONS. FOUR DISTRIBUTIONS PER SUBJECT, ALL WITH KNOWLEDGE OF CHANNEL. (MSEC)



and they are highly correlated over individuals. The range of values is similar to those seen earlier.

### Theoretical Interpretation

Measurements of three behavioral time parameters have been presented in the preceding sections. All three have been determined for each of eight individuals. The mean values for M, K, and Q, over individuals, are 54, 53, and 53 msec., respectively.

It has also been shown that K and Q are the same for the visual channel used in these experiments as they are for the auditory channel and that the correlation between channels, over individuals, is high in both cases.

It is reasonable to conclude that M, K, and Q are one and the same quantity and that this quantity, which will be referred to as  $q$ , is a time constant which enters into certain central-neural processes.

This should not be taken to mean that  $q$  cannot be caused to change but that under "normal" conditions it has a fixed value.

The value of  $q$  is within a few msec. of 50 on the average, at least for young male subjects.

Now the parameters will be discussed and it will be shown that they can be interpreted in simple terms as different manifestations of a single periodic process having a period of  $q$ .

This hypothetical periodic process will be called the "quantum generator." It has the characteristic of generating a series of equally-spaced points in time, one point each  $q$  msec., and these points determine when certain events are permitted to occur within the brain.

The experiments were designed within the context of a theory of attention and that theory, which has been presented in detail elsewhere (1), provides part of the basis for the present interpretation. It is a theory which conceptualizes attention as an all-or-none gating of information from sensory channels into a single, central data processor.

There are four general assumptions. First, it is assumed that there are sensory channels which are independent of each other in two ways: they can be attended to only one at a time and information can be displayed in one with no affect upon others. Second, it is assumed that a signal in an unattended channel can signal attention to switch to its channel. This implies a gross sorting of inputs at a lower level.

Different experiments require different degrees and kinds of control over the direction of attention and the third assumption states merely that such control is possible through instructions, structure of the task, and in various other ways. Finally, the fourth assumption concerns the switching time of attention. It states that when attention is signaled to switch to a channel other than the one being gated at the moment, some time elapses before the switching can be completed.

Interpretation of M.--The measurements of successiveness discrimination, which define the parameter  $M$ , were designed to

determine the time required for attention to switch from one channel to another. For two signals in independent channels to be discriminated as successive rather than simultaneous, it is necessary for the central processor to obtain the information at some point in time that one signal has occurred and that the other has not. If attention can switch from the channel of the first signal to that of the second signal in the interval between the signals, then the necessary information can be obtained. If it cannot, then the signals are effectively simultaneous.

This means, in turn, that the probability that a pair of signals will be discriminated as successive is equal to the probability that attention can switch from the first to the second in the interval between them.

If the time points produced by the quantum generator determine when attention can switch channels, then two neural signals which are separated by one  $q$  will have a probability of unity of being discriminated as successive because no matter when the first signal occurs a switching point will fall between the two signals. And, in general, the probability that a switching point will fall between two signals is a linear function of the interval between the signals as shown in Figure 2.

Therefore,  $M$  is considered to be the fixed time interval which separates points in time at which attention can switch channels. Or, the time points generated by the quantum generator have as one of their functions control over the switching of attention.

From this analysis of the meaning of M, it is necessary to conclude that the time which must elapse between the presentation of a signal and the next attention switching point is equally-likely to be any value from zero to q msec.

Interpretation of K.--In reaction time, channel uncertainty has the effect of adding an increment,  $\delta$ , on some trials and not on others. The mean and the variance of the hypothetical  $\delta$ -distribution are related by:

$$\sigma_{\delta}^2 = K\Delta - \Delta^2$$

But K appears to be equal to q. A simple and sufficient conclusion is that  $\delta$  is equal to q, hence the variance in the above equation is zero and  $\delta = \Delta = q$ .

Restated, the conclusion is that uncertainty adds exactly one q on some trials and nothing on the remaining trials.

Interpreted in terms of the attention theory, when uncertainty results in attention being aligned with the wrong channel when the signal occurs, a delay of exactly q is added because time is required to switch attention. The implication is that exactly one q must elapse between the signal and completion of the switching.

This conclusion is at variance with the conclusion based upon M, which was that the time between receipt of a signal and the completion of switching is equally-likely to be any value from zero to q.

This apparent dilemma exists because  $\delta$  has been equated to the time required to switch attention following receipt of a signal. This equation is not justified and the dilemma is resolved by the interpretation of  $Q$ .

Interpretation of  $Q$ .--This is the least-clearly defined parameter of the three. The information processing model upon which it is based is not fully acceptable in its present form. However, only part of it need be accepted to complete this integration and that part is stage 1.

Messages which enter stage 1 are delayed for an interval equally-likely to be any value from zero to  $Q$  msec. This is the case when attention, which precedes stage 1, is aligned with the correct channel. When it is misaligned on an uncertainty trial, then the delay of  $0-q$  which it would have undergone in stage 1, had it been aligned, is instead absorbed in switching attention. Since the same quantum generator controls the switching as controls the timing of stage 1, the message then enters stage 1 at the beginning of a quantum and must reside there for one full  $q$ . Under uncertainty, the time required to complete stage 1 is zero to  $q$  when attention is correctly aligned and zero to  $q$  plus  $q$  when it is not.

Thus, the conclusion that the interval of time between a signal and the next attention switching point is equally-likely to be any value from zero to  $q$  msec. is compatible with the conclusion that exactly one  $q$  is added to reaction time on those trials on which attention is misaligned.

General Conclusion.--The hypothesis that the brain operates like a time-shared data-processing system with a

cycle time of 50 msec. is strongly suggested by the considerations and data set forth above. It is time-shared in the sense that it can accept data into the central processor from only one of many input channels at a time. The cycle time determines at least two functions: (1) when switching can occur from one input channel to another and (2) when a message being processed can be transmitted from one stage within the central processor to the next.

If M, K, and Q are identical, that is, if they are different ways of measuring the same quantity  $q$ , and if  $q$  is different to some extent for different individuals, then there should be positive correlations among the three measured parameters. Evidence has been presented on this point in recent papers. In (2) it is shown that K and Q are associated over individuals and a similar finding for M and Q has been presented in (4).

Therefore, the evidence for the identity of the three parameters consists mainly of demonstrating that (1) they are equal in absolute magnitude and that (2) they are highly correlated over individuals. Neither of these kinds of evidence would be strongly compelling by itself but together they are, and particularly so since they are amenable to a simple theoretical interpretation which interrelates all of them.

In the next section a third kind of evidence for the identity of the parameters is presented.

### Experiment 3. An Electroencephalographic Measurement

The behavioral results imply the existence of a periodic mechanism within the brain which is capable of defining points in time which are separated by 50 msec. Further, the mechanism may influence wide areas since its behavioral effects are quite molar in nature.

That there are relatively slow, periodic mechanisms within the brain is well-known, of course. The electroencephalographic rhythms, which have been investigated so thoroughly during the past twenty years, testify to their existence. The most prominent of these is the alpha rhythm which has an average frequency of about 10 cps, an average from which individuals deviate only slightly. Not only is the alpha rhythm widespread in the brain but it has also been implicated in attention by various investigators (5).

One might expect time points to be defined by maximum rate of change, if they are generated by a continuously-varying process. This would be at the point where the alpha rhythm crosses the zero voltage line. There are, of course, two such zero-crossings per cycle, hence the interval between zero-crossings of the alpha rhythm averages close to 50 msec., in good agreement with the behavioral time constant  $q$ .

The frequency of alpha is definitely known and it would be trivial to measure it for the eight subjects in this study in order to confirm its close correspondence to  $q$ . However, it would be worthwhile to determine whether individual differences in  $q$  are associated with individual differences in alpha frequency. For this purpose, electroencephalograms were obtained for each of the eight subjects.

It probably should be emphasized that one should not expect a causal relationship between the electrical changes which are the alpha rhythm and any of the behavioral relations which define  $q$ . At best, it may be that the alpha rhythm is one manifestation of a periodic process of some unknown nature and that that process is also the behavioral time quantum generator.

Electroencephalographic tracings were made for each subject in two sessions separated by one week. Records containing alpha were obtained for all subjects only when they were reclining with their eyes shut.

Six recording channels were used, three for the right hemisphere and three for the left. Samples of three consecutive cycles were selected for measurement in such a way that during any one interval of time a sample was taken from only one channel. There were six such samples for each channel or 108 cycles per subject per session.

The results, expressed as the average interval between zero-crossings, are given in Table IV. For the group as a whole, the mean alpha frequency was 10.4 cps. A satisfactorily small error of measurement was achieved as is indicated by the product-moment correlations between the two hemispheres of .89 in session 1 and .98 in session 2.

However, the reliability of the measurement from one session to the next is not as adequate. The correlation of .79 between the two sessions indicates that there are long-term variations in the measure and that more than two sessions are needed to specify the value with precision for each individual.



<u>SUBJECT</u>	<u>SESSION 1</u>	<u>SESSION 2</u>
DC	45.9	44.7
NG	51.5	51.0
NC	51.9	47.6
JC	46.8	48.8
KQ	46.8	47.8
GK	47.5	44.9
JH	40.5	39.8
PM	<u>47.6</u>	<u>50.3</u>
mean =	47.3	46.9

$r(\text{session 1 vs. 2}) = 0.79$

$r(\text{right vs. left}) = 0.89$  (session 1) and  $0.98$  (session 2)

TABLE IV

DURATION OF HALF-CYCLE OF DOMINANT BRAIN RHYTHM IN MSEC. THE TWO SESSIONS WERE ONE WEEK APART. THE MEANS CORRESPOND TO A FREQUENCY OF 10.4 CYCLES/SEC.

The main limitations of this experiment are: (1) the unreliability of the half-cycle measurement; (2) its extremely restricted range (11 msec. from the highest to the lowest individual); (3) the small number of subjects; and (4) the fact that alpha must be measured under conditions which differ from those under which the behavioral measurements are made. These limitations eliminate any possibility of estimating the magnitude of any association which may exist. At best, the presence of association might be detected but even that would have to be treated tentatively.

The values of M, K, and Q are shown in Table V for each subject. The mean of these three is also given as an estimate of  $q$  for each individual. In the last row are the values of the alpha half-cycle averaged over the two sessions. The subjects are arranged in order on the latter scale.

One method of testing for association between  $q$  and EEG is also shown in the table. Each individual is considered as a single observation and he is assigned to one cell of the four-fold table on the basis of whether he is in the upper or lower half of the group on each measure. This very weak statistical analysis is sufficient to show that there is a statistically significant degree of association between  $q$  and the alpha half-cycle. A 2 x 2 table as extreme as the one obtained would occur by chance only about once in one-hundred repetitions. And the direction of correlation is positive: the four subjects who have the largest  $q$  also have the largest alpha half-cycle.

Spearman rank-order coefficients of correlation between M, K, and Q, on the one hand, and EEG, on the other, are .64,

SUBJECT	NG	NC	PM	JC	KQ	GK	DC	JH	MEAN
M	47.2	61.3	62.7	76.7	58.9	46.2	39.4	42.2	54.3
K	78.0	73.0	36.0	61.5	32.5	49.0	39.5	51.5	52.6
Q	65.8	52.9	65.4	55.0	45.8	43.4	45.0	52.5	53.2
mean(q)	63.7	62.4	54.7	64.4	45.7	46.2	41.3	48.7	53.4
EEG	51.2	49.8	49.0	47.8	47.3	46.2	45.3	40.2	47.1

MEDIAN SPLIT

		-	q	+	
EEG	+	0		4	P = .014
	-	4		0	

TABLE V

THREE BEHAVIORAL TIME PARAMETERS AND THE INTERVAL BETWEEN ZERO-CROSSINGS OF THE DOMINANT RESTING BRAIN RHYTHM (MSEC)

.48, and .76. The two larger of these are statistically significant. The average of the three, .63, might be considered in relation to the rank-order correlation of the EEG between session 1 and session 2 which is .64. But this really adds nothing to the earlier conclusion that the correlation is significant because the sampling error of a correlation coefficient is so large with only eight cases that quantitative comparisons are almost meaningless.

These data are summarized in another way in Table VI. For this analysis the eight subjects are divided into two groups, the four highest and the four lowest on the alpha half-cycle measure. For each subgroup the means of each behavioral parameter are given along with the mean of q.

Several points are clarified by this table. The EEG measure and q differ by less than one msec. for the low EEG group but by nearly 12 msec. for the high group. The difference between q and EEG is significantly greater for the high group than for the low. Also, this is true to nearly an equal extent for each of the three behavioral parameters considered separately.

Conclusion.--There is positive association between the interval between zero-crossings of the alpha rhythm and each of the three behavioral parameters. Table VI implies that each of the three is related to alpha in the same way and to nearly the same extent. This finding supports the conclusion that M, K, and Q are identical.

	<u>LOW EEG</u>	<u>HIGH EEG</u>
M	46.7	62.0
K	43.1	62.1
Q	<u>46.7</u>	<u>59.8</u>
mean	45.5	61.3
EEG	44.8	49.5

TABLE VI  
SUMMARY OF ALL DATA WITH EIGHT  
SUBJECTS SPLIT AT EEG MEDIAN

Even though the alpha interval is very nearly equal to  $q$  in absolute magnitude and they are positively correlated, the evidence does not support the hypothesis that the relation between them is one of identity. Individuals who have relatively long alpha intervals yield estimates of  $q$  which are substantially greater than their alpha intervals. Those at the lower end of the scale, however, show very good agreement.

No one of the behavioral parameters can be said to be well-understood and it seems likely that further research on each of them will lead to improved methods of measuring them. Since it is those individuals at the high end who show discrepancies between  $q$  and alpha, it might be that the discrepancies are due to undiscovered sources of error in measuring  $M$ ,  $K$ , and  $Q$ . On the other hand, since the discrepancies seem to be about equal in magnitude for the three, and since they are themselves based upon very different sets of operations, it seems unlikely that the discrepancies can be due to measurement errors. At least it is not obvious at this time that a single violated assumption or source of error would affect all three parameters equally.

Another possibility of accounting for the discrepancy lies in the measurement of the EEG, particularly in the fact that it was measured under relaxed, resting conditions while the behavioral experiments were done under quite different conditions.

One final caution should be inserted. While these data are orderly and sensible and fairly extensive, there are, after all, only eight individual subjects. Many of the finer

discriminations made in the analysis of Experiment 3 might not bear replication. And a replication of the third experiment is clearly called for.

## REFERENCES

1. Kristofferson, A. B.: Attention in Time Discrimination and Reaction Time. NASA CR-194, 1965.
2. Kristofferson, A. B.: Research on Human Attention. Quarterly Progress Report No. 1, Contract NAS 2-2486. Bolt Beranek and Newman Inc., Cambridge, Mass. March 1965.
3. Stroud, J. M.: The Fine Structure of Psychological Time. Quastler, M. H., ed.: Information Theory in Psychology. Glencoe, Ill.: Free Press, 1955. Pp. 174-207.
4. Kristofferson, A. B.: The Psychological Time Quantum and the Discrimination of Succession. Report No. 1233, Bolt Beranek and Newman Inc., Cambridge, Mass. 1965.
5. Lindsley, D. B.: Attention, consciousness, sleep and wakefulness. Ch. LXIV. Sect. 1, Vol. III. Handbook of Physiology. Baltimore, Md.: Williams and Wilkins Company. 1960.