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A QUANTAL INTERPRETATION OF SENSORY CHANNEL UNCERTAINTY AND REACTION TIME AND THE PSYCHOLOGICAL TIME QUANTUM AND THE DISCRIMINATION OF SUCCESSION

by Alfred B. Kristofferson

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

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and

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PREFACE

These papers define a quantal concept of psychophysiological time in quantitatively precise terms. A basic periodicity averaging about 50 msec. is emerging. Three behavioral routes into the concept are defined and they seem to be uncontaminated measurements of a single time constant. They are:

1. The main parameter of a quantal model of the variability of reaction time
2. The time difference between independent signals necessary for 100% detection of succession
3. The increment added to reaction time by channel uncertainty.

The principal evidence so far consists of showing that the three quantities are equal in magnitude, highly correlated over individuals, and the same for different sensory channels.

By way of interpretation, I believe that a single periodicity controls both the timing of the information-processing stages of reaction time and the timing of the switching of attention among channels. This point of view accounts for all of the results.

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CONTENTS

PREFACE iii

A QUANTAL INTERPRETATION OF SENSORY CHANNEL UNCERTAINTY AND REACTION TIME 1

Abstract 1

The Influence of Channel Uncertainty Upon Reaction Time 2

Derivation of K 2

Interpretation of K 4

Measurement of K 6

A Quantal Model of Reaction Time 11

Estimating Q 16

Measurements of Q 16

Conclusion 18

Appendix 21

THE PSYCHOLOGICAL TIME QUANTUM AND THE DISCRIMINATION OF SUCCESSION 24

Summary and Conclusions 24

Introduction. 25

Experimental Results 29

REFERENCES 35

A QUANTAL INTERPRETATION OF SENSORY CHANNEL UNCERTAINTY AND REACTION TIME*

Abstract

Uncertainty as to the channel of the next signal adds an increment δ to reaction time on some proportion of trials. The coefficient K relates the mean and variance of the hypothetical δ-distribution:

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

K can be measured and data from six individuals are given in this report.

A quantal model of reaction time is suggested which approximates the form of many reaction time distributions. Q, the temporal quantum, can be estimated with the aid of the model. Values of Q are given for the same subjects.

Q and K are shown to be virtually identical, averaging 55 msec. for the group.

Individuals differ reliably in Q and K; the correlation between Q and K is very high and positive.

Q and K are both the same for the two sensory channels employed here, implying a central source.

These results suggest that one temporal quantum is consumed in switching attention between sensory channels when conditions are optimal.

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The Influence of Channel Uncertainty Upon Reaction Time

This experiment is one of a series which is being undertaken to test and develop a theory of attention. The general theory has been set forth in a recent report (1). The present experiment was designed to measure the time required to switch attention from one sensory channel to another by measuring the effect upon simple reaction time of uncertainty as to the channel over which the next signal will arrive.

Reaction times to a given signal are recorded for trials on which the subject knows the channel beforehand (t) and for trials on which he knows only that the signal will be one of two possible signals (T) in different sensory channels. On a trial of type T, there is some probability, P, that an additional delay, δ, will be added to the reaction time as a result of the uncertainty. This variable, δ, cannot be measured directly, of course, and a major purpose of this study is to determine indirectly certain of its characteristics.

Derivation of K.--The values of δ form a hypothetical distribution with a mean of Δ and a variance of σ_δ^2. The two observed reaction time distributions have means of $\overline{t}$ and $\overline{T}$ and variances of σ_t^2 and σ_T^2. If δ is independent of t, the relation between the two observed means is:

$$\overline{T} = \overline{t} + P\Delta \tag{1}$$

That is, the mean reaction time under uncertainty is equal to the mean under certainty plus an amount which depends upon the mean of the distribution of uncertainty delays and upon the proportion of trials on which the uncertainty delays are added.

Similarly, the variance will be influenced by uncertainty so that:

$$\sigma_T^2 = \sigma_t^2 + P\sigma_\delta^2 + \left(\frac{1 - P}{P}\right) (\overline{T} - \overline{t})^2 \qquad (2)$$

Manipulating equations (1) and (2) to eliminate P yields:

$$\sigma_\delta^2 = \Delta \left[\frac{\sigma_T^2 - \sigma_t^2}{\overline{T} - \overline{t}} + (\overline{T} - \overline{t})\right] - \Delta^2 \qquad (3)$$

All of the quantities within the brackets of equation (3) are measurable and comprise the coefficient K:

$$K = \frac{\sigma_T^2 - \sigma_t^2}{\overline{T} - \overline{t}} + (\overline{T} - \overline{t}) \qquad (4)$$

and,

$$\sigma_\delta^2 = K\Delta - \Delta^2 \qquad (5)$$

This coefficient, K, can be calculated from data as the ratio of the effect of uncertainty upon the variance to its effect upon the mean, added to its effect upon the mean. The magnitude of K is independent of P. Finally, K fixes the relation between the mean and the variance of the hypothetical δ-distribution in the manner of equation (5) and, it might be pointed out, this relation is entirely independent of the form of the δ-distribution.

Interpretation of K.--If an assumption is made which states an appropriate relation between Δ and σ_δ^2, then K can be used to calculate the parameters of the δ-distribution.

One such assumption yields the "fixed switching time" model. It is simply that δ is a single fixed value or, equivalently, that

$$\sigma_\delta^2 = 0$$

From equation (5), under this assumption,

$$\Delta = K \tag{6}$$

Further, from equation (1),

$$P = \frac{\overline{T} - \overline{t}}{K} \tag{7}$$

which enables one to compute the proportion of trials under uncertainty on which δ is added to t.

Another model, the "scanning model" which was discussed at length in the report alluded to earlier, assumes that the δ-distribution is rectangular or that all values of δ from 0 to 2Δ are equally probable. For such a distribution,

$$\sigma_\delta^2 = \frac{\Delta^2}{3}$$

and, from equations (5) and (1),

$$\Delta = \frac{3K}{4}, \qquad P = \frac{4(\overline{T} - \overline{t})}{3K} \qquad (8,9)$$

Other assumptions, such as a Poisson form, can be entertained in a similar manner, of course.

The theoretical interpretation of K and of the various relations expressed above depends upon the validity of experimental manipulations. If it is indeed true that δ can be identified with the time required to switch attention from one channel to another, then the above equations describe the distribution of attention switching times. This is equivalent to saying that channel uncertainty has no effect upon reaction time other than adding extra delays on trials on which the subject's attention is misaligned, such delays being due to the need to switch to the channel which contains the signal.

In this connection, a word should be said about P. In the treatment above, P is the proportion of trials under uncertainty on which δ is added <u>in excess</u> of those trials under certainty to which δ is added. It cannot be guaranteed that the subject will attend to the relevant channel 100% of the time even when he is informed of the relevant channel. That is, there may be a P associated with certainty trials also which means that values of P calculated as described above can be used to infer the probability that the subject attended to the relevant channel under the uncertainty condition only if the probability of being aligned correctly when certain is known or if it can safely be assumed to be unity. In the latter case, the probability of attending to the signal when uncertain would be the complement of P. This need to check the assumption that P=0 under the certainty condition is one of the reasons for developing a model of reaction time in the second section of this paper.

Finally, the attention switching mechanism is thought of as a central mechanism superimposed upon the various sensory channels and operating independently of them. If this view is correct, the value of K should be the same for all sensory channels. This expectation is tested in this experiment for one visual and one auditory channel.

Measurement of K.--For reasons which have been discussed recently (1), the reaction times in this study were obtained using a three-signal discrimination reaction time procedure. In this method, a single response is involved, either releasing or not releasing a key. There are two visual signals and one auditory. The right one of two adjacent lights or the tone call for a positive response while the left light requires withholding the response. Since there is a signal on every trial, the single response is contingent upon a discrimination among the signals.

Prior to each trial, a cueing signal informs the subject that the next signal, if it is positive, will be auditory, or that it will be visual, or that it may be either. In any event the visual signal to withhold response may occur.

Thus, four distributions of reaction time are obtained:

t_s: auditory, certain of channel

T_s: auditory, uncertain of channel

t_ℓ: visual, certain

T_ℓ: visual, uncertain

Each pair of distributions, t_s T_s and t_ℓ T_ℓ, can be used to estimate a value of K; these are denoted K_s and K_ℓ.

On every trial all three stimuli were presented simultaneously at the beginning of the foreperiod and following the cueing signal. They remained on for approximately two seconds at which time one, and only one, terminated. The subject was instructed to respond by releasing the key, which he had depressed to initiate the trial, if either the 2000-cycle tone or the right light terminated. If the left light terminated, he was to withhold response.

One quarter of the total of eighty trials which comprised a session were catch trials. Fifteen trials of each of the four experimental conditions made up the remainder. The eighty trials were presented in a different random order each day with a short break after each group of twenty trials.

Data have been obtained for six subjects. Two of these, JC and GK, took part in two series of daily sessions while the remaining four participated in a third series as well. The first several days of Series 1 were discarded for each subject due to practice effects. Series 1, 2, and 3 differed in terms of the extent of prior practice, time, and participation by the subjects in other experiments. The total number of useable sessions varied from 30 to 36 for the six subjects, with a grand total of 203 sessions.

The problem of obtaining an estimate of K for a single individual which is unbiased and which has a satisfactorily small error of measurement is a difficult one. Since K is determined in part by the ratio of a variance increase to an increase in mean (see equation (4)), any factor which causes non-parallel changes to occur in means and variances will bias the estimate. The large variability characteristic of reaction times, however, makes a large number of responses necessary for a stable estimate. But experimental sessions which are too long introduce additional bias and reaction time statistics change over long periods of many days, even with well-practiced subjects.

These considerations led to a procedure for obtaining and analyzing data in which the details are probably important (subsequent computations reveal that they are important). As described above, each experimental session is short, no more than one session is ordinarily scheduled in a day, and a large number of sessions are conducted for each individual. However, the data are not collated over days within an experimental condition. Instead, a value of K (actually, one K_ℓ and one K_s) is calculated each day and the final estimates of K are taken as the median of these daily values.

This means that the daily calculated K is based on two samples of 15 responses each, a very small number in view of the variance present. As a result, these values fluctuate widely.

Another factor contributes to the instability of daily values of K. It is P, the probability that uncertainty will add an increment to reaction time. In terms of the attention theory, if a subject attends to a channel nearly as often when he is uncertain as when he is certain that the signal will arrive over that channel, then a relatively small sample of δ-values will differentiate T from t for that channel. As a result, the variance-to-mean ratio can be extremely large and either positive or negative. Many coefficients are required to fix the median with sufficient precision.

The asymmetrical design of the reaction time task was expected to have an influence. The fact that the visual channel contained both a positive and a negative signal while the auditory channel contained only a positive signal might be expected to influence the subjects to attend with higher probability to the visual channel when uncertain. This would have an affect upon the relative stability of K_ℓ and K_s, rendering the former less stable. The results bear out both of these points.

Figure 1 is the distribution of daily values of K. It is composed of 203 cases of K_ℓ and an equal number of K_s. The median of the 406 instances is 51.0 msec. and the modal interval is 50-59. Most of the coefficients (64%) fall within the limits 0-110 and these limits are fairly clearly defined. Values less than zero account for 16% of the total while 19% exceed 110. About 5% fall beyond the limits of the graph in each direction.

There is no difference in central tendency between K_ℓ and K_s. The median for the visual channel is 51.2 while that for the auditory channel is 51.6.

Figure 1 is presented only as a general description. It should not be taken to represent any single individual because there are significant differences among the six subjects, as will be shown below.

Medians were calculated for each subject for K_ℓ, for K_s, and for his combined distribution which is being called K. These results are shown in Table I.

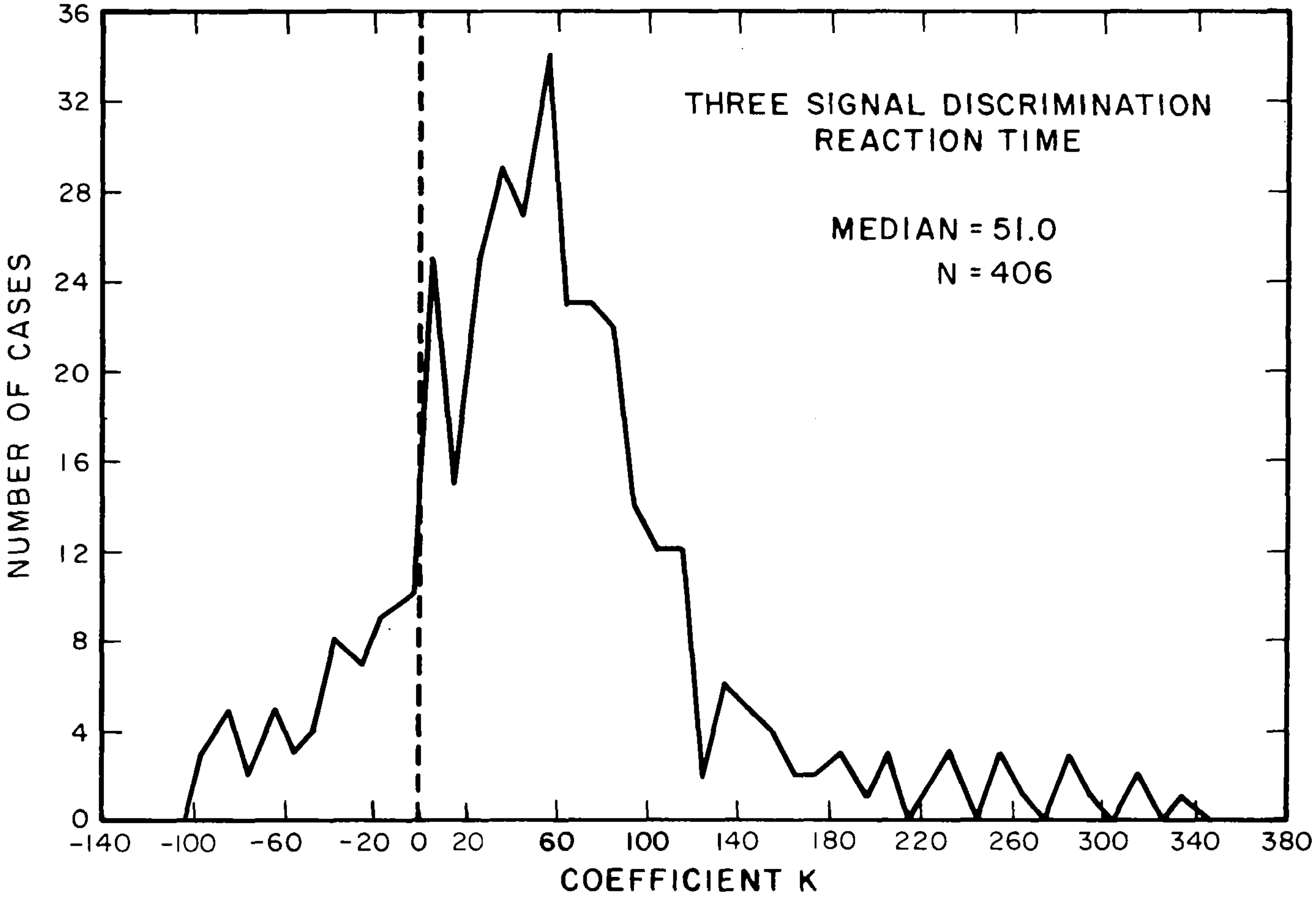

FIG. 1 DAILY VALUES OF K. BOTH CHANNELS ARE INCLUDED FOR ALL SIX SUBJECTS

TABLE I.--MEDIANS OF DAILY VALUES OF K

Subject	K_ℓ	K_s	K
JC	48	70	62
GK	55	46	49
DC	39	40	40
NC	85	50	74
NG	55	82	75
KQ	15	36	33

Individuals differ substantially, the medians of K ranging from 33 to 75. This variation is not wholly sampling error, a conclusion which is implied by the evidence of correlation between K_ℓ and K_s and which will be substantiated in a later section. The rank-order correlation of .64 between K_ℓ and K_s is not quite significant.

Once again, K_ℓ and K_s do not differ, the means of the medians being 50 and 54 msec., respectively.

The statistics describing the data for each subject combined over days but calculated separately for each series are contained in the Appendix. If the means and variances given there are used to calculate values of K, the mean value of K for the group is found to be 55, almost exactly the same as the mean of the K column in Table I. However, individual differences are larger and appear to be less reliable.

A Quantal Model of Reaction Time

This section must be taken as a very preliminary, interim report. A model of reaction time is proposed which is almost certainly little more than a first approximation. And in addition the methods of estimating the main parameter of the model are still very crude. Nonetheless, the first results are compelling enough to demand consideration.

The data of Series 1 and Series 2 define a total of 48 reaction time distributions. Half of these are for the certainty condition and this discussion is based on these 24 distributions. There are two such distributions, one for each series, for each channel, for each of the six subjects.

One of these distributions, selected to illustrate well the main features of the model, is displayed as Figure 2. It is difficult to reject the assertion that this distribution consists of three linear segments, a rapidly rising one on the left, a second which descends rapidly from the peak to, in this case, zero and a third which slopes gradually to form the positive tail.

Of the 24 distributions, 21 are reasonably congruent with this description, as judged by eye. The remaining three appear to contain a fourth segment.

The distributions often go entirely to zero in the trough between the second and third segments. The trough itself is clearly evident in 16 of the 21 triple-segmented distributions.

Finally, to complete this crude characterization it is noted that the three segments seem to share the total span of the distribution about equally.

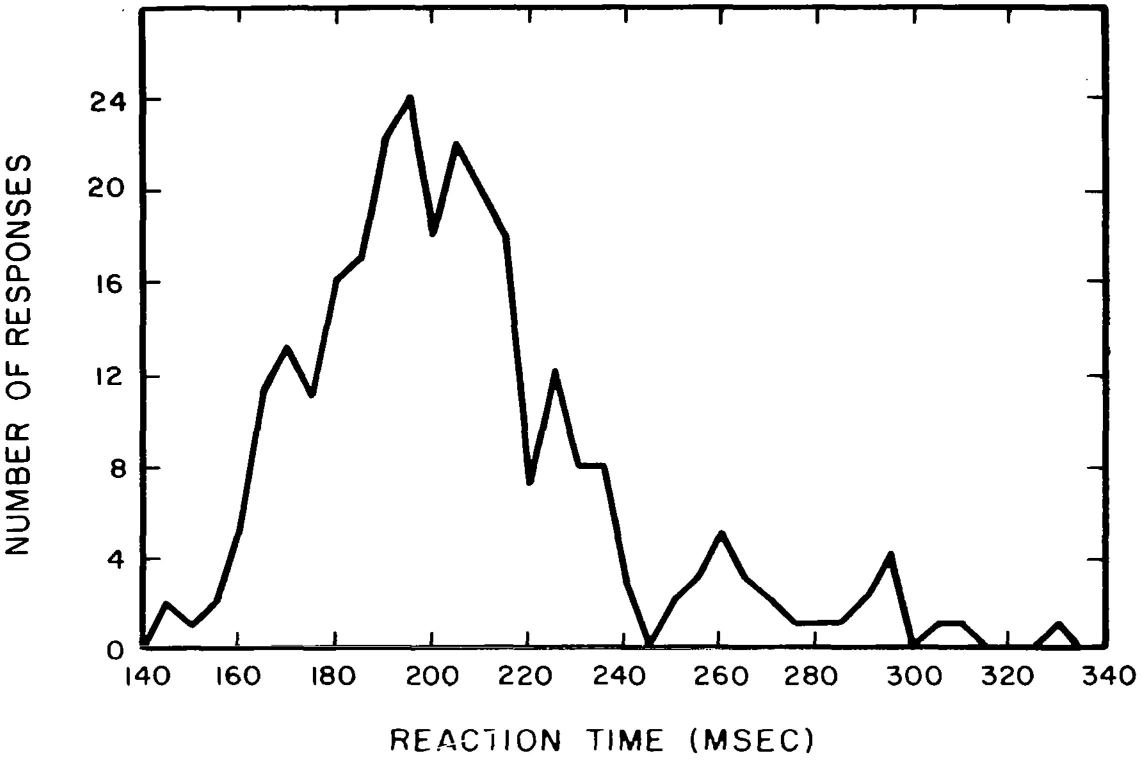

FIG. 2 REACTION TIMES TO VISUAL SIGNAL UNDER CERTAINTY. SUBJECT JC, SERIES 1, N = 268

If one temporarily accepts the notion that these segments are linear and that they span equal intervals of time, models can be inferred which reproduce these qualities. A quantal conception is implied, and one such model is diagrammed in the upper part of Figure 3. This particular model is not proposed seriously at this time; it is no more than a starting point in the search for an adequate model. It is a quantal model in the sense that all events are timed by clocks which tick with the same frequency. Stages 1 and 2 are the primary stages through which all signals pass. They are each periodic in the sense that a signal must persist in each for a duration equally likely to be any value from zero to Q and they are independent in that the time which a signal must remain in one of them is unrelated to the time it must dwell in the other. Stages 1 and 2, of course, generate a triangular distribution which alone spans two quanta. The tail of the distribution, segment 3 in Figure 3, requires postulating a third stage, assuming unreliable gating in 1 or 2 will not do the job. Stage 3 counts one Q from the moment the input enters stage 1 and then operates on stage 2 to generate a probability, P(S), that exist from 2 will be delayed an additional Q if it has not yet occurred.

The distribution in Figure 3 is generated by this very arbitrary model for P(S)=.12. It has the main features: there are three linear segments although segment 2 has a break in it. Point A defines zero, point C defines 3Q and Point B, best identified by extending segment 2 to the abscissa, defines 2Q.

One main point here is that there are a family of possible models of this general form which should be investigated as models of reaction time. The particular model briefly sketched

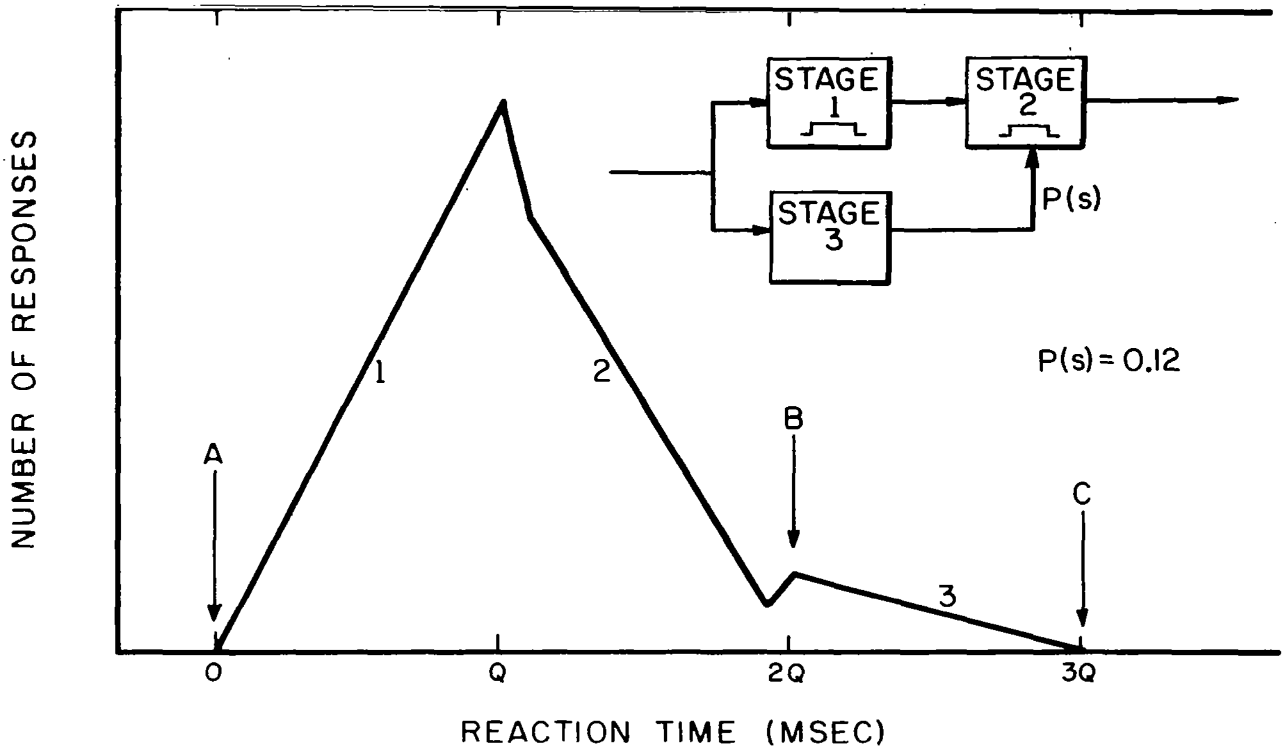

FIG. 3 HYPOTHETICAL REACTION TIME DISTRIBUTION

above is only one candidate. Note that it predicts that the slope of 2 and 3 should covary inversely as P(S) changes while the slope of 1 should remain fixed.

Estimating Q.--Points A, B, and C (see Figure 3) were estimated for each of the 21 three-quanta distributions. Point A was obtained by fitting a line by least-squares to those points which appeared to fall within segment 1 and extending the line to the abscissa. The point at the apex was not used. In a few cases it was necessary to discard a response or two which was obviously far to the left of A.

Point C was obtained in a similar manner although here it is frequently more difficult to judge when scattered points are actually to the "right of C." The determination of C is undoubtedly less precise than that of A.

Point B was estimated by drawing a line by eye through those points which were judged to fall within the major span of segment 2 and extending the line to the base.

This is a very imprecise method and only the results justify it. Obviously, if a model can be found which is adequate, a much more exact fit to all of the data can be achieved.

Q was obtained by dividing the AC distance by three and, separately, by halving the AB distance.

Measurements of Q.--In all but three cases there were two AC distances obtained for each subject for each channel. These were averaged and the values of Q given in Table II are one-third of (C-A). The mean value of Q is 55 msec. for the group and the mean values for the two sensory channels are virtually identical.

TABLE II.--ESTIMATES OF Q(MSEC) FROM AC DISTANCES USING REACTION TIME DISTRIBUTIONS FOR CHANNEL CERTAINTY CONDITIONS

Subject	Auditory	Visual	Both
JC	60	63	61.7
GK	50	43	46.8
DC	52	55	53.5
NC	58	66	62.0
NG	64	61	63.0
KQ	44	48	45.3
	55	56	55.4

Table III shows the estimates of Q obtained from AB distances. For subject KQ point B could not be estimated with confidence and his data are omitted. The values are very similar to those in Table II and the correlation over individuals between Tables II and III is significant.

TABLE III.--ESTIMATES OF Q(MSEC) FROM AB DISTANCES USING REACTION TIME DISTRIBUTIONS FOR CHANNEL CERTAINTY CONDITIONS

Subject	Auditory	Visual	Both
JC	63	52	57.8
GK	51	38	44.8
DC	49	39	44.0
NC	56	52	53.8
NG	66	70	68.0
KQ	indeterminate		
	57	50	53.7

Conclusion

The coefficient K, which describes the distribution of temporal increments which are added to reaction time as a result of uncertainty as to which channel contains the signal, and the quantity Q, which is the temporal quantum within a quantal model which may describe the mechanism of reaction time, are remarkably similar. In Table IV the values of Q, the mean of both determinations, and of K, the over-all daily median, are presented for each subject.

TABLE IV.--BEST ESTIMATE OF Q COMPARED TO MEDIAN DAILY K

Subject	Q	K
JC	60	62
GK	46	49
DC	49	40
NC	58	74
NG	66	75
KQ	45	33
	54	56

Q and K are nearly the same in absolute value, differing by less than 0.002 sec. on the average.

Furthermore, individuals appear to differ reliably in Q and in K. The rank-order correlation of .89 between Q and K is highly significant.

That the estimates of K are more reliable for the auditory channel, as suggested above, is supported by the finding that the rank orders of individuals are identical for Q and K when only the auditory data are used for the comparison.

It has also been shown that both K and Q are the same for the two sensory channels used in this study. This supports the hypothesis that K and Q reflect the operation of timing mechanisms which are centrally located.

Finally, if Q and K are in fact identical, as indicated by their magnitude and by the high correlation between them, it would be parsimonious to conclude that exactly one temporal quantum is required to switch attention between sensory channels.

Appendix

Three-Signal Discrimination Reaction Time Statistics

Series 1

Subject	Sound Certain	Sound Uncertain	Light Certain	Light Uncertain
		Number of Responses		
JC	269	270	268	269
GK	180	178	180	175
DC	212	207	207	206
NC	225	225	222	225
NG	216	210	211	208
KQ	193	197	202	202
		Mean (msec)		
JC	190.8	226.1	206.5	212.1
GK	162.7	215.7	172.6	192.4
DC	209.7	242.5	214.9	227.2
NC	196.2	207.9	212.7	218.6
NG	224.6	272.2	241.8	259.4
KQ	243.3	250.1	244.2	245.5
		Variance		
JC	1193	2031	1015	1461
GK	1231	3077	541	1457
DC	637	1239	1024	1421
NC	1103	2239	1488	1774
NG	2914	2720	2454	2134
KQ	619	966	1037	1156

Appendix

Series 2

Subject	Sound Certain	Sound Uncertain	Light Certain	Light Uncertain
		Number of Responses		
JC	226	226	229	229
GK	359	359	357	354
DC	305	311	315	315
NC	270	270	269	270
NG	265	266	265	267
KQ	225	222	222	223
		Mean		
JC	187.8	222.2	202.6	210.7
GK	150.2	187.6	154.5	167.9
DC	190.8	223.4	201.4	211.3
NC	195.2	197.3	216.8	213.6
NG	186.3	206.0	201.4	208.1
KQ	243.0	253.4	235.2	243.1
		Variance		
JC	2590	3797	1694	2185
GK	547	706	315	790
DC	540	1235	720	951
NC	1330	1515	1784	730
NG	1764	3439	2745	2629
KQ	830	1011	1906	1702

Appendix

Series 3

Subject	Sound Certain	Sound Uncertain	Light Certain	Light Uncertain
Number of Responses				
DC	113	112	110	110
NC	108	113	111	111
NG	89	87	85	87
KQ	90	89	87	90
Mean				
DC	201.9	224.5	196.8	203.6
NC	209.8	213.5	201.5	200.9
NG	188.2	211.1	202.3	201.7
KQ	245.1	262.0	230.8	227.1
Variance				
DC	360	803	624	538
NC	584	767	375	313
NG	589	2018	1587	1760
KQ	876	1181	1501	1365

THE PSYCHOLOGICAL TIME QUANTUM AND THE DISCRIMINATION OF SUCCESSION

Summary and Conclusions

A further analysis of some previously reported data, in the light of recent theoretical advances, is presented. It is shown that four-signal discrimination reaction time distributions yield estimates of Q, the period of the quantum generator which times the information processing stages in reaction time, which agree well with the values of Q reported earlier for three-signal reaction time data. However, it is necessary to assume four-quanta distributions for the auditory channel.

Single estimates of Q are arrived at for each of fourteen subjects. These same subjects took part in a second experiment in which successiveness discrimination functions were measured. From these functions a parameter M is inferred which is also quantal in nature.

It is shown that M and Q are very nearly the same in magnitude, about 55 msec. for the group. Further, the correlation between them is highly significant over individuals.

This independent measurement of the time quantum strengthens the evidence presented earlier for a single periodic time base which controls a variety of molar neurophysiological events. The coefficient K and the parameters Q and M may be identical although different for different individuals.

Since the ability to discriminate two independent signals as successive may be limited by the time required to switch attention from one to the other, these data support the conclusion arrived at earlier that the time required to switch attention from one sensory channel to another ranges from zero to one quantum.

Introduction

This paper presents evidence concerning the validity of a third method of measuring the duration of a quantum of psychological time. This method, involving the discrimination of successive from simultaneous pairs of independent sensory events, is qualitatively different from the two methods based on reaction time which were described in the first section. It is an entirely independent measurement and it is one which seems to have greater face validity.

In the first section I defined two concepts. One of these, called K, is a coefficient which describes the relationship between the mean and the variance of a hypothetical distribution: the distribution of time increments which may be added to reaction times as a result of uncertainty as to the sensory channel over which the next signal will arrive. While we cannot directly measure either the mean or the variance of this distribution of uncertainty delays, we can measure K in terms of relations among the statistics of distributions of reaction times collected under conditions of certainty and uncertainty.

The second concept is Q, a time constant which is assumed to determine the duration of each event in a three-parameter model of reaction time. It is shown how the magnitude of Q can be inferred from the span of an obtained reaction time distribution.

Values of K and of Q are given for each of six individuals and three important conclusions are tentatively established. It is shown that K and Q are the same in absolute magnitude, averaging about 55 msec. for the group but differing among individuals. Further, K and Q are highly correlated over individuals. Finally, K is the same for the visual channel used in the experiments as it is for the auditory channel, and the same is true of Q.

These results urge a very simple interpretation: Each individual has a quantum generator which controls both the timing of the stages in reaction time and the delays added by channel uncertainty. The frequency of this generator is different for different individuals. Since

$$K = \frac{\sigma_\delta^2}{\Delta} + \Delta \qquad (1)$$

in which σ_δ^2 and Δ are the variance and mean of the hypothetical uncertainty delays, it follows that any distribution of delays for which the mean and the variance combine appropriately to agree with the obtained value of K might be the true distribution. However, if we wish to retain the assumption that there is only one quantum generator per individual, the conclusion that exactly one quantum is added on those trials on which uncertainty lengthens reaction time is the most acceptable one. For if one Q is invariably the uncertainty delay, then $\Delta=Q$ and $\sigma_\delta^2=0$, and equation (1) becomes K=Q, which agrees with the obtained result.

We have proposed (2) that the switching of attention from one sensory channel to another is also controlled by a basic fixed-period time base. In this context, the period is denoted M. Since the frequency generator is independent of sensory input, the time which must elapse before attention can switch, upon being signalled to do so by some input, may be any value from zero to M depending upon the time which remains in the period in which the input arrives. The distribution of switching times is therefore rectangular and extends from zero to M.

In reaction time under uncertainty, it may be that extra delays are added only on those trials when attention is misaligned and that the added delays are due to the added requirement to switch attention. But if the added delay due to uncertainty is always one Q in duration, how do we reconcile this with the assumption that the switching time may be any value from zero to M?

The resolution of this problem is quite simple. The same clock controls the switching of attention and the first stage of reaction time. If attention is aligned with the channel which contains the signal, then the signal passes immediately into stage 1 of the reaction time model and must remain there until the end of the current period. But if attention is misaligned, it cannot switch until the end of the current period whereupon it enters stage 1 at the beginning of the next period, since the timing of stage 1 is controlled by the same clock and must dwell there for one full period. Hence, the time to switch attention may be any value from zero to one period but the delay added to reaction time will always be exactly one period.

This synthesis supposes an identity between M, the period assumed in the successiveness discrimination model, and Q. The purpose of this paper is to present evidence for this identity.

The data which I discuss next have been presented in an earlier report (1). The remainder of this paper concerns two of the experiments reported there. In one of these, reaction time data were obtained using a four-signal discrimination reaction time procedure for each of sixteen subjects. The same subjects also took part in the second study in which their successiveness discrimination functions were determined.

A reaction time trial consisted of the presentation of two tones and two lights at the beginning of the foreperiod. Two seconds later one of the four terminated. If either the right light or the high tone terminated, a response was to be made by releasing the single response key. If either the left light or the low tone terminated, the response was to be withheld. On some trials the subject knew in advance which modality would contain the next signal while on the remaining trials he knew only that it could be in either modality.

This procedure yielded highly variable reaction times and proved to be a fairly complex task. In attempting to account for some of the variability, I speculated that the two auditory signals did not fall within a single channel and that three channels, two auditory and one visual, were in fact involved. The analysis which is presented here bears out that speculation.

In the second experiment the subject was presented successively two-light-sound pairs on each trial. The interval between the offset of the light and the sound was zero for one pair and one of several positive (light preceding sound) values for the other pair. The subject had to try to indicate whether the light terminated before the sound in the first or in the second pair. A function was compiled for each subject relating the probability of a correct detection of the successive pair to the interval separating the light and the sound.

An attention-switching model based on a quantum generator set the requirements for this experiment and was used to interpret the results. It is discussed in detail in the report (1) as well as in an earlier paper (2). For present purposes it will suffice to say that the functions were reasonably linear, as demanded by the quantal model, and that a straight line was fitted to the data for each subject. These lines intersect the chance probability level (.50) at an interval called x which is interpreted as the difference between the afferent conduction times in the two channels. The lines rise with increasing time interval to intersect the P=1.00 level at an interval interpreted by the modal to be one period of the quantum generator above x. In this context the period is called M and it is calculated by subtracting the P=.50 and P=1.00 intercepts.

Experimental Results

Two of the sixteen subjects are discarded from this analysis because their performance on the successiveness discrimination task and on part of the reaction time task was extremely different from the other fourteen. Their data are included in the original report. The effect of omitting them is to reduce the size of the correlation to be discussed below because they were at the upper extreme in both experiments.

Four frequency distributions of reaction time were drawn for each subject for the purpose of estimating Q according to the methods discussed earlier. As before, only those distributions for the certainty condition, one visual and one auditory, were used. The visual distributions appear very similar in form to those obtained using the three-signal procedure and they are assumed to span three quanta. The auditory distributions are different in that a fourth quantal segment seems to be added between the first and the second segments as defined by the model discussed in the first section of this report.

This additional assumption, that these auditory distributions span four quanta, is here made for all fourteen subjects. The visual distributions are treated as before. All of the values of Q are based on lines drawn by eye. The total span of each distribution was so determined and also the point B separating the second from the third segment (the third from the fourth for the auditory data). Q is therefore taken as one-third of the total span (the AC distance) for the visual data, as one-fourth of AC for the auditory, and as one-half and one-third for the visual and auditory AB distances respectively.

The results are presented in Table I and they are in good agreement with those reported before. The over-all mean values of Q are 59.8 msec. for the visual channel and 55.9 for the auditory (they were 56 and 55, respectively, for the three-signal data). This result supports the extra assumption that the four-signal auditory distributions are four-quanta distributions. Also, the estimates based on the AB distance do not differ appreciably from those based on the AC distance, confirming the earlier finding in this report and supporting the idea incorporated in the reaction time model that the positive tail of the distribution is one quantum in length.

TABLE I.--ESTIMATES OF Q(MSEC) FROM FOUR-SIGNAL DISCRIMINATION REACTION TIME DISTRIBUTIONS AND OF M(MSEC) FROM SUCCESSIVENESS DISCRIMINATION FUNCTIONS

Subject	AC Distance		AB Distance		Q*	M
	Q_ℓ	Q_s	Q_ℓ	Q_s		
RB	65	50	47	46	52	51
SB	62	51	65	67	61	94
GH	66	64	62	55	62	71
GS	58	35	51	40	45	47
PM	56	54	73	51	58	63
HG	47	54	43	49	48	51
LW	63	64	67	68	66	68
RH	77	62	56	55	62	59
DP	73	72	70	64	70	93
JC	60	57	57	56	58	77
DH	69	67	69	75	70	80
GK	61	63	40	41	51	46
TM	46	58	55	45	51	45
JH	62	45	55	58	54	42
Mean	61.8	45.9	57.9	55.0	57.7	63.4

Two of these subjects, JC and GK, also participated in the three-signal experiments. The mean Q is 58 and 51, respectively, for them here; before it was 61 and 48.

The mean of Q is given for each subject in the column headed Q* and the value of M inferred from the successiveness discrimination function is beside it. For the fourteen subjects, their mean values are 58 and 63 msec., with M being slightly, but insignificantly, larger. The hypothesis that they are of equal magnitude is a tenable one.

Q_ℓ and Q_s are correlated over individuals, the rank-order coefficients being .71 for those based upon AB and .51 for AC. These are statistically significant and have to be evaluated in view of the approximate method by which Q is estimated here and the relatively small number of cases determining each frequency distribution.

Finally, and of great importance, is the evidence of correlation over individuals between Q* and M. The rank-order coefficient of correlation between these variables is .76 which is significant at well beyond the .01 level.

Experience since these experiments were completed indicates that M diminishes gradually with practice over many more sessions than were involved here. This is especially true for those subjects who show large values of M early in practice. It is probable that more reliable and valid determinations of M can be made than those which are given here.

An additional analysis was made of the effect of channel uncertainty in the four-signal reaction time task. The coefficient K was calculated for each session, each subject and each channel in the manner described. A total of 304 coefficients resulted and these are shown as a single frequency distribution in Figure 1. In this compilation all coefficients based on an a or b of less than 15 msec. are excluded.

The only interesting outcome of these calculations is the two clear peaks in the distribution, one at 60 msec. and the other at 110 msec. This suggests that in this complex task channel uncertainty sometimes added one quantum to reaction time and sometimes two. Most of the coefficients are probably based on sets of trials which contain some one- and some two-quanta events and it is unlikely that a more detailed analysis can separate these.

Nonetheless, one further breakdown of the data was carried out which adds an item of information worth noting. The median of the daily values of K_ℓ and K_s were extracted for each subject. The group means of these medians were 69 for K_ℓ and 111 for K_s, suggesting that uncertainty was very likely to add 2Q when it affected the auditory channel, which I have speculated was really a dual channel, and highly likely to add a single Q to the visual reaction time.

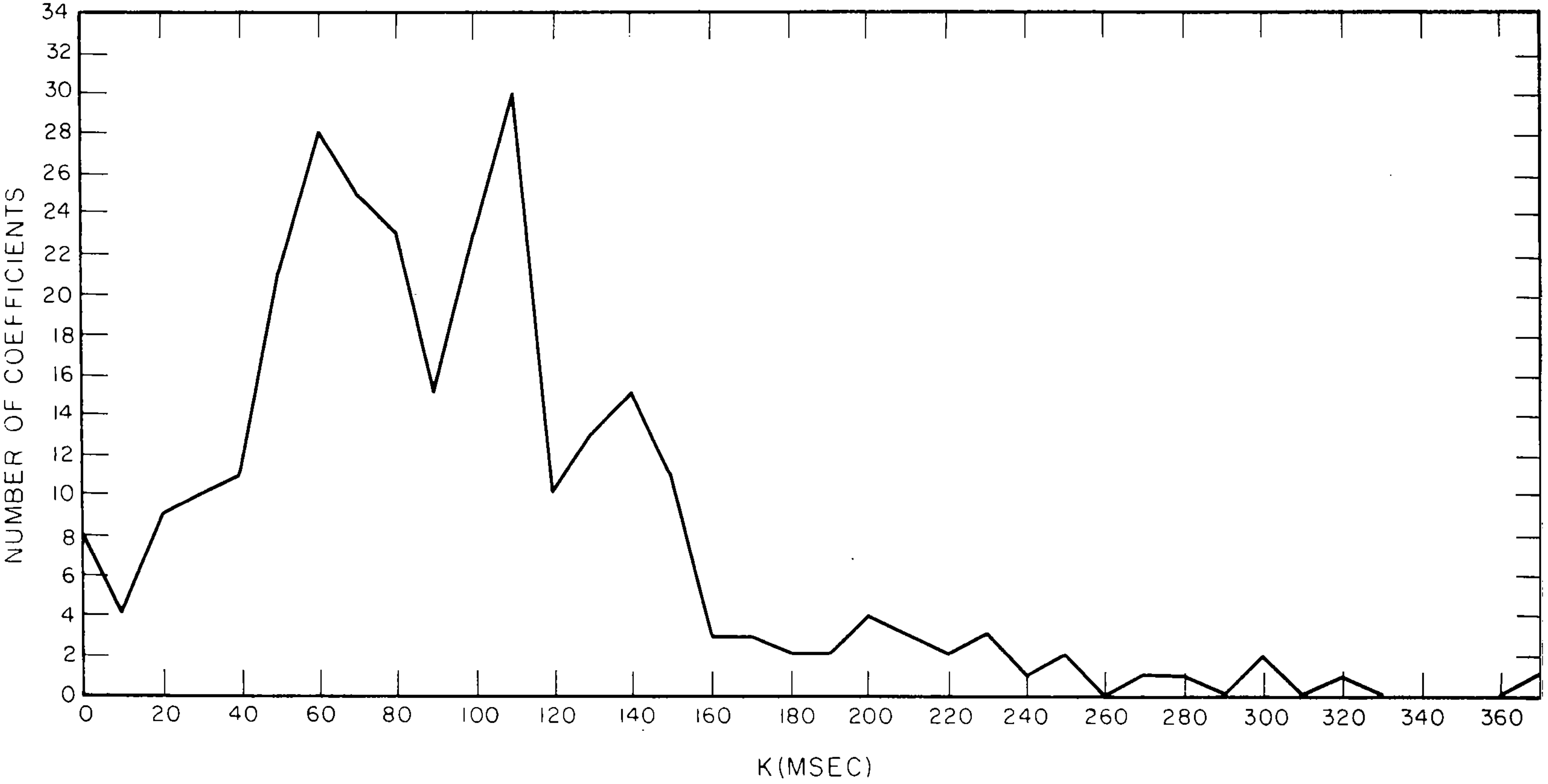

FIG. 1 FREQUENCY DISTRIBUTION OF K_L AND K_S COMBINED. FOUR SIGNAL DISCRIMINATION REACTION TIME FOR 14 SUBJECTS. TOTAL NUMBER OF K-COEFFICIENTS = 304

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