

A real-time criterion theory of duration discrimination

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The common idea that a measure is taken of a duration stimulus over its temporal extent, and that the decision as to whether the stimulus is relatively long or short is based upon such a measure, is shown to be incorrect. Two experiments, which require speeded responding in duration discrimination and consider response latencies as well as response probabilities, demonstrate that the response that is made is determined by the outcome of a race between an internally timed interval, the criterion, and the presented stimulus. The onset of the stimulus triggers the criterion; if the criterion ends first, the response "long" is elicited. Duration discrimination is a matter of temporal order discrimination, and in the limit, "short" responses are simple reactions while "long" responses are time estimation responses. A specific model of the real-time criterion hypothesis is tested, and these initial tests generally confirm it. From this, it is concluded that errors in duration discrimination are due entirely to variability of the criterion and that afferent latencies are not necessarily variable. This adds additional evidence for the existence of deterministic afferent latencies.

Previous theories of duration discrimination have assumed as an input process some mechanism which takes a measure of the temporal extent of the duration stimulus (see the review by Allan & Kristofferson, 1974a). Such an *interval-measure* hypothesis is not the only possibility, as the review also pointed out, and one purpose of the present paper is to demonstrate that that hypothesis is incorrect, at least under certain conditions which often prevail in duration discrimination experiments.¹

In many experimental situations, the metric information about the presented stimulus that is made available by the interval-measure hypothesis is more than is necessary to make the discrimination. In such situations, mechanisms which provide only order information are sufficient. A second purpose of this paper is to provide a specific mechanism of this kind. It is one of a class of mechanisms which follow from a *real-time criterion* hypothesis of the input process, a hypothesis which is an alternative to that of interval measure.

The real-time criterion hypothesis is shown in Figure 1 and will be discussed in the context of a particular discrimination situation which uses the many-to-few method (Allan & Kristofferson, 1974b). A set of four duration stimuli is shown at the top of Figure 1. Each stimulus consists, say, of two identical 10-msec auditory pulses, P_1 and P_2 , which occur in succession. The onset of P_2 occurs D msec after

the onset of P_1 , and the stimuli differ only in D . On each trial, one stimulus only is presented and one of two responses is required. A response meaning short, $R(S)$, is correct for S_1 and S_2 , and the second response, $R(L)$, is correct for S_3 and S_4 . This application of the method divides the set of values of D at the midpoint of the set, and that midpoint (MP) is the base duration. The proportion of responses which are $R(L)$, called $P(L)$, for each S , are the discrimination data.

The real-time criterion hypothesis is shown at the bottom of Figure 1. It states that a criterion, C ,

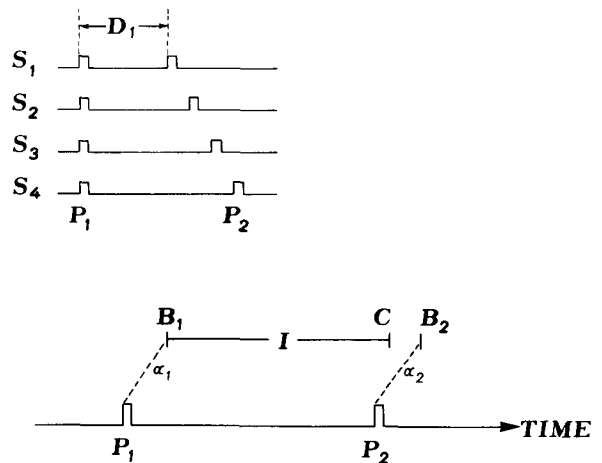


Figure 1. Above: A set of four duration stimuli. The stimulus duration of S_1 is D_1 , the onset-to-onset time of the two brief energy pulses. Below: Schematic of the real-time criterion hypothesis. Each energy pulse causes an internal event B following afferent latency α . Another internal event C , is triggered by B_1 after an internally timed delay I . The response $R(L)$ occurs if C precedes B_2 , and $R(S)$ occurs whenever B_2 precedes C .

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which is an internal time-point event triggered by P_1 , occurs following P_1 by a time which is the sum of α_1 , an afferent latency of P_1 , and I , which is an internally timed interval. A second internal time-point event B_2 is caused by P_2 and occurs following an afferent latency of α_2 . Response choice is determined by the temporal relationship between C and B_2 . A response $R(L)$ results when C occurs first and $R(S)$ when B_2 occurs first. In this view, duration discrimination is seen to be a matter of temporal order discrimination, and the goal of integrating these phenomena, along with successiveness discrimination, seems nearer (Allan, 1975; Kristofferson & Allan, 1973).

The time at which C occurs can be adjusted by changing the sum of α_1 and I . In the single-stimulus procedure under discussion here, this adjustment would be made in the course of practice with the stimulus set, and C should come to be placed near $(MP + \alpha_2)$. With two-alternative forced choice, it is possible that the first stimulus sets a value of $(\alpha_1 + I)$, which is then used to evaluate the second stimulus.²

There is a clear basis for choosing between the two general hypotheses about the input process. The real-time criterion hypothesis says that $R(L)$ is triggered by C , which in turn was triggered by P_1 . The other response, $R(S)$, is triggered by P_2 by way of B_2 . Thus, there are two distinct causal chains: P_1 - B_1 - C - $R(L)$ and P_2 - B_2 - $R(S)$. In general, $R(S)$ should be time-locked to P_2 and $R(L)$ to P_1 . Short responses should always occur after P_2 (i.e., after the end of the stimulus duration), and the time following P_1 at which $R(S)$ occurs should increase with increases in D . But the time at which $R(L)$ occurs should be independent of the end of the stimulus duration and, in general but with an exception to be explained later, $R(L)$ should occur at the same time with respect to P_1 regardless of the duration of the stimulus. In fact, it is quite possible for $R(L)$ to be made correctly even before the stimulus duration has ended, a happening which obviously is not possible under the interval-measure hypothesis. The latter hypothesis would, in general, expect the times of occurrence of both responses to depend upon D .

These considerations require one to measure response latencies as well as response probabilities.

A Specific Model

Since the experiments clearly show that the real-time criterion hypothesis holds and that the interval-measure hypothesis fails, a specific real-time criterion model will be developed in this section.

The time between C and B_2 is γ and

$$\gamma = (\alpha_2 + D) - (\alpha_1 + I). \tag{1}$$

Response choice is governed by γ , $R(L)$ occurring when $\gamma > 0$ and $R(S)$ when $\gamma < 0$. The proportion

of responses which are $R(L)$, $P(L)$, therefore depends upon D , I , α_1 , and α_2 , and the psychophysical function, $P(L) = f(D)$, is determined by the two afferent latencies and I . The variance of the psychophysical function, and thus the fineness of duration discrimination, is therefore, assuming independence,

$$V(\gamma) = V(I) + V(\alpha_1) + V(\alpha_2). \tag{2}$$

It would be unreasonable to assume that the two afferent latencies are identical, but there are grounds for the assumption that both of them have zero variance (Kristofferson, 1976). That assumption is made as part of this specific model, and for this model

$$V(\gamma) = V(I). \tag{3}$$

Variable error and the size of the duration threshold are determined solely by variability in the internal interval I . The theoretical distribution which generates the psychophysical function is simply the distribution of C , i.e., the distribution of times of occurrence of C measured with respect to P_1 .

The distribution of C is shown in Figure 2. It is assumed to be an isosceles triangle with a base of $2q$ msec, since it has been shown for vision (Allan & Kristofferson, 1974b; Allan, Kristofferson, & Weins, 1971) and for audition (Kristofferson, Note 1) that such a form fits the psychophysical data very well. The cumulative form of this distribution is a fully bounded sigmoid function (Kristofferson & Allan, 1973), which provides at least as good a fit as does a normal ogive (Allan et al., 1971). The convolution of two independent uniform distributions, each with a span of q , generates the triangle, and q is a unit of central temporal variability which has been called the "time quantum" (Kristofferson, 1967).

For stimulus j , $\bar{P}(L/S_j)$ is the probability that C is less than B_{2j} . The four duration stimuli yield B_2

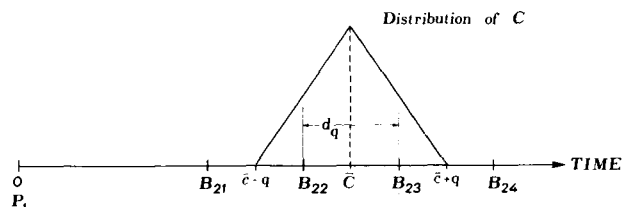


Figure 2. A specific model of the real-time criterion hypothesis. All discrimination errors are generated by variability in C which is assumed to have a distribution as shown: an isosceles triangle with base = $2q$. B_2 is shown for each of four duration stimuli. $P(L)$ for S_j is the proportion of area under the triangle to the left of B_{2j} . α_2 has no variance, but α_1 and α_2 are not necessarily equal. \bar{C} occurs at $(D_c + \alpha_2)$, D_c is the psychophysical criterion, and psychophysical range is defined as $(\bar{C} \pm q)$.

values which cut the distribution at different points. The proportion of the area of the triangle to the left of B_{2j} is $\bar{P}(L/S_j)$.

For any two duration stimuli for which B_2 falls within the distribution, such as S_2 and S_3 in Figure 2, the obtained response probabilities are sufficient to calculate d_q , the distance between the two B_{2s} in units of q (Kristofferson & Allan, 1973). If it is assumed that α_2 is the same for the two stimuli, then d_q in milliseconds will be equal to ΔD , the difference in duration between S_2 and S_3 , and

$$q = \frac{\Delta D}{d_q} \quad (4)$$

Thus, q can be estimated from the response probabilities, as can D_c , the psychophysical criterion which is the duration of the stimulus for which B_2 falls at the expected value of C .

The model, as developed up to this point, requires that d_q be a zero-intercept linear function of ΔD . Allan et al. (1971) found that to be the case. They also found, through an analysis of ROC curves, that the members of a stimulus set all appear to have the same psychophysical variance. Their results led them to propose the "onset-offset" theory of duration discrimination which contained the isosceles triangle as a formal representation. They concluded that (a) there is a perfect mapping of stimulus duration into psychological duration and (b) all psychophysical variance is associated with the afferent latencies.

The present model retains the formal representation but places all the variability in the criterion rather than in the stimulus. The stimuli appear to have the same variance merely because it arises from a source which is the same for all of them. The perfect mapping is due to the fact that everything, internal and external, occurs in real time and there is no transformation of stimulus time into psychological time.

Figure 2 shows that the outside members of the stimulus set, S_1 and S_4 , are chosen to be outside the distribution. They should be discriminated perfectly and they are always included in a stimulus set for the purpose of monitoring the subject (Allan & Kristofferson, 1974b).

Once q has been estimated, the variance of C can be calculated:

$$V(C) = V(I) = \frac{q^2}{6}. \quad (5)$$

Response Latencies in Speeded Duration Discrimination

Extending the model to response latencies for the case in which the subject is asked to make his responses $R(S)$ and $R(L)$ as rapidly as possible

causes several interesting features to emerge. Since $R(S)$ is a direct response triggered by P_2 , it should, in the limit, yield a latency distribution which resembles the simple reaction time distribution. The distribution of $R(L)$ latencies should, in the limit, resemble a distribution of delayed reaction times or "time estimation" responses.

If we let λ_S and λ_L represent the response latencies [the time from P_1 to $R(S)$ and $R(L)$, respectively] for a stimulus of duration D , and define K_S as an independent random variable to represent the time between B_2 and $R(S)$, and K_L as the time between C and $R(L)$, then

$$\lambda_S = \alpha_2 + K_S + D$$

and

$$\lambda_L = \alpha_1 + I + K_L. \quad (6)$$

The difference between the two latency variances for any D is therefore

$$V(\lambda_L) - V(\lambda_S) = V(I) + V(K_L) - V(K_S). \quad (7)$$

For any D , the expected value of λ_S (see Equation 6) is

$$E(\lambda_S) = \alpha_2 + E(K_S) + D$$

and

$$E(\lambda_S) - D = \alpha_2 + E(K_S) \quad (8)$$

is the mean latency of $R(S)$ measured from P_2 rather than P_1 .

For all D greater than $(D_c + q)$, since $[\alpha_1 + E(I)] = [\alpha_2 + D_c]$, it follows from Equation 6 that the expected value of λ_L is the single value

$$E'(\lambda_L) = \alpha_2 + D_c + E(K_L),$$

in which the prime mark indicates the restricted range of D . Thus, within that range, i.e., $D > (D_c + q)$, $E(\lambda_L)$ is independent of D and $E'(\lambda_L)$ measured from D_c rather than P_1 is

$$E'(\lambda_L) - D_c = \alpha_2 + E(K_L). \quad (9)$$

The theoretical variables K_S and K_L each represent the total delay between one of the *response triggers* and its associated response. These response triggers, C and B_2 , are defined differently. However, they are in some sense juxtaposed by the requirement to discriminate and the two responses may be virtually identical. That K can sometimes be identical in variance for simple RT and time estimation responses

has recently been demonstrated (Kristofferson, 1976). But that $K_S = K_L$ in the present context can only be a working assumption which leads to the expectation, from Equation 7, that $V(\lambda_L) - V(\lambda_S) = V(I)$ and further, from Equation 5, that

$$V'(\lambda_L) - V(\lambda_S) = \frac{q^2}{6}, \quad (10)$$

in which $V'(\lambda_L)$ is $V(\lambda_L)$ for $D \geq (D_c + q)$. Duration stimuli above the psychophysical range, *viz*, longer than $(D_c + q)$, should always elicit R(L) and they should all have the same latency variance, a variance greater than $V(\lambda_S)$ by $q^2/6$. Thus, from the variance difference of Equation 10, an estimate of q can be obtained which should agree with that calculated from the response probabilities via Equation 4. Further, the distribution of λ_L , in this range, should be the convolution of the distribution of λ_S with a triangular distribution of base $2q$.

For stimulus durations within the psychophysical range, $(D_c - q) < D < (D_c + q)$, $V(\lambda_L)$ is a function of D . Referring to Figure 2, when B_2 is within the distribution, those values of C which are effective R(L) triggers are those to the left of B_2 . As B_2 moves leftward through the distribution, both the variance and the mean of the effective C decrease and as $(C - q)$ is approached, the distribution of λ_L approaches the distribution of λ_S in all respects.

Finally, it follows from Equations 8 and 9 that the mean latency of R(S), measured from the onset of P_2 , should be equal to the mean latency of R(L) measured from the psychophysical criterion, and using stimuli for which $D > (D_c + q)$, when two conditions are met: (1) $E(K_S) = E(K_L)$ and (2) α_2 has the same value when the two different response latencies are measured.

Response Competition and Other Complications

Both response triggers, B_2 and C , occur on every trial, but only one of the two responses occurs. Each trigger must be a negative signal for the opposite response as well as a positive signal for its own response. The first trigger must inhibit the response caused by the second trigger (both responses are never made on a trial, even when speeded), and it is probable that the inhibitory component of the second trigger will have some effects upon the response to the first trigger. The inhibitory effect of the second trigger upon the first must be zero when the interval between triggers is large, but it must increase as that interval becomes smaller, although not necessarily monotonically. If it is monotonic, then the amount of inhibitory effect should increase as the probability that the first trigger will be first decreases. For example, in Figure 2, when S_3 is presented, B_{23} occurs before C with small probability, but when it

does so occur, C occurs very soon thereafter. Response competition should be maximum for R(L) when $D = (D_c - q)$ and for R(S) when $D = (D_c + q)$ rather than for stimuli near the criterion D_c as might be expected on other grounds.

The decision rule which determines response choice states that the response associated with the first trigger is the response which occurs on every trial. That rule works well as far as discrimination probabilities are concerned and it will be retained. But it is possible that at least sometimes the response that occurs is the one associated with the second trigger and a response competition theory of duration discrimination might be formulated.

Response latencies are another matter. It seems quite possible that the latency of the response to the first trigger will be affected by the second trigger when the second occurs soon after the first. Extensive preliminary experiments showed this to be the case: there is much "response competition" in the latency data, especially when D is within the psychophysical range, when one of two possible overt responses must be made on each trial. Using a *one-response procedure*, in which in some sessions the response is R(L) and no overt response is made as R(S), while in other sessions that is reversed, greatly reduces the response competition effect. In those preliminary experiments, while latencies did depend upon whether one or two responses were required, discrimination performance did not. Such a result would suggest that discrimination errors are not due to response competition and careful systematic experiments are needed on this point.

Speeded duration discrimination was characterized above as a combination of simple RT and time estimation. As a simple RT experiment, it is one in which the RT signal occurs only on some trials, the subject must be generating I at the moment the RT signal occurs, and the foreperiod varies. As a time estimation experiment, it is one in which the TE response is countermanded on some proportion of the trials. Given these considerations and what is known about RT and TE, it would indeed be remarkable if, in the limit, latency distributions could be obtained which resembled simple RT and TE.

The experiments which are reported next are intended to determine whether an interval measure strategy or a real-time criterion strategy is used in duration discrimination when a single stimulus, many-to-few method is employed. If the evidence is clear in favor of the real-time criterion strategy, then the predictions of the specific model developed above will be tested.

METHOD

An experimental session in Experiment 1 consisted of three blocks of 100 trials each with a brief pause between blocks.

Within any session, the blocks were identical and the duration of a session was about 35 min.

On each trial, one duration stimulus was presented and the subject attempted to classify it as "long" or "short." A single response procedure was used so that in some sessions the response was R(L) while in other sessions it was R(S). At the end of each trial, the subject was told whether the stimulus had been long or short. Each occurrence of a response was recorded by the computer along with its latency in milliseconds from the onset of the stimulus pulse which marked the beginning of the stimulus duration. The responses were buttonpresses, as described in detail elsewhere (Kristofferson, 1976).

Each trial began with a 100-msec auditory warning signal followed 1,000 msec later by the duration stimulus. The duration stimulus consisted of two identical auditory pulses, P_1 and P_2 , and the stimulus duration was the time D between the onsets of P_1 and P_2 , as shown in Figure 1. The auditory pulses each had a duration of 10 msec. They were 1,000-Hz sinusoids gated at zero crossing with a rise-decay time of 2.5 msec and a loudness of 68 dB re 0.0002 dynes/cm² when on continuously. The stimulus patterns, responses, and computer program were the same as those used to study response-stimulus synchronization (Kristofferson, 1976). The only difference was that in the present experiment a visual feedback signal occurred at the end of the response period to tell the subject whether the duration had been "long" or "short."

In every session, there were four duration stimuli: S_1 and S_2 were designated short and S_3 and S_4 long. The one of the four to be presented on a trial was selected randomly, and they were equally likely to be selected. Thus each was presented about 75 times during a session in Experiment 1. All 300 trials were included in the final data analysis. D_1 and D_4 were set so that S_1 and S_4 were outside the psychophysical range and S_2 and S_3 were placed within the psychophysical range and separated by a ΔD of about one q unit.

Two experiments are reported below. Experiment 1 consisted of an intensive study of a single midpoint using a single subject, the author, who had had extensive prior experience. Two young adult males who had had no previous experience were the subjects for Experiment 2.

EXPERIMENT 1

Sets of four stimulus durations with a fixed mid-

point of 1,150 msec were used throughout this experiment. The inside members, S_2 and S_3 , were never changed; they had durations of 1,100 and 1,200 msec, respectively. The durations of S_1 and S_4 were varied so that B_{21} took various positions below $(\bar{C} - q)$ and B_{24} covered a range above $(\bar{C} + q)$ (refer to Figure 2).

Some details of experimental design are given in Table 1. A total of 114 sessions were conducted, organized into 19 cycles of 6 sessions each. All changes in D_1 and D_4 were made between cycles, and the values of each are given in the table. For the first 5 cycles, the single response signaled the decision "short"; its meaning was reversed for the final 14 cycles.

The experimental subject had participated in similar duration discrimination experiments for several hundred sessions before beginning this one. These included many different midpoints with unsped responding followed by several different midpoints with speeded responding but with two responses. Immediately prior to the present experiment, he had done many sessions with midpoints close to the 1,150 used here but with two speeded responses. His discrimination performance was therefore specifically and highly trained for this experiment before it began.

Table 1 shows that performance was exceedingly reliable. When the monitoring stimuli S_1 and S_4 were presented, a small number of errors occurred during the first 5 cycles and a somewhat larger number for a few cycles following the reversal of response meaning at the beginning of Cycle 6. During the final 10 cycles (18,000 trials), no errors were made on S_1 and S_4 ; *the response always occurred when S_4 was presented and it never occurred when S_1 was presented.*

The reversal of response meaning also affected

Table 1
Psychophysical Data for Experiment 1

Cycle	R	P(L/ S_1)	P(L/ S_2)	P(L/ S_3)	P(L/ S_4)	D_1	D_4	D_c	q
1	R _S	.004	.156	.935	.996	1030	1270	1141	92.6
2	R _S	.000	.124	.919	.998	1030	1270	1146	90.9
3	R _S	.000	.171	.948	.998	1000	1300	1138	91.5
4	R _S	.000	.178	.950	1.000	970	1330	1137	92.0
5	R _S	.000	.174	.899	.998	950	1350	1143	104.1
6	R _L	.005	.191	.908	.997	970	1330	1140	104.9
7	R _L	.004	.203	.898	.993	970	1330	1140	109.8
8	R _L	.002	.185	.907	1.000	970	1330	1141	104.1
9	R _L	.000	.281	.946	.998	970	1330	1127	108.6
10	R _L	.000	.219	.936	1.000	970	1330	1134	102.0
11	R _L	.000	.171	.936	1.000	970	1330	1139	94.6
12	R _L	.000	.213	.933	1.000	970	1330	1135	101.9
13	R _L	.000	.166	.933	1.000	970	1330	1140	94.5
14	R _L	.000	.144	.906	1.000	970	1330	1145	97.2
15	R _L	.000	.127	.907	1.000	970	1375	1147	93.9
16	R _L	.000	.282	.942	1.000	970	1550	1127	110.1
17	R _L	.000	.201	.924	1.000	970	1550	1138	102.5
18	R _L	.000	.181	.941	1.000	970	1550	1138	94.9
19	R _L	.000	.146	.914	1.000	970	1550	1144	95.7

Note.—Each cycle is six consecutive sessions, hence each proportion is based upon 450 trials. D_1 and D_4 are the durations of S_1 and S_4 . D_2 and D_3 were fixed at 1100 and 1200, respectively. All times are in milliseconds. Subject A.K.

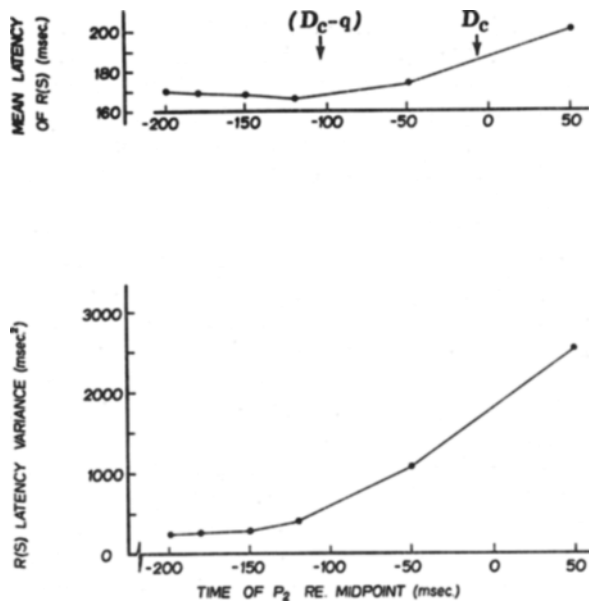


Figure 3. Mean and variance of R(S) latencies, measured from P_2 , as a function of the time at which P_2 is presented. Zero is 1,150 msec, the midpoint of the stimulus set. The lower half of the psychophysical range is the region between the arrows. Below that range, the mean latency is 168, the SD is 16.7, and R(S) is time-locked to P_2 .

latency variability. The variance of R(L) latencies decreased slowly during Cycles 6-10. It remained constant thereafter until Cycle 16. Increasing D_4 to 1,550 for Cycle 16 was accompanied by a small increase in latency variance, which diminished during cycles 16 and 17.

These minor perturbations following Cycle 5 and Cycle 15 also appear in Table 1 as small changes in the parameter q . For these reasons, Cycles 6-10 and 16-17 are omitted from the final analysis.

The remaining 12 cycles meet the stringent criteria of measurement: latency variances appear to be stationary and virtually no errors occur when one of the outside members of the stimulus set is presented. The mean value of the parameter q is 95.3 msec during these 72 sessions. For the first 5 cycles, q averages 94.2 msec. Thus, there is no indication here that discriminability depends upon which response is used.

Response Latencies

In Cycles 1-5, the time of occurrence of R(S) was measured for each of six values of D_i . Figure 3 shows, in the upper graph, the mean response latency as measured from the onset of P_2 as a function of the time between P_2 and the midpoint of the stimulus set (1,150 msec). The position of the psychophysical criterion and the point one q below the criterion are indicated by arrows. The lower graph shows the corresponding variances.

When P_2 occurs more than one quantum before

the criterion, R(S) is strictly time-locked to P_2 . The response occurs on average about 168 msec after P_2 regardless of when P_2 is presented, and the variances average 279 msec² (SD = 17 msec).

Frequency distributions of R(S) for D equal to 950, 970, and 1,000 msec can be seen in Figure 4. They have a slight positive skew and a minimum near 135 msec. They are the same regardless of when P_2 is presented.

The means, variances, and distributions of R(S) latencies are typical of those obtained in simple reaction time experiments under the most tightly controlled conditions (Kristofferson, 1976). All responses are shown in Figure 4; there are no outlying latencies. In the present experiment, P_2 occurs before ($D_c - q$) on one-fourth of the trials. When it does so occur, R(S) is certain to occur and R(S) will occur within a 100-msec window following P_2 regardless of when P_2 is presented within the range. Further, R(S) never occurs on the one-fourth of trials on which P_2 is presented later than ($D_c + q$).

It is concluded that short responses are, in the limit, simple reaction times triggered by P_2 and that under these rather complex experimental conditions these simple RT distributions are homogeneous in the sense that all of the responses are triggered by the action stimulus.

Frequency distributions of R(S) latencies for D equal to 1,030, 1,100, and 1,200 msec are displayed in Figure 5. As P_2 enters the psychophysical range, the skew becomes increasingly pronounced, but the minimum latency does not seem to change, staying about the same as in Figure 4. The minimum latency is time-locked to P_2 over the entire range.

While R(S) is time-locked to P_2 , R(L) is not. The distributions of R(L) when D equals 1,330, 1,375, and 1,550, shown in Figure 6, demonstrate that R(L) occurs at the same times following P_1 regardless of the time at which P_2 is presented, providing that P_2 is presented after ($D_c + q$). In fact, R(L) often

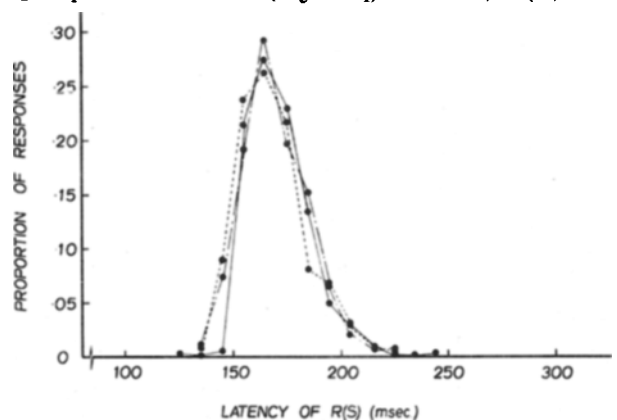


Figure 4. Frequency distributions of R(S) latencies for the three leftmost points of Figure 3. Bin size = 10 msec. There are no outlying latencies. Latency measured re P_2 . R(S) is simple RT to P_2 .

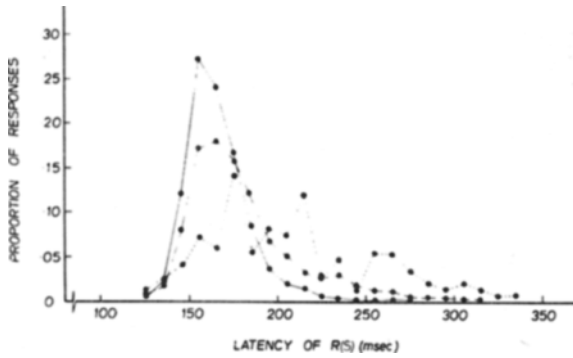


Figure 5. Frequency distributions for the three rightmost points of Figure 3. The minimum RT does not change, but the variance increases as P_2 moves upward within the psychophysical range. Latency re P_2 .

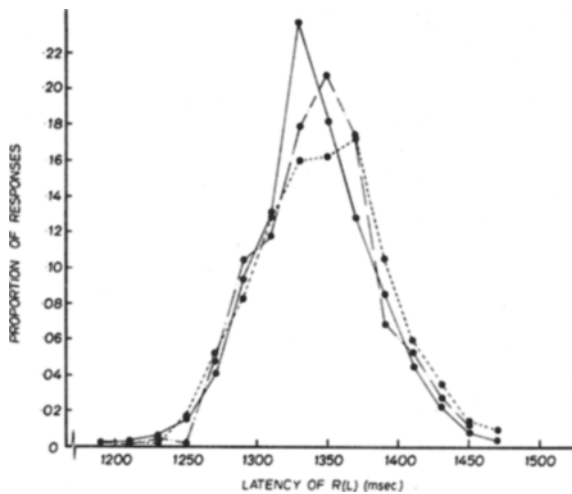


Figure 6. Frequency distributions of R(L) latencies when P_2 is presented above the psychophysical range at 1,330 (solid line), 1,375 (dashed), and 1,550 msec (dotted). The means are 1,340, 1,343, and 1,347, and the variances are 1,704, 1,703, and 2,035, in the same order. Bin size = 20 msec. No outlying latencies. The time of occurrence of R(L) does not depend upon the time at which the stimulus duration ends. Latency re P_1 .

occurs before P_2 ; in the extreme case of $D = 1,550$, it always does. Since in addition, R(L) never occurs when S_1 is presented, it is concluded that R(L) is never triggered by P_2 .

According to the specific model developed in the introduction, when P_2 is presented within the psychophysical range, the distribution of R(L) should be truncated: the longer latencies should disappear but the shorter latencies should be unaffected. Figure 7 shows this truncation effect. As P_2 moves downward toward ($D_c - q$), the mean and the variance of R(L) do diminish. For this subject, the alignment of the left edges of the distributions is not perfect; the truncated distributions shift to the left by a small amount which increases with the depth of the truncation.

Response Latencies and Response Probabilities

Within the psychophysical range ($D_c \pm q$), response latencies yield an unclear picture, probably due to the temporal proximity of C and B_2 . But outside that range, the latencies are well behaved. According to Equation 10, the variance of R(L) above the range should be greater than the variance of R(S) below the range by $q^2/6$. The mean value of q , calculated from the response probabilities for S_2 and S_3 , is 95.3 msec. $V(C)$ is therefore, 1,512 msec². The difference between the two latency variances, calculated from the latencies of S_1 and S_4 for the same 12 cycles as was q , is 1,799-279 = 1,520 msec². Put differently, the size of the quantum can be calculated from either the discrimination probabilities or the latency variances, and the result is the same, for this subject.

The mean latency of R(S), measured with respect to P_2 in Cycles 1-5, is 168 msec for those D below the psychophysical range. During Cycles 11-15 and 18-19, the mean value of the psychophysical criterion is 1,141 msec and the mean latency of R(L) is 1,342 msec when D is above the psychophysical range. The difference between these is 201 msec, substantially more than 168. Referring back to Equations 8 and 9 and the later discussion of them, it is necessary to conclude either that $E(K_S)$ is not equal to $E(K_L)$ or that α_2 is different in the later cycles from what it is in the earlier cycles, or both.

EXPERIMENT 2

Two naive subjects, J.G. and P.W., were studied in this experiment, with the midpoint of the stimulus set fixed at 850 msec for both of them. The values of S_1 and S_4 were 730 and 970 msec for both, except as noted below, while S_2 and S_3 were always 800 and 900 for J.G. and 820 and 880 for P.W. Each session consisted of four blocks of 100 trials each, and four consecutive sessions comprise a cycle. J.G. did 15 cycles and P.W. did 16.

J.G. used R(L) as his single response for the first 7 cycles. He then switched to R(S) for the remainder of the experiment. The reverse order was used for P.W.—R(S) for 9 cycles followed by R(L) for 7 cycles.

For J.G., S_4 alternated between 970 and 1,030 msec from session to session during Cycles 6 and 7 while S_1 alternated between 720 and 740 msec during Cycles 13 and 14. For P.W., S_1 alternated between 720 and 740 during Cycles 7 and 8 while S_4 alternated between 950 and 990 during Cycles 15 and 16.

During the first 4 cycles for J.G. and the first 3 cycles for P.W., the subjects were allowed to respond when they wished, no mention being made of speeded responding or of the fact that latencies were being measured. They were thereafter instructed to respond as rapidly as possible and given information about their latencies at the end of each session.

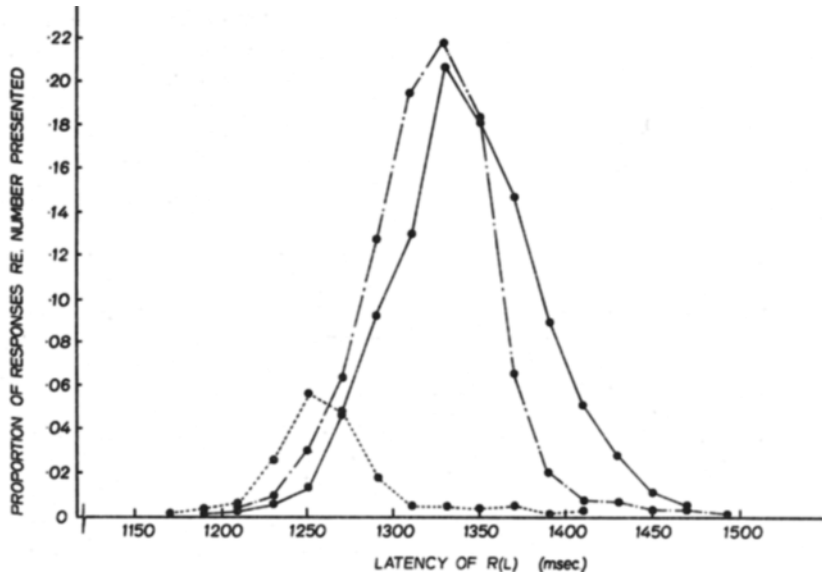


Figure 7. Truncation of the R(L) distribution when P_2 falls within the psychophysical range. Proportions based upon number of stimulus presentations; thus when P_2 occurs at 1,100 msec (dotted line), R(L) is less likely to occur, but when it does occur it does so more rapidly (mean = 1,261) and with less variability (Variance = 932). The dashed line is the distribution for $D_3 = 1,200$; its mean and variance are 1,323 and 1,234. The solid line is the composite of the three distributions of Figure 6.

Response Probabilities

A summary of the parameters obtained from the response probabilities is given in Figure 8 for S_2 and S_3 in the upper graph and for S_1 and S_4 in the lower. For both subjects, obtained values of q were substantially higher when the response was R(L) than when it was R(S).

Instructions to respond rapidly affected latencies greatly, of course. For J.G., R(L) for S_4 occurred at a mean time of 1,260 msec following P_1 in Cycle 4; in Cycle 5, that latency decreased to 1,050 msec. For P.W., when S_1 was presented in Cycle 3, R(S) occurred at a mean time of 1,060 msec while in Cycle 4 it occurred at 925 msec. Despite these gross changes in latency, discrimination accuracy was not noticeably affected by speeding, although, of course, the design of this experiment does not include the features required to make this a firm conclusion.

Both subjects made errors on S_1 and S_4 in every cycle of the experiment. The error rate, ϵ , has been interpreted as the probability that the stimulus is not processed when it is presented and that the response is due to some other cause in such cases (Allan & Kristofferson, 1974b). The error rates are not large, but the ideal of zero is not achieved here as it was in Experiment 1. Even a small error rate of this kind suggests that the latency distributions will not be homogeneous. The error levels, too, were unaffected by speeding the responses.

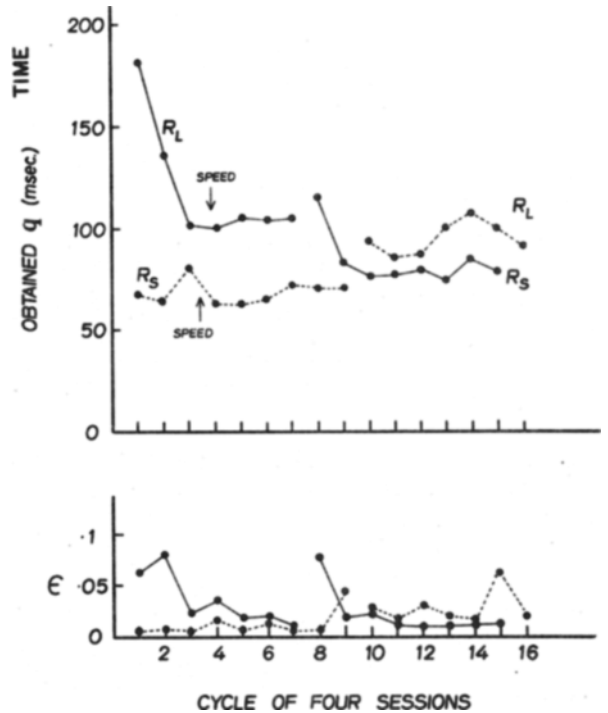


Figure 8. Duration discrimination results from Experiment 2. The upper graph shows values of q calculated from P(L) for S_2 and S_3 trials. The lower graph is of the error rate recorded on S_1 and S_4 trials: $\epsilon = (1 - K) = 1 - P(R_L/S_4) + P(R_L/S_1)$. Subject J.G. yielded the solid lines, P.W. the dotted lines.

Response Latencies

The latencies of R(S) on S_1 trials did not reach and maintain a stable level for either subject. This is evident in Figure 9. Both the mean and the variance reach their lowest levels in the final cycle for each subject, and it is likely that they would have diminished even more.

During the final cycle, the means were 191 and 164 msec following P_2 for J.G. and P.W., respectively; the variances are 474 and 384 msec². These are close to the values obtained in Experiment 1 and all of them are well within the typical simple RT range.

The time of occurrence of P_2 was alternated between 720 and 740 msec from session to session during the two cycles just before the final cycle for both subjects. The results are shown by the frequency distributions in Figures 10 and 11. It is apparent that delaying P_2 by 20 msec shifts the response distribution to the right by about the same amount, 24 msec for J.G. and 28 for P.W.

These distributions resemble simple RT distributions, as was the case also in Experiment 1. However, in Experiment 2, there are a few scattered latencies that are far from the mean, as might be expected from the nonzero values of ϵ .

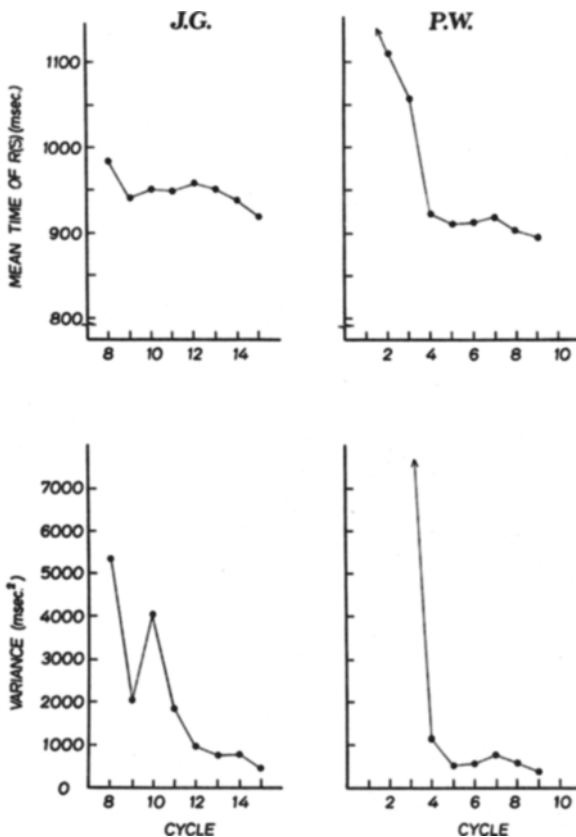


Figure 9. Latency means relative to P_1 , and variances, for R(S) on S_1 trials for the two subjects of Experiment 2.

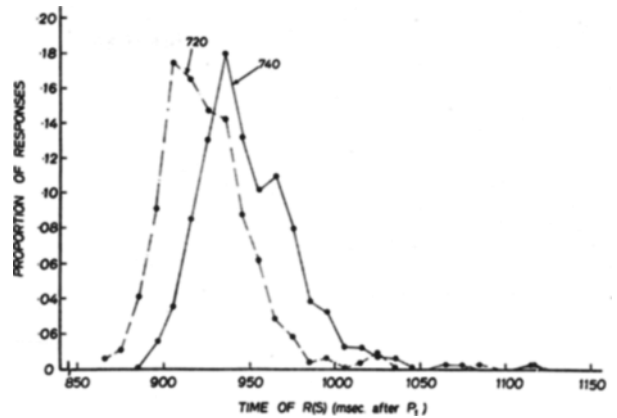


Figure 10. Frequency distributions of R(S) on S_1 trials for $D_1 = 720$ and 740 msec. Subject J.G.

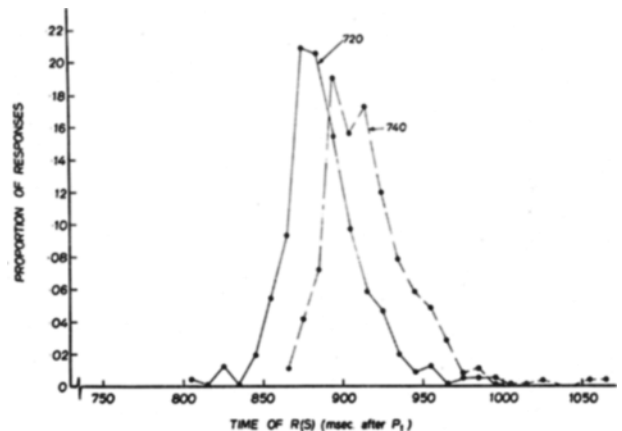


Figure 11. Frequency distributions of R(S) on S_1 trials for $D_1 = 720$ and 740 msec. Subject P.W.

Like the R(S) latencies, the R(L) latencies did not reach and maintain a stable level in the course of this experiment. During the final two R(L) cycles, the duration of S_4 alternated from session to session between two values for each subject. The result is given in the form of frequency distributions in Figure 12, and the findings of Experiment 1 are confirmed. Many R(L) occur before P_2 , and the mean latency of R(L) is independent of the time at which P_2 is presented.

The predicted truncation of the R(L) distribution by S_2 and S_3 is even more clearly evident here (Figures 13 and 14) than it was in Experiment 1. For both subjects, the left edges of the distributions are unaffected by the truncation. The truncation is clean for J.G. but it is not for P.W., who has a long, positive tail for both S_2 and S_3 .

Response Latencies and Response Probabilities

Because of the nonzero error rates and nonstationarity of the latencies in this experiment, it is pointless to consider the relations between probabilities and latencies in fine detail.

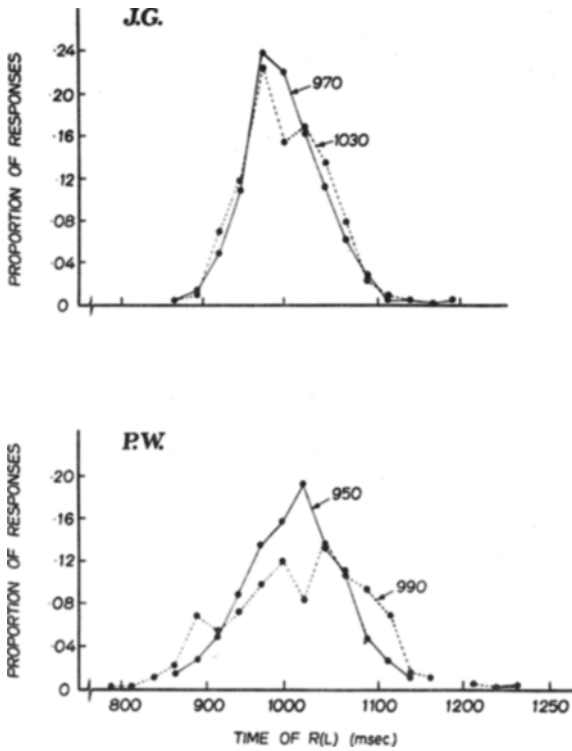


Figure 12. Frequency distributions of R(L) for two values of D_c (as indicated) for each of the two subjects of Experiment 2. For the top graph, mean = 989 and 991 and variance = 2,262 and 2,334 for 970 and 1,030, respectively. For the lower graph, mean = 1,001 and 1,006 and variance = 3,113 and 5,528 for 950 and 990, respectively.

The latency variance of R(L) is much greater than that of R(S), and the latter is similar to that of simple RT. The variance difference is somewhat larger than in Experiment 1, but had greater experimental control been achieved, that difference would probably be reduced.

The mean latencies of R(S) are 191 and 164 msec re P_2 for J.G. and P.W., respectively. The means for R(L) are 161 and 178 msec, in the same order, re D_c .

DISCUSSION

Analyzing a duration stimulus, and discriminating between duration stimuli using the responses R(L) and R(S), is accomplished by a real-time criterion mechanism. The alternative, that a measure is taken of the stimulus duration over its temporal extent and the decision is based on such a measure, is rejected. Instead, the beginning of the duration stimulus triggers an internal time interval which runs along with the stimulus duration. If the internal interval ends first, the response R(L) is selected and elicited. But if the sensory signal that is the end of the duration stimulus is received before the internal interval has ended, then R(S) is the consequence.

The response R(S) is caused by P_2 , the end of the duration stimulus. Under ideal conditions, as in Experiment 1, it always occurs when it should (S_1 trials) and never when it should not (S_2 trials). When it does occur, it does so within a narrow time window following P_2 by an amount that is fixed and independent of the times at which P_2 occurs. R(S) is time-locked to the end of the duration stimulus. The other response, R(L), is quite the opposite. When it is certain to occur, the time at which it occurs is unrelated to P_2 and, in fact, the overt R(L) may occur even before the end of the duration stimulus.

Both experiments confirm the foregoing in detail in every case, and it is concluded that short responses are caused by the end of the duration stimulus and long responses are caused by the beginning of the duration stimulus. The proof of this conclusion is strong but it is not yet complete. Additional experiments are required to establish that R(L) is time-locked to P_1 and that R(S) is not.

Speeded responding was required in these experiments, and it is possible that that forces a subject into a real-time criterion mode of processing. Some evidence is given that discrimination performance is unaffected by speeding the responses, and that supports the view that the real-time criterion is also used when responding is done at leisure, but it does not prove it.

Certain deductions from the general conclusion are also confirmed and add weight to it. One is that

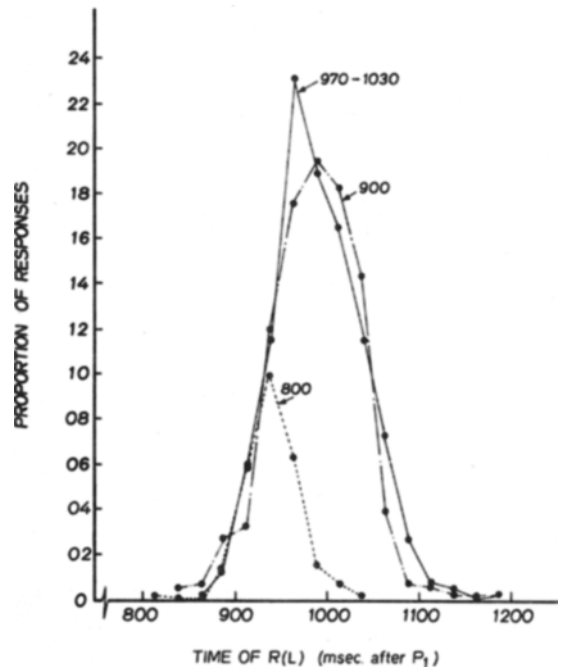


Figure 13. Truncation of the R(L) distribution by P_2 , occurring within the psychophysical range at 800 (S_2) and 900 msec (S_3). The solid line is the composite of the two distributions obtained on S_3 trials. Subject J.G.

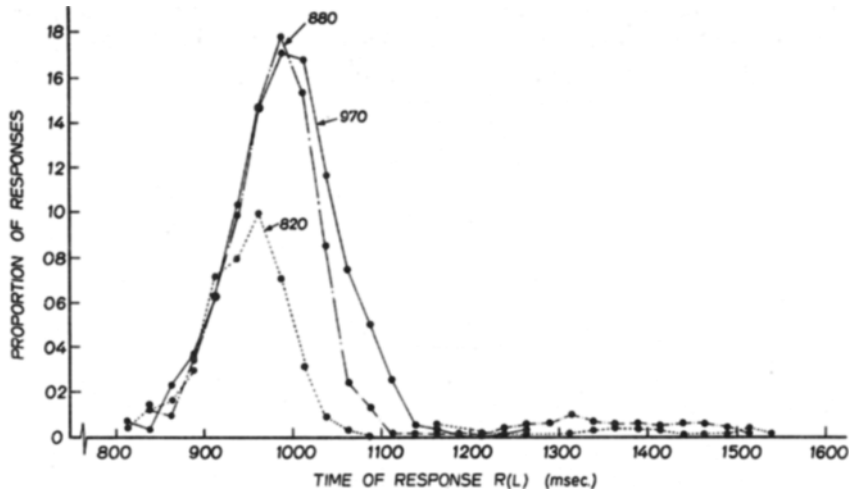


Figure 14. Truncation of the R(L) distribution by P_2 occurring within the psychophysical range at 820 (S_2) and 880 msec (S_3). The solid line is the distribution obtained on S_4 trials when D_4 was 970. Subject P.W.

R(S) should resemble simple reactions to P_2 . That is found to be true in every case: the latencies of R(S) form distributions which are typical in all respects of simple RT distributions (for a discussion of what is "typical," see Kristofferson, 1976). Another deduction is that, since R(L) is a response initiated by P_1 , but only after an interpolated delay, the distributions of R(L) latencies should resemble distributions of "time estimation" responses. This too is borne out: in Experiment 1, the ratio of SD to mean for R(L) is 0.03. That ratio and the shape of the distributions agree well with the time estimation data reported earlier (Kristofferson, 1976, especially in Figure 13).

Thus there are two causal chains to consider on a duration discrimination trial: $P_1 \rightarrow R(L)$ and $P_2 \rightarrow R(S)$. Since response choice depends upon whether an event C in the P_1 chain occurs before or after an event B_2 in the P_2 chain, and since the psychophysical variance is much greater, usually, than the total latency variance of the P_2 chain, it might have been deduced that most of the psychophysical variance in duration discrimination is in the P_1 chain preceding C. That is, errors in duration discrimination are due mainly to variability in the internal criterion interval.

In fact, the specific model tested above goes even further and proposes that *all* of the variability in duration discrimination is due to variability in the time at which C occurs. The time between P_2 and its sensory effect, B_2 , is assumed to be deterministic. In Experiment 1, where the measurement criteria are met, this model is confirmed; the same variance of C, and hence the same value of the parameter q , are recovered from both the latency variance and the response probabilities. In Experiment 2, in which stable latency levels were not shown to be achieved

and the error rate on S_1 and S_4 trials was nonzero, only a qualitative agreement with the model can be seen.

The specific model is also supported by the relatively sharp truncation of the R(L) distribution which occurs when P_2 is presented within the psychophysical range. This cutoff, which is already blurred by the variance in K, would be blurred further to the extent that α_2 , the afferent latency of P_2 , is variable. It would be possible to determine theoretical truncated distributions by calculating the convolution of the truncated triangular section with the R(S) distribution, but this would gain little because of the obvious presence of some degree of latency interaction between C and B_2 when they occur in temporal proximity within the psychophysical range. It would be useful if one wished to study the response competition effects, but for present purposes this too must be left as a qualitative finding.

One other result from Experiment 2 requires some comment. Discrimination performance, as indexed by the parameter q calculated from the response probabilities, is substantially poorer when the single response is R(L) than when it is R(S) (see Figure 8). Table 1 shows that this was true also in Experiment 1 during the first 30 sessions using R(L). But in Experiment 1, in which sessions were continued until the latencies had definitely stabilized, the difference in q between R(S) and R(L) conditions did not exist after stability was attained.

There is a difference between the R(S) and R(L) conditions which is inherent in the procedure and which may account for the greater difficulty in attaining stability when R(L) is the response. When a response is made, the sound produced by the response can be heard. This response sound, perceived in relation to P_2 , functions as a highly efficient

feedback signal under certain conditions (Kristofferson, 1976). When the response being made is R(S), the response sound follows P_2 on every trial by a substantial amount. But when R(L) is used, the response sound may often occur close in time to P_2 when S_4 is presented, depending upon the value of D_4 , and attempts to synchronize the response sound with P_2 may conflict with the psychophysical discrimination, thereby inflating the variance of C. If this is so, there should be a critical value of D_4 that is compatible with D_c and a stimulus set containing such an S_4 should require much less practice to achieve stability.

There is a prediction of the specific model which will provide another strong test of it. Changes in base duration, i.e., in the midpoint of the stimulus set, should cause changes in discriminability, q , which are accompanied by quantitatively identical changes in the latency variances of R(L) and by negligible changes in the latency variance of R(S). Such changes should occur if the changes in midpoint are large, but there may be little change if they are small (Allan & Kristofferson, 1974b).

Kristofferson (1976) has demonstrated an S-R causal chain which contains an adjustable and deterministic temporal segment. He suggested that that segment might be within the afferent latency. If so, and if it is within α_1 , as defined here, then the specific real-time criterion model would predict that in the limit there should be a range, at the lower end of the base duration scale, within which duration discrimination is independent of base duration and also virtually perfect. The experiment needs to be done to determine whether such a limit exists, there being no evidence of "virtually perfect" discrimination in past experiments.

Finally, what of the interval-measure hypothesis?³ Its rejection obviously does not mean that a measure of a stimulus duration cannot be taken, coded, and stored in memory. The real-time criterion mechanism itself suggests that this is possible and also that the memory representation can be decoded into a real, if internal, time interval. What is rejected is the hypothesis that an order decision about a stimulus duration is based upon a comparison between a coding of the presented stimulus and a representation held in memory. It may be that under some circumstances such does occur, but that it does now must be demonstrated. Such judgments about duration, based upon comparison of interval measures, may follow different laws than those based upon real-time processing, but we cannot know until the former have been shown to be isolated.

However, it is not even necessary to assume that these internal time intervals are stored in "coded" form. It is possible that they are simply the real

duration of automatic, highly stable, memorial chains of the kind proposed by Schneider and Shiffrin (in press).

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NOTES

1. Our review (Allan & Kristofferson, 1974a) pointed out that all three of the quantitative theories that existed at that time assumed that the input process for a duration stimulus could not be complete until the stimulus had ended, and therefore that correct decisions and responses could not occur until after stimulus termination. One theory (Creelman, 1962) states that hypothetical random pulses are counted while the stimulus is present and that decisions are based upon the total count. The second theory is similar, except that time quanta of fixed duration are counted (see Allan & Kristofferson, 1974a, for references). The third theory is the onset-offset model (Allan & Kristofferson, 1974b), which is discussed later in the present paper.

Thomas and Weaver (1975) have proposed a theory of perceived duration which they have applied to mapping two brief stimulus durations into three response categories. Their theory states that perceived duration, upon which discrimination is

assumed to depend, receives a contribution to its magnitude from a timer which measures the temporal extent of the stimulus. They restrict their theory to stimulus durations less than 100 msec, but that restriction is imposed not because the operation of the timer is thought to be different for longer durations.

Massaro and Idson (1976) have also proposed a theory of perceived duration which they apply to the discrimination between two brief durations using two responses. The theory is similar to the Thomas and Weaver theory, both being multiple-component theories which make perceived duration a function of variables in addition to stimulus duration. Massaro and Idson point out some differences between their theory and that of Thomas and Weaver. Massaro and Idson state that discrimination increases as the difference in perceived duration of the two stimulus durations increases. Perceived duration begins to grow at stimulus onset and the rate of growth depends upon the duration of the stimulus. It is difficult to understand how that can be so, since the information necessary to set the rate parameter cannot be available to the system until after stimulus offset. For that reason and others, the present author cannot determine whether theirs is an interval-measure hypothesis or how their theory would apply to longer stimulus durations.

Hannes Eisler (1975) presents a theory of subjective duration which encompasses psychophysical scaling of duration and duration discrimination within the same framework. He states that duration discrimination depends upon a comparison of two subjective durations. Each subjective duration is the total accumulated content of a hypothetical sensory register which integrates over the time of the duration stimulus. This is in an

interval-measure hypothesis, and Eisler applies it to long and short durations.

2. When the stimulus set is symmetrical around its midpoint, errors are minimized when the criterion is placed at the midpoint. That is what subjects do, with great accuracy. If the set is made asymmetrical by, say, lengthening D_4 , then the midpoint between S_2 and S_3 should still control the placement of the criterion, providing S_1 and S_4 are both far enough from that midpoint to give error-free performance. Subjects can also do that with considerable success, but sometimes the asymmetry does have an effect upon the placement of the criterion. But even with a symmetrical set, the criterion can easily be shifted away from the midpoint by, for example, calling S_4 "long" and the other stimuli "short." The criterion is then placed between S_3 and S_4 . It is more accurate to say that "base duration" is the psychophysical criterion as measured for any particular combination of experimental conditions.

Experiments by Stubbs (1976) suggest the interpretation that when only two stimulus durations comprise the set, one much longer than the other, a criterion is established which falls near the geometric mean of the two durations, rather than at their midpoint.

3. The experiments reported in this paper demonstrate the real-time criterion mechanism only for relatively long stimulus durations. Whether brief durations can be discriminated in the same way remains to be determined.

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