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Psychophysical theories of duration discrimination*

LORRAINE G. ALLAN and A. B. KRISTOFFERSON
McMaster University, Hamilton, Ontario, Canada

There are few quantitative theories of duration discrimination and few established empirical phenomena to guide theorizing. This paper discusses three such theories and several empirical findings. The theories assume that the discrimination is based only upon information extracted from the temporal extent of the stimulus pattern, and experimental evidence is presented that clearly supports this assumption for many stimulus patterns. Recent findings which indicate that duration information is analyzed in certain ways that are fundamentally different from other stimulus dimensions are reviewed, the duration discrimination psychometric function is examined, and the time-order error is discussed. The three theories are compared in terms of their ability to incorporate the empirical data.

There are few quantitative theories of duration discrimination and few established empirical phenomena to guide theorizing. This paper summarizes the empirical findings and then discussed three such theories.

The theories are typical psychophysical theories in that they postulate an input process, a decision process, and a response process. In each case, the input process is thought of as one which takes a measure of the temporal extent of a stimulus pattern, compares the measure either to an internal standard or to the memory of a measure of a standard stimulus, and triggers a response, which may or may not be biased, depending on the outcome of the comparison process.

Stimulus patterns which differ in temporal extent differ in other ways as well, and the idea that the input process operates only on the temporal extent of the stimulus, and that no other useful input information influences the decision process, is always open to question. All three theories assume that the discrimination is based only on the temporal extent of the stimulus. Data are presented in the first of the following sections which clearly support this assumption for many stimulus patterns. Then recent findings that indicate that duration information is analyzed in a fundamentally different manner from other stimulus dimensions are reviewed, the time-order error in duration discrimination is discussed, and the discriminability function for duration discrimination is examined. The three quantitative theories of duration discrimination are then presented, and discussed in terms of their ability to incorporate the available data.

THE INFLUENCE OF ENERGY-DEPENDENT CUES ON DURATION DISCRIMINATION

Since duration has to be marked by energy signals, it is conceivable that the O bases his discrimination between two different durations on some aspect of the stimulus other than its duration. To be more specific, consider the task of discriminating between two brief flashes of light which differ in duration. Data from a number of psychophysical studies (e.g., Aiba & Stevens, 1964; Raab, 1962; Stevens & Hall, 1966; Stevens, 1966) have indicated that for stimuli whose durations are less than a critical duration, Os tend to label a brief intense flash of light as equal in apparent brightness to a longer, less intense flash. Furthermore, the data suggest that the relationship between luminance and duration is a reciprocal one, so that the apparent brightness of a flash does not change as long as the product of flash luminance and flash duration is constant. This reciprocal relationship is referred to as Bloch's law or the Bunsen-Roscoe law. The value of the critical duration depends upon the luminance of the flash and appears to decrease as a power function of luminance (Anglin & Mansfield, 1968). Thus, for durations where Bloch's law holds, it has been suggested that the visual system summates or integrates the light input without regard to its distribution in time.

Zacks (1970), however, has shown that, even though the detectability of brief light flashes depends upon the time-intensity reciprocity, the temporal and intensity information do not necessarily become individually unavailable. He showed that a 4-msec flash and an 81-msec flash, which were equated for total energy, were equally detectable, and that detection improved in the same manner for the two stimuli as energy level was increased (by increasing luminance). However, any pair of these equally detectable 4- and 81-msec stimuli could be discriminated at a level exceeding chance, discrimination performance improving as detectability increased. These data can be used to support the argument that equally detectable stimuli for which Bloch's law holds can be discriminated, the basis for discrimination being temporal.

Allan, Kristofferson, and Wiens (1971) demonstrated that discriminable changes in luminance had no systematic effect on duration performance. It could be argued that since changes in the duration of a brief flash result in changes in the apparent brightness of the flash, it is possible that when Os are asked to discriminate between brief flashes of different durations but of equal

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luminance, their discriminations are based on apparent brightness rather than duration. If the O is basing his discrimination on the difference in apparent brightness between a short stimulus, S_0, of duration d_0 and a long stimulus, S_1, of duration d_1, then decreasing the luminance of S_1 should result in decreased discriminability. However, if he is basing his discrimination on the difference in duration between the two stimuli, a decrease in the luminance of S_1 should not affect the discrimination between the two stimuli. Allan et al (1971) varied the luminance of S_1 (15, 13, or 11 fL) while keeping S_0 fixed at 15 fL. The duration of S_1 was always 120 msec, the duration of S_0 was 100 msec, and the difference in luminance between the two stimuli, ΔI, was constant during a session but varied between sessions. They found that the variations in discriminability as a function of ΔI were small for all five Os and not systematically related to changes in ΔI. Averaged over the five Os, the probability of a correct response, P(C), was .83, .83, and .84 for ΔI equal to 0, 2, and 4 fL, respectively. On the other hand, when both d_1 and d_0 were 100 msec, that is, when the difference in duration, Δd, was 0 msec, discriminability increased as a function of ΔI for all Os, indicating that the changes in ΔI were large enough to be discriminated. Averaged over four Os, P(C) was .52, .61, and .77. Thus, discriminable changes in the luminance of S_1 need not affect the duration discrimination function.

Nilsson (1969), using empty intervals bounded by 1-msec flashes of light, demonstrated that large variations in the luminance of both flashes, 50, 200, and 2,000 mL, did not affect discrimination performance for stimuli in the 0-75-msec range. Rousseau and Kristofferson (1973) have shown that large variations in the duration of a 50-fL light marker does not affect performance for stimuli in the 100-msec range. In their study, the onset of the empty interval to be judged was marked by a flash of light, the offset by a 500-msec, 2,000-Hz tone. Discrimination was essentially constant for light markers of 10, 500, and 4,000 msec.

Thus, the luminance of filled visual intervals in the 100-msec range (Allan et al, 1971), the luminance of visual markers of empty intervals in the 0-75-msec range (Nilsson, 1969), and the duration of a visual signal marking the onset of empty intervals in the 100-msec range (Rousseau & Kristofferson, 1973) appear to be unimportant in duration discrimination.

Duration discrimination studies using auditory stimuli have been somewhat more frequent, and while the results are not as consistent, in general they are in accord with the visual findings.

Abel (1972a) found that for auditory intervals filled with noise, a change in intensity from 85 to 65 dB did not affect discrimination performance for d_0 values of 5, 40, and 320 msec. Creelman (1962) also examined the effect of signal voltage on the discrimination of filled auditory intervals. In his experiments, a 1,000-Hz tone was presented in a wide-band white noise background of constant voltage. For d_0 equal to 100 msec, he found performance to improve with increases in tone voltage only at low signal-to-noise ratios, the dependence becoming negligible as the tones were made loud and clear above the noise background. It can be argued that at low voltages the O had difficulty in detecting the presence of the tone against the noise, and this of course would result in poorer discrimination performance. In another study, Creelman used two voltages and varied d_0 from 40 to 640 msec. He found an interaction between signal voltage and d_0. The difference in performance as a function of tone voltage was greater, the shorter the value of d_0. Again, this could be interpreted in terms of the O having more trouble detecting the low-voltage, short-duration tones than low-voltage, longer duration tones. This interpretation is consistent with results from studies which investigated the effect of stimulus duration on auditory detection performance (Green & Swets, 1966). On the basis of his data, Creelman concluded that "duration discrimination depends on sufficient intensity to mark the time unambiguously; it depends on detectability but not on loudness [p. 589]." Henry (1948) varied the amplitude of 500-Hz filled intervals for three values of d_0, 47, 77, and 277 msec. Four amplitudes were used, 20, 40, 60, and 80 dB. These variations in amplitude had little effect at any of the d_0 values, except for a tendency for somewhat poorer performance for the 20-dB, 47-msec stimulus. Again, this tendency was probably a result of decreased detectability of the low-amplitude, short-duration tone.

Thus, for auditory intervals filled with noise (Abel, 1972a) or pure tones (Creelman, 1962; Henry, 1948), changes in amplitude do not appear to affect discrimination performance for stimuli ranging in duration from 5 to 640 msec, as long as the stimulus whose duration is to be judged is easily detectable.

Abel (1970) varied the duration of 2,000-Hz markers of empty intervals from 4 to 16 msec for d_0 values in the range of 25 msec. She found these variations to have no systematic effect upon performance. In a later study, Abel (1972b) varied both the duration and the amplitude of noise burst markers for 11 d_0 values from .63 to 640 msec. Three different markers were used: (a) 10 msec, 85 dB; (b) 300 msec, 70 dB; and (c) 10 msec, 70 dB. She concluded that "when the amplitude of the marker is fixed at 70 dB, performance improves to some extent . . . as its duration is decreased from 300 to 10 msec [p. 522]." This is not at all clear from her data. The two functions relating discrimination performance to d_0 show considerable overlap. In fact, at four levels of d_0, there are reversals (performance was worse with the 10-msec marker than with the 300-msec marker). The probability of obtaining seven differences in the predicted direction out of a possible 11, if in fact there is no difference between the two conditions, is high (.274). The amplitude of the marker, on the other hand, did appear to be an important variable. Discrimination performance was better, for all values of

d_0 for the 10-msec, 85-dB markers than for the 10-msec, 70-dB marker. However, Carbotte and Kristofferson (1973) have shown that for d_0 equal to 50 and 250 msec, the amplitude of 10-msec, 2,000-Hz markers of empty intervals has little effect on performance. Three marker amplitudes were used, 61, 72, and 98 dB. Averaged over Os, the probability of a correct response for the 98-dB marker differed from that of the 61-dB marker by only .02 units. While for d_0 equal to 150 msec this difference was somewhat larger, .04 units, it was still small considering the large change in amplitude. Unfortunately, their data cannot be directly compared with Abel's amplitude data, since the two studies used different discriminability measures. It appears, however, that variations in discriminability as a function of amplitude are considerably less than in Abel's study, even though Carbotte and Kristofferson used larger variations in amplitude (61-98 dB vs 70-85 dB).

Thus, for empty auditory intervals, the duration of the marker does not affect discrimination performance for d_0 values from .63 to 640 msec (Abel, 1970, 1972b). Although, according to Carbotte and Kristofferson (1973), the amplitude of the marker has a negligible effect on performance, Abel's (1972a) data would indicate further research.

In summary, over a large range of d_0 values, for both visual and auditory stimuli, discrimination of filled intervals appears to be independent of the intensity parameters of the stimuli as long as they are easily detectable. Similarly, discrimination of empty intervals is independent of the temporal and intensity parameters of the stimuli that bound the interval to be judged. The only possible exception to this, so far as is known, is the amplitude of the markers of empty auditory intervals. The available data suggest that a model for duration discrimination should represent the O as basing his decision on the temporal information available in the stimulus.

COMPARISON OF DURATION DISCRIMINATION DATA WITH DATA FROM OTHER PSYCHOPHYSICAL DISCRIMINATION TASKS

Our investigations have led us to the conclusion that there are at least two important ways in which duration discrimination differs from discriminations along other stimulus dimensions. It is well established that in many discrimination tasks involving the sequential presentation on the same trial of the two stimuli to be compared, the temporal interval between the two stimuli is an important variable, discriminability decreasing as the interval is lengthened. For example, Kinchla and Smyzer (1967) and Tanner (1961) have shown this effect for loudness discrimination, Bull and Cuddy (1972) and Moss, Myers, and Filmore (1970) for pitch discrimination, Kinchla and Allan (1969, 1970) for visual movement discrimination, and Allan (1968) for spatial position discrimination. A number of quantitative "memory" models to account for decreased discriminability with increasing interstimulus interval (ISI) have been proposed (Kinchla & Allan, 1969; Massaro, 1970; Wickelgren, 1969).

Results from comparable duration discrimination studies do not show such an effect. Allan, Kristofferson, and Rice (1974) varied the ISI in a forced-choice duration discrimination task, with the intervals being defined by brief visual dark flashes. A light was continuously on, except during the interval whose duration was to be judged. They found that varying the ISI from 500 to 2,000 msec had no effect on discrimination performance for d_0 equal to 50 msec. Averaged over three Os, the probability of a correct response, P(C), was .75, .77, .74, and .73 for Δd equal to 10 msec, and .94, .94, .92, and .95 for Δd equal to 30 msec, for ISI equal to 500, 1,000, 1,500, and 2,000 msec, respectively. Similar results were found for light flashes for d_0 equal to 100 msec and Δd equal to 20 msec (Allan et al, 1974). Averaged over three Os, P(C) was .84, .86, .86, and .85 for ISI equal to 500, 1,000, 1,500, and 2,000 msec, respectively. Small and Campbell (1962), using filled auditory intervals, found that ISIs of 5, 200, 800, and 3,200 msec had no effect on performance for duration stimuli in the 400-msec range. As stimulus duration was shortened (40, 4, and .4 msec), the shorter values of ISI (5 and 200 msec) resulted in a *decrement* in discriminability relative to the constant discriminability level at the longer values.

One possible explanation of the absence of a decrement in discriminability with increasing ISI is that the O actually ignores one of the stimuli on each trial. Variations in ISI would therefore be an ineffective variable. It has often been suggested in the literature (for example, Harris, 1952; Bull & Cuddy, 1972) that a "roving-standard" design increases the likelihood that the O makes a comparative judgment on each trial. Carbotte (1973) examined the relationship between duration discrimination performance and ISI, making use of the roving-standard design. Two empty intervals bounded by 10-msec, 2,000-Hz pulses were presented on each trial. Six values of ISI (0, 125, 250, 500, 1,000, and 2,000 msec), four values of d_0, ranging between 115 and 250 msec, and one value of Δd were used. During a session, ISI was constant and d_0 was varied, the four values occurring with equal frequency in each block of trials. Carbotte's results are similar to those of Small and Campbell (1962). Variations in ISI from 500 to 2,000 msec had little effect on performance. For ISIs less than 500 msec, performance is disrupted relative to the fairly constant level for ISIs greater than 500 msec.

It appears that the processing of duration information differs in some fundamental way from the processing of other sensory information (amplitude, pitch, movement, position). Lengthening the temporal interval between the two stimuli to be compared does not produce a decrement in discriminability. This is the case for dark flashes, light flashes, empty auditory intervals, and filled auditory intervals. Manipulation of ISI over the same range of values does produce a decrement in other psychophysical discrimination tasks.

The other important way in which we know duration discrimination data to differ from other psychophysical data is in the relationship between forced-choice (FC) and single-stimulus (SS) performance. A SS discrimination task involves the presentation of one of two possible stimuli, S_1 or S_0, on each trial and the requirement that the O indicate which stimulus was presented. A FC discrimination task involves the sequential presentation of the two stimuli on each trial—either S_1 followed by S_0 or S_0 followed by S_1—and the requirement that the O indicate the order in which the stimuli were presented. Green and Swets (1966) have presented data from a number of detection studies which clearly indicate that performance in a FC task is superior to that in a SS task. Viemeister (1970) compared loudness discrimination performance from a SS task and a FC task and found FC to be superior. In general, current psychophysical models predict better performance in a FC task than in a SS task (for example, Green & Swets, 1966; Kinchla, 1969; Kinchla & Allan, 1969).

Two duration discrimination studies have been reported in the literature which did not observe this differential performance. Allan et al (1974), using brief dark flashes, tested three Os with the FC paradigm and three with the SS paradigm. Two values of d_0 were used, 50 and 100 msec. On the average, there was little difference in performance between the two tasks. In that study, the absence of a difference in performance between the two tasks could be interpreted as resulting from using two groups of three different Os. However, Carbotte (1973), using empty auditory intervals and two d_0 values, 150 and 250 msec, found no systematic difference in discriminability between the two tasks when the same three Os were tested under both tasks.

These data suggest to us that a viable model for duration discrimination will differ in some fundamental aspects from current psychophysical models which predict an ISI effect, and better FC than SS performance.

THE TIME-ORDER ERROR IN DURATION DISCRIMINATION

For historical reasons, no discussion of duration discrimination would be complete without the inclusion of the time-order error. In the FC paradigm, for any set of d_1 and d_0 values, there are two possible stimulus sequences on any trial, S_1S_0 or S_0S_1. Thus, there are two types of correct responses:

$$P(R_{10} \mid S_1S_0)$$

$$P(R_{01} \mid S_0S_1),$$

where R_{10} denotes a long-short response and R_{01} a short-long response. The early systematic investigations of duration discrimination (e.g., Blakely, 1933; Stott, 1933, 1935; Woodrow, 1935, 1951; Woodrow & Stott, 1936) were mainly concerned with the effect of the order of presentation of the two duration stimuli upon comparative judgments. These studies often found that for durations briefer than a critical duration, d_c, $P(R_{10} \mid S_1S_0) > P(R_{01} \mid S_0S_1)$, the difference between the two conditional probabilities decreasing as the stimulus durations approach d_c, where d_c is referred to as the time-order indifference duration. For durations longer than d_c, the difference is in the opposite direction, $P(R_{01} \mid S_0S_1) > P(R_{10} \mid S_1S_0)$, the difference becoming larger as stimulus durations increase. The difference in magnitude between the two conditional probabilities is referred to as the time-order error. It should be noted that in duration discrimination interest has been in the relationship between stimulus duration and the relative size of the two conditional probabilities. In other discrimination tasks (for example, brightness, amplitude, weight), the time-order error function has been identified with the relationship between ISI and the relative size of the two conditional probabilities. It has often been found that $P(R_{01} \mid S_0S_1) > P(R_{10} \mid S_1S_0)$, the difference increasing as ISI is increased (Woodworth & Schlosberg, 1954).

The basic interpretation of the time-order error in duration discrimination offered by Blakely, Stott, and Woodrow was that the perceptual or internal duration of the first stimulus gravitated towards the value of d_c during the ISI. Thus, for duration values briefer than d_c, the effective difference in duration would be greater when S_1S_0 was presented than when S_0S_1 was presented, resulting in larger values of $P(R_{10} \mid S_1S_0)$ than of $P(R_{01} \mid S_0S_1)$. For duration values longer than d_c, the effective difference in duration would be greater when S_0S_1 was presented, resulting in larger values of $P(R_{01} \mid S_0S_1)$ than of $P(R_{10} \mid S_1S_0)$. These investigators found that as they accumulated more data their explanation of the time-order error had to be elaborated. The distinguishing feature of the various explanations was that the phenomenon was a perceptual or sensory one. The effective difference in duration between the two stimuli was the important determinant.

Kinchla and Allan (1969) and Kinchla and Smyzer (1967) suggested that the time-order error in amplitude and in movement discrimination could be conceptualized as a response preference or response bias phenomenon rather than a perceptual one. This is true also in duration discrimination. While no direct tests of these alternative explanations have been conducted, the perceptual interpretation of the time-order error has difficulty incorporating the data reported by Allan et al (1974), Carbotte (1972), and Creelman (1962). In essence, these studies indicate that the relationship between the two conditional probabilities appears to be O-dependent rather than duration-dependent. For the same duration values, for some Os there is no difference between $P(R_{10} \mid S_1S_0)$ and $P(R_{01} \mid S_0S_1)$, for some $P(R_{10} \mid S_1S_0) > P(R_{01} \mid S_0S_1)$, and for others $P(R_{10} \mid S_1S_0) < P(R_{01} \mid S_0S_1)$.

A model of duration discrimination must provide for unequal conditional probabilities in the FC task, but such provision need not be made in the conceptualization of the input process.

RELATIONSHIP BETWEEN DISCRIMINABILITY AND d_0

A successful model for duration discrimination will have to predict the manner in which discriminability changes as a function of stimulus duration. It is well established that our intuitions are correct, namely, that for a given difference in duration, discriminability decreases as d_0 increases. However, the nature of this function is not established, and it is not possible to create it from the existing literature because of the variety of discriminability measures and psychophysical paradigms that have been used. One fact is clear. Weber's law does not hold (e.g., Abel, 1972a, b; Allan et al, 1971; Allan & Kristofferson, 1974b; Blakely, 1933; Creelman, 1962; Kristofferson, 1973; Rousseau & Kristofferson, 1973; Small & Campbell, 1962; Stott, 1933). Discriminability is not constant for a constant $\Delta d/d_0$ ratio. The accepted generalization is merely that discriminability is a monotonic decreasing function of d_0.

Allan et al (1971) reported data which even question the existing generalization that discriminability is a monotonic decreasing function of d_0. Visual duration discrimination data were presented which clearly demonstrated that for six of the nine Os discriminability for two values of d_0, 50 and 100 msec, did not differ, for two Os performance was slightly better for d_0 equal to 50 msec, and for the remaining O performance was consistently superior for d_0 equal to 100 msec. More recently, Allan and Kristofferson (1974b) have reported light-flash data for duration stimuli from 70 to 1,020 msec. Again, the data clearly indicate that discriminability is not a monotonic decreasing function of d_0. Discriminability remains constant over large variations in stimulus duration. Kristofferson (1973) has presented similar data for empty auditory intervals ranging from 100 to 1,600 msec, and Rousseau and Kristofferson (1973) for empty intervals, marked by a light at the onset and a tone at the offset, for d_0 values from 100 to 2,000 msec. In the Rousseau and Kristofferson study, discriminability was constant over the complete range of d_0 values.

In summary, our investigations of the discriminability function for light flashes, empty auditory intervals, and empty intervals bounded by a light at the onset and a tone at the offset indicate that variations in stimulus duration do not always affect discriminability. Discriminability often remains constant over wide ranges of d_0 values.

Kristofferson (1973) and Allan and Kristofferson (1974b) have presented data which help to resolve the apparent contradiction between their results and duration discrimination results from other laboratories. In essence, we have found the amount of practice an O has with a particular set of duration values to be a critical variable. Inexperienced Os always yield functions which show discriminability to be a monotonic decreasing function of stimulus duration. Highly practiced Os often yield functions which show discriminability to remain constant over certain ranges of duration values.

QUANTITATIVE MODELS FOR DURATION DISCRIMINATION

Three *quantitative* models have been developed which describe performance in situations which require judgment about stimuli which differ in duration. These models all assume that the O bases his decision on the available temporal information rather than on other cues, such as brightness or loudness, which may sometimes be available.

Creelman's Model

Creelman (1962) developed the first quantitative model for duration discrimination. The model represents the O as using a mechanism which accumulates pulses during the duration to be judged. The source of the pulses is viewed as a large number of independent elements, each with a fixed probability of firing at any given moment. The distribution of pulses associated with a stimulus of duration d_i msec can be approximated by a normal distribution with mean and variance equal to λd_i, where λ is a *constant* representing the rate of firing of the pulse source. Thus, both the variance and the mean value of the internal duration of a stimulus increase in direct proportion to the duration of the stimulus.

Creelman developed his model to account for data from a FC duration-discrimination task. He assumed that on each trial the O compared the number of pulses obtained during the two durations by subtracting the number produced by the second stimulus from the number produced by the first stimulus. If the first stimulus is the longer one (d_1), the comparison process results in a normal distribution of differences with mean $\lambda\Delta d$. Alternatively, if the first stimulus is the shorter one (d_0), the comparison process results in a normal distribution of differences with mean $-\lambda\Delta d$. In both cases, the variance is $\lambda(2d_0 + \Delta d)$. He assumed that the O adopted a criterion difference in number of pulses, and if the observed difference was greater than this criterion that he responded that the long stimulus occurred first.

Creelman did not discuss the decision process for the SS paradigm in terms of his model. If the signal detection decision process is assumed (Green & Swets, 1966), then in the SS case the O could be represented simply as adopting a criterion number of pulses. If the observed number of pulses on a trial is greater than this criterion, the O responds long.

The Creelman model predicts that an O's ability to discriminate between two durations depends on the duration values used as well as on the difference between the two durations. Specifically,

$$d'_{SS} = \frac{\lambda^{1/2}\Delta d}{d_0^{1/2}}$$

$$d'_{FC} = \frac{2\lambda^{1/2}\Delta d}{(2d_0 + \Delta d)^{1/2}},$$

where d'_{SS} denotes a criterion-free discriminability measure for the SS task, and d'_{FC} for the FC task.[1] Thus, the model specifies that, for

$$\Delta d < 2d_0,$$

discriminability in a FC task should be better than in a SS task. Specifically,

$$\frac{(d'_{FC})^2}{(d'_{SS})^2} = \frac{4d_0}{2d_0 + \Delta d}.$$

Note also that the model predicts that for both SS and FC, d' is a monotonic decreasing function of d_0, when d_0 is increased and Δd held constant.

Creelman (1962) reported data from a FC duration discrimination task using filled auditory intervals as stimuli. On each trial, two successive tones which differed in duration were presented. The study was quite extensive and Creelman concluded that under some conditions that model provided a reasonable interpretation of the data.

The first duration-discrimination data we reported (Allan et al, 1971) were not in agreement with the predictions of the Creelman model. In that study, we used the on-period of a light to indicate the stimulus duration, the SS task, and duration values between 50 and 150 msec. We found, through an analysis of operating characteristic (OC) curves, that our data did not support the unequal variance assumption of the Creelman model. As well, the data were not in agreement with the predicted function relating d'_{SS} to d_0. Since then, we have reported data from many studies, both SS and FC, using light flashes, dark flashes, empty auditory intervals, and empty bimodal intervals, which do not support the Creelman model (Allan & Kristofferson, 1974b; Carbotte, 1972; Kristofferson & Allan, 1973; McKee et al, 1970; Rousseau & Kristofferson, 1973). The model does not account for the observed relationship between d' and d_0, or for the obtained similarity in FC and SS performance.

Abel (1972a, b) has argued that her data, from a FC task using filled and empty auditory intervals, were in agreement with the predictions of Creelman's model, for some values of d_0. The Creelman model specifies that λ remains constant with variations in d_0. For empty intervals (1972b), she concluded that "for any marker condition, λ is relatively constant for values of T ranging between 10 and 320 msec [p. 524, where T is equivalent to d_0 in the present paper]." However, her Fig. 2 clearly shows a large and fairly consistent change in λ as a function of d_0 for all three markers. For example, for the 10-msec, 85-dB marker, λ decreases from about 400 counts/sec to 150 counts/sec for a change in d_0 from 10 to 320 msec. For filled intervals, Abel (1972a, p. 1223) concluded that "λ is fairly constant . . . for values of T ranging from .16 to 80 msec." Again, Fig. 2 in her paper shows fluctuations in λ over the range, in the order of 350 counts/sec. Unfortunately, the sampling distribution of λ is not specified by the Creelman model, and therefore it is not possible to demonstrate statistically whether the fluctuations in λ are greater than those expected by sampling error.

On the basis of the available duration discrimination data, we have concluded that any decision theory model which predicted a monotonic increase in variance as a function of duration would be unable to account for much of the available data.

Quantal Counting Model

A number of theoretical formulations concerned with temporal factors in perception have postulated that internal time is quantized (for example, Stroud, 1955). Our first attempt at a quantitative model for duration discrimination, the quantal counting model, had as its basic postulate that internal time is quantized (Abel, 1970; Allan, Kristofferson, & Wiens, 1970; Carbotte & Kristofferson, 1971; McKee et al, 1970). The quantal counting model is a specific application of Kristofferson's (1967, 1970) time quantum theory. The time quantum theory postulates that the processing of some aspects of temporal information is under the control of an internal timing mechanism which generates a succession of equally spaced points in time. These points occur at the rate of one every q msec and are independent of the presentation of the external stimulus. The quantal counting model states that stimulus duration is transformed into internal duration by means of this timing mechanism. It is hypothesized that the internal duration produced by a stimulus duration is obtained by counting time points. If a stimulus of duration d_i msec is presented,

$$xq \leqslant d_i \leqslant (x + 1)q,$$

where x is a nonnegative integer, then x time points will be counted with probability P(x), and (x + 1) time points will be counted with probability [1 − P(x)], where

$$P(x) = \frac{(x + 1)q - d_i}{q}.$$

Thus, the quantal counting model specifies that internal time is quantized and exists only in multiples of the quantum.

The quantal counting model can be viewed as a discrete state psychophysical model. The relationship between the internal state of duration and the overt response will depend upon the O's response bias or decision strategy. A variety of possible decision strategies have been considered in conjunction with the quantal counting input process and theoretical psychometric functions determined.

We have found that the simple counting mechanism postulated by the quantal counting model has had difficulty accounting for various aspects of the duration discrimination data which we have accumulated in our laboratory (Abel, 1970; Allan et al, 1970; Carbotte, 1972; Carbotte & Kristofferson, 1971; McKee et al, 1970). The predicted discriminability functions for variations in d_0 and in Δd, and the predicted relationships between SS and FC performance are generally not in accord with the observed data.

Onset-Offset Model

Allan et al (1971) proposed a decision theory model to account for the SS light flash data reported in that paper. The model states that, over a range of duration values, the variability in internal durations, which is produced by repeated presentations of a stimulus of fixed duration, is independent of stimulus duration. The model specifies that all the variability in the internal durations is the result of variation in the times, with respect to stimulus time, at which the internal durations begin and end. For any stimulus duration, d_i, the perceptual onset and offset latencies are each independently uniformly distributed over a range of q msec. This results in a triangular distribution of internal durations, $f_i(I)$, spanning 2q msec, which has a mean equal to thephysical duration of the stimulus and a variance $(q^2/6)$ which is independent of stimulus duration.

The O is represented as adopting a criterion internal duration and comparing the internal duration on each trial to this criterion. If the internal duration generated by stimulus duration d_i is greater than the criterion, he responds long; otherwise, he responds short. The model predicts that an O's ability to discriminate between two stimulus durations depends only on the difference between the two durations and is independent of their durations. Specifically,

$$d_{q,SS} = \frac{\Delta d}{q},$$

where $d_{q,SS}$ denotes a criterion-free discriminability measure for the SS paradigm.

Allan et al (1971) reported that the OC curves generated from the data of three of the Os indicated that the internal durations evoked by a brief light flash can be approximated by a triangular distribution whose variance is independent of the duration of the flash. In general, d_q was directly proportional to the duration difference between the two stimuli, and for six of the nine Os was independent of stimulus duration, for the range of durations used (50 to 150 msec). For these Os, the data were adequately described by assuming variability, and therefore q, to be independent of Δd and d_0. The light flash and empty auditory interval data we have reported since then (Allan & Kristofferson, 1974b; Kristofferson, 1973) cover a much larger range of duration values, 70 to 2,000 msec. These data also indicate that the distribution of internal durations can be closely approximated by the triangular distribution, that the means of these distributions are directly proportional to stimulus duration, and that the variability is constant over very large variations in stimulus duration.

Taking into consideration the lack of an ISI effect and the similarity between FC and SS performance, Kristofferson and Allan (1973) and Allan and Kristofferson (1974a) proposed the response comparison decision process for the FC task. They suggested that the O adopts a criterion internal duration, C, and makes an independent decision after each stimulus presentation. His response on each trial is then based on these two decisions. Such a decision process yields the prediction that for a fixed criterion, SS and FC psychometric functions should be identical. Specifically, for equal stimulus presentation probabilities

$$P(C) = \tfrac{1}{2}\left[\int_C^{d_1+q} f_1(I)dI + \int_{d_0-q}^{C} f_0(I)dI\right].$$

The shape of the psychometric function depends upon the placement of the criterion, but *not* upon the paradigm, SS or FC. These functions are described in detail by Allan and Kristofferson (1974a). The response comparison decision process is also compatible with the lack of an ISI effect. The length of the temporal separation between the two durations to be compared is unimportant as long as the O has enough time to make a decision about the duration of the first stimulus.

SUMMARY AND CONCLUSIONS

The three theories of duration discrimination discussed in this paper assume that the discrimination is based only upon information extracted from the temporal extent of the stimulus pattern. The experimental evidence clearly supports this assumption for many stimulus patterns which are typically employed in duration experiments. But it is likely that there are duration stimuli for which the assumption does not hold, and it must be reconsidered for each new experiment.

We have found duration discrimination to differ from discriminations along other sensory continua in that forced-choice performance is not superior to single stimulus performance and discriminability between two signals does not deteriorate as the interval between the stimuli is increased. We have also consistently found an O's ability to discriminate a constant difference in duration to be independent of the duration values over wide ranges of duration values.

The available evidence favors the onset-offset model proposed by Allan et al (1971). The model, however, has to be elaborated to account for the duration discrimination function over the entire range of durations. Two directions for future research are clear. It is important to establish the manner in which variability changes with variations in stimulus duration. Over what ranges of durations is the variability constant? Does the size of the range change as one moves from very brief stimuli to longer stimuli, and by how much does the variability change when it does change? We are presentedly engaged in attempts to answer these questions for a variety of duration markers.

In our original model, we specified that all of the variability in the internal durations was the result of variability in the perceptual onset and offset latencies, and that the variability in these latencies was independent of stimulus duration. This independence appears to be true over a large range of stimulus durations. However, the dependence that is observed as one moves from one stimulus range to another would imply that the variability in the perceptual onset latency is a function of stimulus duration. This is not a very likely possibility. An alternative is to postulate that the variability represented by the triangular distribution is part of the criterion mechanism. We are pursuing that alternative, among others.

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NOTE

1. The formula for d'_{FC} printed in Creelman (1962) is incorrect.

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ERRATUM

HERRICK, R. M. Foveal light-detection thresholds with two temporally spaced flashes: A review. Perception & Psychophysics, 1974, 15, 361-367–The note that appears on p. 367 contains a production error. The complete note should correctly read: "1. Actually, only in an earlier study (Bouman & Van den Brink, 1952) did they present p vs i plots. Most of their data were presented in plots employing an index based on p. The index has a value of 1.0 when the two flashes occur simultaneously, and 0.0 when the two flashes were widely separated in time. Bouman & Van den Brink's index may be written as follows: Index = $-[P_\infty/(P_o - P_\infty)] + [1/(P_o - P_\infty)]p$, where P_∞ is the probability of a "Yes" with two flashes separated by a very long interval, P_o is the probability of a "Yes" with two flashes at zero interval, and p is the probability of a "Yes" with two flashes at a particular interval. For the data of any one session, P_o and P_∞ are constants, and the equation relating the index and p is simply the equation of a straight line, with an intercept of $-[P_\infty/(P_o - P_\infty)]$ and a slope of $[1/(P_o - P_\infty)]$.