The latencies of correct and incorrect responses in discrimination and detection tasks: Their interpretation in terms of a model based on simple counting

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A model for two-choice discrimination based on a process of simple counting is described, and two experiments are performed to test the predictions of the model concerning the graph of latency as a function of response proportion. Two main forms of this graph are identified and predicted to arise in different circumstances. The experimental results support the model, and its possible extension to other psychophysical situations, especially signal detection, are then discussed. It is compared with a model derived directly from the detection situation, and the usefulness of testing these models is pointed out.

It is evident that response latencies in discrimination and detection tasks are of considerable importance in the assessment of associated theoretical models. For example, the relevance of latency is intrinsic to the evaluation of stochastic models of choice behavior (e.g., Stone, 1962; Estes, 1960; Atkinson et al, 1965), and an awareness of the latency-accuracy trading relationship in choice times reflects the influence and validity of the decision theory approach (e.g., Coombs, 1964; Snodgrass et al, 1967). In the field of signal detection, there are indications that the features of latency may be accounted for by an extension of the classical signal detection model (Gescheider et al, 1969), thus affording a wider assessment of detection theory. One prominent measure of latency data in choice tasks is the quantitative difference between correct and incorrect responses. This tends to differ with particular tasks: in choice reaction time, it appears that correct response latencies are, on the average, longer than incorrect latencies, and attempts have been made to use or explain this fact by theoretical arguments (e.g., Laming, 1968); in psychophysical discrimination (e.g., the judgment of which of two stimulus intensities is the greater) the opposite appears to be the case, so that correct mean latencies are shorter, at least when the discrimination is difficult (Kellogg, 1931; Pike, 1968); with detection tasks the matter may depend upon whether S + N or N is presented (Carterette et al, 1965). In this paper a particular stochastic model of the "random walk" type (cf. Atkinson et al, 1965; Audley & Pike, 1965; Laberge, 1962) will be examined for its ability to account for latency features in difficult two-choice discrimination, and a preliminary comparison will be made with a model derived from signal detection theory.

The main criterion to be used in this analysis is that of the form of the graph giving mean latency (L) for correct and incorrect responses as a function of their response frequencies (P) for each level of difficulty of discrimination. If correct and incorrect mean latencies are plotted against proportion correct (P = c) and incorrect (P = 1 − c), respectively, then the axis P goes from 0 to 1 and a range of conditions of discrimination difficulty will generate pairs of points on the LP graph. Each incorrect mean latency has a P value of from 0 to 0.5 and each correct latency of from 0.5 to 1. For earlier uses of the graph, see Luce (1960) or Laberge (1962) where the P axis is referred to as response probability. The mean latencies are best expressed as proportional to the latency at P = 0.5 since the graphs are then standardized for comparison between Ss and models (e.g., see Fig. 1). Note that accuracy is zero at P = 0.5 and increases as the pair of points for correct and incorrect responses diverge to P = 1 and 0, respectively. The curve will, in general, be asymmetrical since the mean latencies for correct and incorrect responses will not, in general, be equal.

THE ACCUMULATOR OR COUNTING MODEL

The model will be described only for the case of two choices. The extension to more than two choices is straightforward, although the expressions involved become more complicated and the theoretical LP curve would not be so simply described in terms of correct and incorrect responses. First, a description is given in terms of a process which changes its state in each discrete time interval, so that the total time to a response in each "trial" is the sum of a number of equal time intervals. This is typical of most "random walk" models (Atkinson et al, 1965).

Suppose the two overt responses are A and B. Then the model supposes that associated with these will be covert counting or accumulating processes, C(A) and C(B), respectively, such that C(A) will count covert predecisional events a and C(B) will count covert predecisional events b. These events, a and b, are otherwise undefined but will occur with probabilities p and $q = 1 - p$, respectively, so that in each time interval either a or b, but not both, will occur and be counted. The probabilities p and q may be related to the discrimination difficulty, and $p > 0.5$ will be associated with the correct response, A. An overt response will occur when k events of one kind, a or b, have been counted so that response A occurs if C(A) counts k events a before C(B) counts k events b. The first time interval will begin at stimulus onset, but the duration of each interval is a parameter which is of no consequence in determining the shape of the LP graphs in proportional form.

Given the above postulates and assuming counting commences at stimulus onset and an overt response ensues immediately a count of k occurs, then the range of response latency is from k to $2k - 1$ time intervals. The probabilities of correct and incorrect responses occurring at time t are:

$$\mathrm{Prob}(t = k + v) = p^k \binom{k + v - 1}{v} q^v = P(v)$$

for the correct response, and

$$q^k \binom{k + v - 1}{v} p^v = Q(v)$$

for the incorrect response. Then the overall probabilities of the two overt responses are

$$\sum_{v=0}^{k-1} P(v) \text{ and } \sum_{v=0}^{k-1} Q(v),$$

and the mean times to a response may be given as the expected values, i.e.,

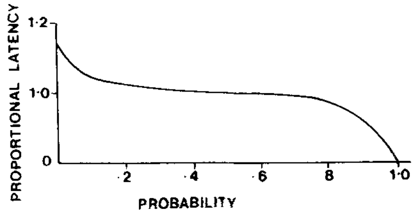

Fig. 1. Theoretical latency-probability function for the counting model. Type A—when the value of k is constant.

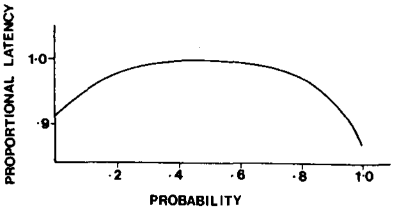

Fig. 2. Theoretical latency-probability function for the counting model. Type B—when the value of k varies from trial to trial.

$$\sum_{v=0}^{k-1} (k + v)P(v) \Big/ \sum_{v=0}^{k-1} P(v)$$

and

$$\sum_{v=0}^{k-1} (k + v)Q(v) \Big/ \sum_{v=0}^{k-1} Q(v)$$

for correct and incorrect responses, respectively. Thus the two LP points for any value of p and k may be obtained, and a range of these values generates the theoretical LP curve. For the case of k constant throughout a series of "trials," the LP curve will be similar to that of Fig. 1 (Type A), and, in proportional form, the shape is very nearly identical for all values of k. It should be noted that correct responses are always shorter than incorrect. As k increases for a given value of p, both latencies also increase and so does the probability of a correct response.

If the value of k is allowed to vary from trial to trial, the following will generally be the case. When k is at its higher values, then the latencies are at their longest and the probability of a correct response is greater. When k is at its lowest values, the reverse holds. Over a series of trials, these effects combine to produce a decrease in the difference between correct and incorrect latencies, and, given sufficient variation in k, the incorrect latencies will become shorter than correct latencies. In general, the LP curve will now tend to become as shown in Fig. 2 (Type B).

Two similar forms of LP curves may also be produced if response bias exists. This may be described in terms of the model by having constant but unequal values of k for the two responses. For example, if some implicit preference for "right" responding existed, then this "dominant" response would have a lower k value than the "nondominant" response. In this case, separate LP curves may be drawn for dominant and nondominant responses, and the dominant curve will be Type B and the nondominant Type A, the extent of the difference in shape depending upon the amount of bias. The dominant response will, of course, have an observed response frequency greater than the nondominant frequency.

The above description in terms of discrete time intervals may be modified to account for a process in which events a and b occur in nondiscrete or random fashion (Pike, 1968). However, the results concerning comparative mean latencies and response probabilities remain the same, and hence, the LP graphs are not altered.

The continual decrease of the Type A curve from P = 0 to P = 1 is a particularly important feature of the model, since other random walk models predict that for low values of P (i.e., incorrect responses associated with less difficult discrimination) the latencies are faster than for P = 0.5 (Pike, 1968). A model derived from signal detection theory which also predicts the Type A LP curve will be discussed later. The two forms of curves derived from the counting model are predicted by two different situations. The Type A would be expected in a task where Ss' response criteria are stable and constant, such as may be expected with well-practiced Ss but particularly with Ss who are quite sure of the criterion in terms of speed vs accuracy. It is these latter two response characteristics which are largely controlled by the values of k. Conversely, the Type B curve would be expected in tasks in which Ss were uncertain as to response criterion, such as may occur when ambiguous instructions are given concerning speed and accuracy, and Ss thus tended to fluctuate from trial to trial in their subjective emphasis on these.

Experiment 1 was originally performed to assess the validity of different kinds of stochastic model for discrimination behavior (Pike, 1967). The accumulator model appeared to fit the data best, and the results from other work (e.g., Kellogg, 1931) also supported the model. Experiment 2 was subsequently performed to investigate the situation where Ss were uncertain as to whether speed or accuracy of response was required, and

Table 1
Summary of Response Frequencies (f) and Mean Latencies (m) for Differing Degrees of Difficulty of Discrimination

	f	m	f	m	f	m	f	m	f	m
	Ratio of Spatial Extents Being Discriminated									
S 1	76:80		77:80		78:80		79:80		80:80	
Correct	118	3.04	184	3.22	174	3.97	129	4.48	51	4.8
Incorrect	1	5.20	13	4.62	23	4.63	70	4.60	49	4.36
S 2	99:101		62:63		497:503		249:251		1:1	
Correct	670	1.55	365	1.68	180	1.63	133	1.74	78	1.61
Incorrect	134	1.71	144	1.72	76	1.64	75	1.76	50	1.68
S 3	99:101		62:63		497:503		1:1			
Correct	768	2.91	234	3.54	105	3.26	81	3.54		
Incorrect	149	3.27	66	4.10	47	3.47	48	4.07		
S 4	99:101		1:1							
Correct	655	8.45	176	9.15						
Incorrect	156	11.90	100	9.8						
S 5	99:101		1:1							
Correct	450	2.65	84	3.18						
Incorrect	128	3.16	56	2.97						
	Ratio of Single Stimulus to Standard									
S 6	76:80		77:80		78:80		79:80		80:80 (Standard)	
Correct	451	1.18	350	1.25	322	1.28	239	1.30	46	1.25
Incorrect	56	1.45	114	1.43	112	1.45	129	1.36	36	1.30
S 7	76:80		77:80		78:80		79:80		80:80	
Correct	104	1.15	188	1.30	174	1.28	103	1.30	30	1.28
Incorrect	24	1.46	69	1.32	70	1.35	62	1.35	15	1.35

Note—Latencies are in seconds. The table is in summary form, e.g., data for alternative stimulus presentations (e.g., larger on right or left) are combined.

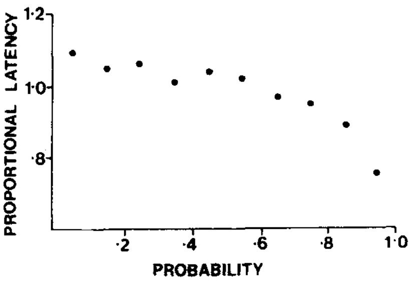

Fig. 3. L-P graph for seven Ss combined. Latencies are averaged within intervals of P of 0.1, and the average points placed at midintervals.

consequently, the Type B LP curve is predicted.

EXPERIMENT 1

Method

The task of discrimination of judging spatial extent was performed over a range of difficulty of discrimination with differing ranges for different Ss (see Table 1). Seven Ss were presented with either two adjacent extents for simultaneous comparison or one extent for single stimulus judgments. The spatial extents were marked by either the two intervals between three small spots of light or, in the single stimulus case, the space between two spots, in both cases in a dark background. Ss were required to press one of two response keys indicating whether the larger extent was judged right or left or, for single stimuli, whether the stimulus was judged smaller or larger than the average. Response latencies were recorded and grouped for each level of difficulty.

Apparatus and Procedure

The stimulus light spots were at one end of a viewing tunnel 30 in. in length and of rectangular dimensions 6 x 4 in.; the stimuli were white spots on black slides behind which was a light source. The stimulus variable, spatial extent, was changed between trials by having the slides fixed to the outer part of a large rotary disk, easily controlled manually. The standard stimulus was 1 in. (i.e., distance between spots), and there were two variable ranges, as given in Table 1. Stimuli were randomized with respect to position (i.e., largest extent right or left) and to presentation within sessions of 60 trials. More of the easier discriminations were presented to obtain sufficient incorrect responses at these levels. Ss viewed the stimuli binocularly through the tunnel.

The Ss were instructed to respond by making a careful judgment, without any haste and with accuracy being emphasized. The response was made by pressing the key on the side judged "larger" or, in the single stimulus case, the key for the "larger" or "smaller" judgment. Ss were informed that the possible responses were correct with equal probability. The experiments took place in a semidark room so that through the tunnel only the spots could be observed when the light source was on. An auditory warning signal occurred 2 sec before the stimulus spots came on, and the response time was measured from stimulus onset until the keypress. Ss were given at least 60 training trials initially and 20 practice trials with each session in order for response latencies to level off, which appeared to be the case. Information of performance in terms of numbers of incorrect was given on completion of each session. Each S received a fairly large number of trials (see Table 1), two Ss receiving both the simultaneous and the single stimulus conditions (S 2 and S 6 are the same individual and so are S 4 and S 7).

Results and Discussion

The mean latencies for correct and incorrect responses for each level of difficulty are given in Table 1 for each S. The LP graph combined for all Ss is drawn in Fig. 3 and was derived in the following manner.

For each S, mean latencies were put into proportional form by calculating the latency for P = 0.5 by interpolation from his graph in raw latency form. These proportional mean latencies were then averaged over Ss for intervals of P of 0.1 to obtain the points of Fig. 3. It is assumed that this is a valid procedure insofar as the total graph of proportional LP points shows a well-defined curve, which Fig. 3 reflects in a direct manner. The simultaneous and successive comparison data are combined, since there are no obvious differences in the separate graphs. LP curves are similarly and separately drawn for the dominant and nondominant responses in Fig. 4. Dominance differed with respect to "right" and "left" for Ss, but considerable bias was present, and hence, this affords a good test of the model's prediction. Although nearly all the correct mean latencies are shorter than incorrect, as may be seen in Table 1, the separate latencies for the two stimulus arrangements (i.e., larger extent on right or left) show several reversals in this respect due to the bias effect. The first four moments of the latency distributions were computed, and the distribution shape indices thus obtained. Full details of these results such as individual data and confidence categories of response are given in Pike (1967).

The overall LP graph appears to correspond fairly well with the Type A form, and the separate curves of Fig. 4 confirm the prediction from the effects of bias that the dominant response LP curve will be Type B and the nondominant response LP curve will be Type A. No attempt will be made here to fit these curves to model parameters, since the standard methods do not appear to work well for LP curves and is in any case best attempted with individual data (cf. Hayhoe, 1969). It should be apparent from the graphs that good evidence exists for the operation of a simple counting process in difficult discrimination, certainly so far as comparison with other more complicated stochastic processes is concerned (cf. Pike, 1968). It should be pointed out, however, that the individual graphs are not, on the whole, as clearly of the same form as illustrated here, and two of the seven Ss have graphs intermediate in form between Type A and Type B. The individual latency distribution moments for separate conditions of difficulty show considerable variation, as is to be expected (e.g., see Kendall & Stuart, 1961). However, if the distribution indices of shape are averaged over conditions for each S separately, then they come close to the values predicted by the counting model as compared with the theoretical values predicted by other models. These indices are very sensitive to error fluctuation (cf. Snodgrass et al,

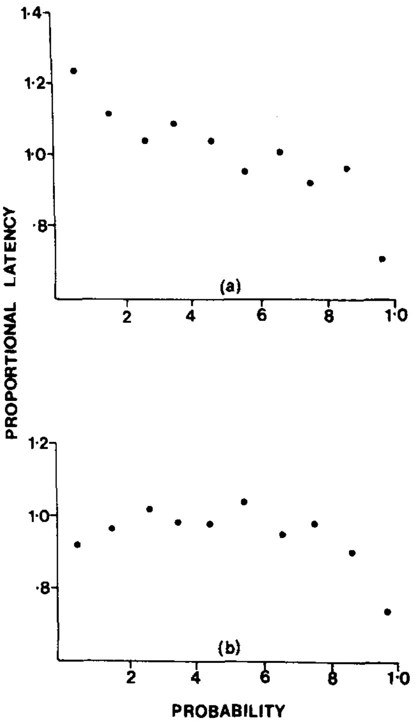

Fig. 4. L-P graphs for seven Ss combined. Latencies are averaged within intervals of P of 0.1 and the average points placed at midintervals. (a) Nondominant response; (b) dominant response (greater overall frequency).

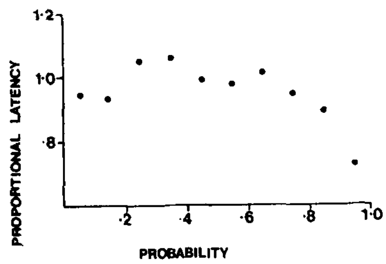

Fig. 5. L-P graph for 23 Ss of Experiment 2. Combined as in Fig. 3.

1967), and Kendall and Stuart (1961, Chap. 6) have pointed out the difficulty in estimating theoretical values of these indices from moments of empirical distributions for purposes of comparison with theoretical models. In view of this, details of these indices are not presented here (but see Pike, 1967).

EXPERIMENT 2

The Ss of Experiment 1 were very carefully instructed in an attempt to bring about stability of response criterion. This appears to have worked well, and the results support the Type A LP curve in this situation. As a consequence, it was decided to investigate the case where the possibility of response criterion fluctuation is introduced by allowing the instructions to be deliberately ambiguous with regard to speed or accuracy. It was also decided to change the stimuli in an attempt to reduce the response bias which is so severe in Experiment 1 and may be interfering with the measures of latency. Although bias turned out to be useful in the previous experiment, the present prediction based on criterion fluctuation would best be tested without its interference. Changing the stimulus does, of course, allow a confounding to occur in the comparison of the experiments, but this was thought unlikely to be of any consequence in the particular prediction concerning the form of the LP graphs. One of the reasons for bias may be distortion of the visual field (anisotropy), which may be small but important in difficult discrimination of linear extent. (Another is, of course, some form of response preference.) The task of numerousness judgment was used since this is evidently less affected by such distortion. A correlational test was also introduced in this experiment, and hence, a larger number of Ss, performing fewer trials, was required.

Method

The stimuli were circular areas of randomly spaced spots of light in a dark background. Simultaneous comparisons of two such circular areas were made, and Ss were required to press a response key corresponding to the judgment of the larger number of spots being in the right or left circular area. Of a total of 33 Ss, 23 received a range of conditions of difficulty, and the remainder received only one condition. The number of Ss in this experiment enabled a test to be made of the significance of the correlation between latency variation and the difference in correct minus incorrect mean latencies. The predicted relationship from the model in the case of criterion fluctuation is a positive one, i.e., the greater the fluctuation in k and consequent latency variation, the greater that difference will be.

Apparatus and Procedure

The stimuli were projected from 2 x 2 slides (negatives of black dots on white), held in a Kodak slide changer, onto a ground-glass screen. The projection was made through the window of a soundproof room in which the S was seated. The projected stimuli (i.e., the circular areas of dots) were each 2 in. across and 1.5 in. apart and were at a distance of approximately 24 in. from the S. Response latencies were recorded on a timer-counter.

An auditory warning signal occurred 1 sec before the stimulus onset (i.e., projector light onset), and the latency was timed from then until the S's response key was pressed. There were two of these keys, for "left" and "right" responses, and two signal lights indicated to E which key had been pressed. Ss sat immediately in front of the screen, and keys and communication between E and S was possible.

Ss were requested to judge the area, right or left, in which the greater number of spots appeared without attempting to count, which was in any case virtually impossible because of the random arrangement and numbers of spots. They were instructed to make the judgment "accurately, but as quickly as possible," so that the precise manner of response was deliberately left uncertain and ambiguous.

The range of difficulty presented to 23 Ss consisted of a standard of 40 spots, and a variable of 40 ± 2, 4, or 6. The stimuli (standard and variable) were presented in a randomly assigned order. Ten Ss were presented only with the 44-spot variable with random presentation of the right-left order.

Results

The overall LP graph for the 23 Ss who received a range of discrimination difficulty is presented in Fig. 5. It was derived as explained in Experiment 1. The separate graphs for dominant and nondominant responses were drawn and are presented in Fig. 6. The coefficient of variation (the standard deviation of the latencies divided by the mean latency) was calculated for each S for the 44-spot condition (i.e., 33 Ss), and these indices were correlated with the difference of correct minus incorrect mean latencies, each difference being divided by its associated overall mean to effect a standardization. The correlation was .346, which is significant at the .05 level.

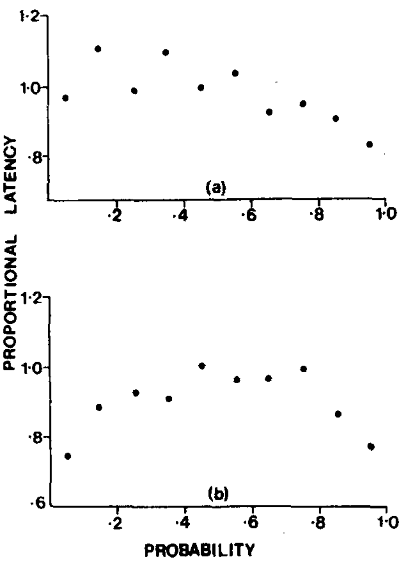

Fig. 6. L-P graph for 23 Ss of Experiment 2. (a) Nondominant response; (b) dominant response.

The overall LP graph appears to conform to Type B; this is reflected in the fact that only 39 out of 66 correct latencies are shorter than incorrect. The prediction from the assumption of variability of response criterion (k) is, therefore, borne out, and the significant correlation is in line with such variability and its consequences. The correlation would not be expected to be a large one since for a constant value of k the reverse relationship of a negative correlation holds (i.e., the obtained correlation should really be tested against a negative value instead of zero). The separate LP graphs of Fig. 6 may be compared with those of Experiment 1; it is clear that response bias is still an interfering factor from the difference in shape between the graphs. It is difficult to make a direct comparison of the bias from the data of both experiments because of the large difference in the power of the tests involved to estimate the bias effect, the smaller numbers of trials in this experiment giving weaker tests. Also, the conditions of difficulty are not compatible. It remains possible that bias is less prevalent in a stimulus situation in which sensory distortion (i.e., of the effective stimulus) is less likely to occur, but implicit response preference is clearly an alternative explanation for the response bias.

DISCUSSION

Both experiments have appeared to support the model, at least insofar as LP graphs are concerned. It should be reemphasized that few models can predict the Type A LP curve. Thus, the very fact of its appearance may indicate the operation of a counting process. The results of Experiment 2 and the biased LP curve results strengthen the conclusion that this kind of process is responsible for some aspects of decision behavior. The question arises concerning the applicability of the model to other related situations, particularly those of easy discrimination, choice reaction, and signal detection. As envisaged by Laberge (1962), the model would be appropriate to different latency situations, including simple RT. In this respect, Pachella and Pew (1968) have obtained results supporting a generalized random walk model for simple RT. Their model is similar to that derived by Edwards (1965) from the proposals of Stone (1960) and has several features in common with the counting model. It was used by Fitts (1966) to describe the effects of speed and accuracy set upon choice RT.

When the discrimination is easy, the task confronting S is similar to that in choice reaction, since he has to decide between stimuli which are easily distinguishable and make the appropriate response. For example, the two stimulus patterns formed from a pair of straight lines with alternating positions are easily discriminated if the lengths are in the ratio of anything greater than about 9:10, and each arrangement can thus be regarded as a two-choice reaction stimulus. It is not surprising, therefore, if similarities occur in latency data from these task situations; in both, it appears that correct times are longer than incorrect ones (e.g., see Laming, 1968; Hale, 1968). The errors that occur have usually been suggested to relate to time taken to perceive or correctly select a response (cf. Welford, 1960; Smith, 1968). As described above, the counting model can account for faster average error latencies by assuming that the value of k fluctuates from trial to trial. Hence, if the model is to describe CRT and easy discrimination it must specifically predict such fluctuation. However, verifying this independently of obtaining shorter incorrect latencies would present a difficult problem. Also, CRTs are generally much shorter than difficult discrimination times, and in applying the counting model to the former it would probably be essential to consider input and output time. The entire latency would then be similar to those from a general gamma distribution (e.g., McGill & Gibbon, 1965), and more complicated analyses would be necessary to obtain the LP curves of the underlying counting process. This also applies in the case of simple reaction time. Another prominent characteristic of choice reaction times is sequential dependencies (cf. Rabbitt, 1966) which would be explained by the counting model in terms of the effects of response feedback upon a varying k.

Catlin and Gleitman (1968) tested two versions of the counting model in a selective learning situation and found fair agreement with data for one of these. They interpret the model for the situation of a single response by assuming that the value of k is the same as it would be in the two-choice case. This assumption may be questioned if the purpose of the counting process is to allow implicit competition to occur between the possible responses, since this form of competition is not required in the single response case. The problem is related to one which has been discussed in learning theory (Spence, 1960) in relation to latencies at choice points. The latter have, in general, been insufficiently studied and here the random walk models may be particularly appropriate as orientation responses (e.g., VTEs) may be related to covert predecisional events. Bower's (1959) model is only a start in this direction.

It was mentioned in the introduction that a latency model derived from signal detection theory can explain the shape of the LP curve, at least of the Type A. In the yes/no signal detection situation, differences occur in the latencies of correct and incorrect responses which have been observed and discussed by Carterette et al (1965), Sekuler (1966), Friedman et al (1968), Wolfendale (1967), and Gescheider et al (1968, 1969). The latter authors have attempted to account for them by supposing that the S must perform a discrimination task to determine on which side of the criterion the observation point lies. The discrimination is then more difficult as the point becomes near to the criterion and thus produces a longer latency of response. It is apparent that correct and incorrect mean latencies will vary with changes in detectability, and the order of these changes is confirmed experimentally (Gescheider et al, 1969). It may be shown that the Type A LP graph will be generated according to this model as the criterion point varies along the distribution of observation points, essentially because the smaller the "incorrect" area under the distribution the nearer will incorrect observations be to the criterion and hence be more difficult to discriminate. A Type A LP graph may, in fact, be derived from the data of Gescheider et al (1969).

It is not difficult to extend either the signal detection model to two-choice discrimination or the counting model to detection, and it thus becomes apparent that a comparison of the two models is required (cf. Audley & Mercer, 1968). The counting model can be incorporated with the signal detection model by supposing that a sequence of observation points is necessary for a decision and with points above or below the criterion corresponding to the events a and b of the counting model. This type of model is similar to the sequential decision process of Stone (1960), which has been examined in terms of the accuracy-time trading relationship by Birdsall and Roberts (1965). In this case, however, the sequential decisions are usually based on the accumulation of likelihood ratios (or a combined, algebraic, counting), rather than a simple counting, and the model will predict equal correct and incorrect mean latencies (Pike, 1968). Sequential observations have been studied by Swets and Green (1961), but there the observations were overt and repeated presentations of the stimulus were thus necessary. Another form of counting model has been proposed by McGill (1967) to describe auditory detection outcomes; this may be modified to describe detection latencies. Choosing between these interpretations is clearly an experimental problem, particularly with regard to the use of variations in the basic signal detection situations. At the moment the simple counting model would appear to possess advantages insofar as it can give rise to Type B LP curves under certain conditions. It is not obvious how the signal detection model plus discrimination assumptions can do this, because criterion fluctuations in that model should not affect the form of the LP curve. Also, the appearance of differing curves for dominant and nondominant responses is even more difficult to predict. It is clear that an experimental comparison of the basic models would aid the understanding of psychophysical processes generally, at least in the manner in which these processes control response latency.

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