On the rate of acquisition of visual information about space, time, and intensity*

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The temporal course of acquisition of visual information was mapped by measuring the speed and accuracy with which Ss could discriminate the position, intensity, or duration of a stimulus that was varied independently on these three binary dimensions. The speed-accuracy tradeoff was different for each of the three discrimination tasks, with performance substantially superior in the position discrimination task. In the intensity and duration discrimination tasks, there were systematic changes with RT in the relative influences of the three stimulus variables over the two alternative responses, suggesting three phases of the corresponding perceptual processes: an initial dominance by position of the stimulus, a subsequent joint influence by both intensity and duration, and finally an exclusive control by the correct dimension. The results demonstrate that Ss can selectively attend to various dimensions of the same stimulus, with concomitantly varying time constants. The perceptual processes being tapped by a discrimination task depend upon instructions and upon RT.

One of the interesting characteristics of visual perception is the tendency to respond to stimulation integrated over relatively long periods of time. A reliable phenomenon, known as Bloch's law, is that visual detection thresholds are determined by the total energy occurring within a "critical duration" of roughly 100 msec, independent of the luminance at any point in time (see Graham, 1965). This temporal integration has also been obtained with above-threshold energy levels, in tasks requiring brightness discrimination (Graham & Kemp, 1938) and magnitude estimations of brightness (Stevens, 1966). Additionally, Eriksen (1966) has shown how the same principle can account for results in experiments on backward and forward masking.

The pervasiveness of temporal summation phenomena misled many students of visual science to assume that the reciprocity of intensity and duration resulted from retinal processes, which supposedly produce equal neural responses for all stimulus presentations containing equal energy within a "critical duration." The clearest demonstration that this conclusion was unjustified was contributed by Zacks (1970), who asked the direct question: Can Ss *discriminate* between equally detectable flashes containing equal energy but differing in duration and intensity? Zacks showed that the discrimination between equal-energy stimuli of 4 and 81 msec was nearly as accurate as the detection of these flashes, rejecting the hypothesis that the peripheral visual system responds identically to such stimuli.

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Indeed, stimuli that produce identical behavior in one task need not do so in another task.

Additional evidence against the site of temporal integration being located in the peripheral visual system has been provided by experiments that compared the duration of temporal integration for various behavioral indicators. Kahneman and Norman (1964) found complete summation for intervals of 200-350 msec in a form-discrimination task, as compared to a typical critical duration of about 100 msec for the same stimuli in a brightness-matching task. In contrast, Raab and Fehrer (1962) reported critical durations of less than 5 msec for simple RT. Although subsequent studies have noted methodological weaknesses in the Raab and Fehrer (1962) experiment and have obtained larger values for a critical duration, simple RT has continued to show a different dependence upon the intensity and duration of stimulation than have other behavioral indicators (Grossberg, 1968; Kietzman & Gillam, 1972). The temporal characteristics of visual perception revealed by behavioral data evidently depend upon the O's task.

The present experiment is concerned with choice RT as a measure of the temporal characteristics of visual perception. Two alternative hypotheses for the discrepancy between simple RT and various indicators based on the choice of response are (a) that different response systems are served by different perceptual processes, and (b) that RT and choice tasks have demanded attention to different perceptual attributes of the stimulus input. The first hypothesis raises logical problems in drawing inferences from results obtained with either indicator: If different behavioral indicators do not converge upon the same perceptual characteristic, then the contributions of perceptual processes cannot be distinguished from peculiarities of the response systems.

An alternative hypothesis is that RT and verbal indicators have disagreed not so much because they have utilized different behavioral indicators, but because they have been used in tasks that demand attention to different attributes of stimulation. The relevant stimulus information for most verbal choice tasks is provided by the energy or brightness of the stimulus, irrespective of how the luminance is distributed in time. Detection tasks demand the discrimination of increments in energy between stimulus and background; the same can be said for acuity and form identification tasks (as in Kahneman & Norman, 1964); and brightness estimation tasks, by definition, require attention to differences in energy. But energy has been irrelevant in RT tasks, where the relevant information has pertained to the temporal point of onset rather than to the luminance at any point in time. Thus, when S attends to various perceptual attributes, he may operate on the same stimulus input with different perceptual processes, with concomitantly varying temporal characteristics and varying dependencies on stimulus parameters. One can argue that the visual system has evolved to be much more sensitive to the spatial distribution of energy than to absolute levels of energy (e.g., Notterman, Filion, & Mandriota, 1971), and that changes in the spatial distribution of energy are therefore likely to be more rapidly detected by processes with short time constants. The suggestion that temporal characteristics vary with attention to different stimulus dimensions is supported by Kahneman and Norman's (1964) finding of a difference in the critical durations for form identification and brightness matching tasks. These two alternative hypotheses about the discrepancy between the temporal characteristics of choice behavior and simple RT were tested by measuring both the speed and accuracy of choice RT responses in tasks requiring attention to different stimulus dimensions.

The aim of the present experiment was to map the temporal course of acquisition of visual information about the position, intensity, and duration of stimulation. In separate experimental conditions, Ss were asked to discriminate between two alternative positions, intensities, or durations of a stimulus varying in these three independent binary dimensions, and measures were made of their speed and accuracy in performing these discriminations. The position discrimination task is presumably comparable to the simple RT tasks that have typically been used to evaluate the influence of stimulus intensity on RT, in that the relevant stimulus information is provided by the spatial and temporal point of stimulus onset rather than by the luminance, duration, or energy of the stimulus. Lappin & Disch (1972b) report the effects of intensity in a very similar task. In the intensity and duration discrimination tasks, however, the S's attention is more appropriately paid to the energetic dimensions of the stimulus rather than to its spatial position. Although most verbal report tasks have demanded attention to

energy, they have seldom asked for a discrimination of the intensity or duration alone when stimuli were varied in both dimensions [Zacks' (1970) experiment is an exception]. RT measures have apparently not previously been applied to discrimination of the duration or intensity of stimulation.

Performance was described by the "latency operating characteristic" (LOC)—the functional relation between RT and discrimination accuracy (see Lappin & Disch, 1972a, b). This method of analysis offers several advantages over simple RT. First, the combined use of speed and accuracy measures may avoid the potentially contaminating influence of varying response criteria on the relation between stimulus variables and RT. The strong assumption that simple RT eliminates the contribution of choice processes and is invariant over changes in decision criteria is probably unrealistic and unnecessary. Second, and more important, the discrimination accuracy of responses at a fixed RT should reflect the amount and kind of perceptual information available after a fixed duration of perceptual processing. If the duration of perceptual processing covaries with RT, then responses may be differentially correlated with the position, intensity, and duration of the stimulus, depending upon the RT. The analysis of the multifactorial confusion matrices at each value of RT provides an opportunity for determining the relative contributions of each of the three independent stimulus dimensions to a given discrimination at a given point in the perceptual process. This analysis of the temporal course of the influence of each stimulus dimension offers a more detailed portrayal of the perceptual process than conventional RT or accuracy measures applied individually.

METHOD

Stimuli

The stimuli were two luminous disks, 1 deg in diam and 40 min to the right or left of the fixation point centered in a 5½-deg square luminous background. The stimuli also varied in intensity and duration. The two luminances were 34.3 and 3.4 cd/m², added to a 24.0-cd/m² background that was continually present. The two durations were 50 and 5 msec, calibrated with a photomultiplier and oscilloscope. Luminances were monitored and adjusted before each session with a Pritchard photometer. The stimuli were presented with an Iconix three-channel tachistoscope and associated Iconix timing, power, and logic equipment. A tape reader was used to program the position, intensity, and duration of the stimulus for each trial.

Procedure

A trial began when S depressed both of the telegraph response keys—one with the right hand and one with the left—and the stimulus always appeared 1 sec later. The eight alternative stimuli were presented randomly, with the constraint that each appear five times in each block of 40 trials. E recorded the stimulus, response, and RT (measured from stimulus onset), and gave verbal feedback concerning the RT and correctness of the response. E then advanced the tape reader, and the resulting

click signaled S that he could initiate the next trial. The intertrial interval was about 2-4 sec.

S was instructed to respond at an RT that would correspond to an error rate of approximately 25%. In separate blocks of sessions, the Ss were asked to discriminate between the two alternative positions, durations, or intensities; the stimulus set was always the same, only the instructions were changed. In the position task, S attempted to release the left key if the stimulus was to the left and the right key if the stimulus was to the right of the fixation point; in the duration task, the left key was assigned to the short stimulus, and in the intensity task, the left key was assigned to the low-intensity stimulus. Four consecutive experimental sessions were run under each of the three discrimination tasks, with a minimum of two practice sessions before the data collection for each task. A session consisted of 40 practice trials followed by 360 experimental trials. The sequence of discrimination tasks was counterbalanced across Ss.

Subjects

The Ss were five male and one female (C.S.) volunteers. K.D., J.H., and J.L. had participated in previous RT experiments; L.G., A.S., and C.S. had not.

Analysis

The LOC analysis has been described in detail elsewhere (Lappin & Disch, 1972a, b). For present purposes, the essential idea is that the RTs are rank-ordered into blocks of some constant number of trials and the stimulus-response confusion matrix is then constructed for each such set of responses with similar RTs. The measure of discrimination accuracy is $-1n\eta$,¹ from Luce's choice theory (see Luce, 1963); the measure of speed is the median RT.

The confusion matrices were composed of eight stimuli and two responses, the stimuli being represented as combinations of three independent binary variables. The S's performance can therefore be conceptualized as a partition of this three-dimensional stimulus space into two response categories. Accordingly, the perception of the eight stimuli under each discrimination task can be described by three distances—between the centroids of the two response classes along each of the three orthogonal dimensions—corresponding to the position, duration, and intensity of the stimuli. This scheme is illustrated in Fig. 1. The parameters of this discrimination space are presumably dynamic, with the lengths of the three stimulus dimensions and the orientation of the response partition all changing with RT and instructions. The confusion matrices for various values of RT are assumed to reflect these parameters at various stages of development in the perceptual process. Our measure of distance in this discrimination space is the measure $-1n\eta$, and it is calculated for each of the three orthogonal stimulus dimensions.²

RESULTS

The position task was intended to be comparable to the simple RT tasks that have typically been employed to determine the effects of intensity and duration on RT. An initial question, then, pertains to replication of the typical finding in these experiments—that simple RT is inversely related to intensity but is independent of duration. The present results on this phenomenon are shown in Fig. 2, which gives the LOC functions for each of the four combinations of intensity and duration in the position task. (These functions were calculated from the pooled RTs of all six Ss, and the variability may reflect in part slight variations in the extent to which

Fig. 1. Schematic illustration of a perceptual representation of the eight stimuli and a categorization into two response categories. The discriminability of any two points is represented by the Euclidean distance between them. In this particular case, the categorization is based primarily upon position, to a lesser degree upon duration, and is virtually independent of intensity.

different Ss contribute to each point. Such pooling was necessary in order to obtain sufficient data to compare the discrimination accuracy for each stimulus at each point in time. Approximately 135 trials are contained in each point.) The two-segment linear functions plotted in Fig. 2 were fit to the data for each of the four stimuli by the method of least squares, where one line segment was the function $-1n\eta = 0$ and the second segment was the function given in Fig. 2. These functions accounted for 97%, 95%, 91%, and 93% of the variance in the accuracy measures in the long high-, long low-, short high-, and short low-intensity stimuli, respectively. Since the discrimination accuracy is given for each of the four stimuli at fixed RTs, the simplest comparison is based on the values of $-1n\eta$ at the 12 values of RT where discrimination is above chance ($RT > 150$ msec). By sign tests on each of the six pairs of four stimuli, discrimination accuracy was significantly higher for both of the high-intensity stimuli than for both of the low-intensity stimuli ($p < .01$ for three of the comparisons and $p < .05$ for the other), and there was no significant difference between the short and long high-intensity stimuli or between the short and long low-intensity stimuli. Thus, the results in the position task replicate previous findings that RT decreases with intensity but is relatively independent of duration.

Comparisons among the three separate discrimination tasks are provided by Figs. 3 and 4. Figure 3 shows the LOC functions for each of the six Ss under each of the three discrimination tasks. Each point is based on 120 trials. As may be seen, performance in the position task was substantially superior to that in either of the other tasks. Performance in the intensity task was reliably better than in the duration task, although there was little

Fig. 2. Latency operating characteristics of each of the four combinations of duration and intensity in the position discrimination task. The data were pooled across all six Ss. Each point is based on approximately 135 trials.

or no difference for Ss A.S. and C.S. (Considering the last eight points on the duration function for each of the Ss, in only 8 of the 48 cases is the duration discrimination more accurate than the intensity discrimination.)

Comparisons among the discrimination accuracies for the three tasks are not, however, an important concern of this study. The three discriminations have not been matched in difficulty or in compatibility with the two response alternatives. Judging from the data in Figs. 3

and 4, it appears doubtful that the two alternative intensities and durations could have been perfectly discriminated, even if the Ss were given unlimited time to respond. The position dimension is obviously more salient than either of the other two dimensions, but our aim is to generalize to typical previous experiments on the effects of duration and intensity on RT. Questions about matching the dimensions are interesting but perhaps deceptively complex when one considers matching in terms of discrimination at a given RT, in

Fig. 3. Latency operating characteristics for each of the three discrimination tasks for each S. Each point is based on 120 trials.

Fig. 4. Latency operating characteristics for the pooled data from all six Ss, showing the discrimination on each of the three stimulus dimensions in each of the three discrimination tasks. The data in Part A are for the position discrimination task, in Part B for the duration discrimination task, and in Part C for the intensity discrimination task. The starred points in each figure give the total discrimination distance between the S's two response categories, equal to the square root of the sum of squared $-\ln \eta$ values on the three individual dimensions. Each point is based on 720 trials.

terms of the RT for a given discrimination accuracy, in terms of the slope of the LOC function, in terms of magnitude estimation, or etc. For the present, it is sufficient to notice that the LOC functions for the three discrimination tasks differ in several respects.

The main results are presented in Fig. 4, which shows the contribution of each of the three stimulus dimensions to the two response categories at various values of RT in each of the discrimination tasks. These LOC functions are based on the pooled data from all six Ss, totaling 720 trials per point. These functions give not only the accuracy in discriminating the relevant stimulus dimension, as described by the E's instructions, but also the discrimination of the other two stimulus dimensions that were irrelevant from the E's point of view. (These measures of accuracy in discriminating each of the three component dimensions were computed from 2 by 2 confusion matrices, obtained by adding together the response frequencies for the four stimuli with the same value on a given dimension.) On the simplifying assumption that the three dimensions are independent and therefore orthogonal in the perceptual space,² we may also compute the total distance between the two response categories: If d_T is the length of the discriminant function separating S's two response categories, and d_P , d_I , and d_D are the distances along the three stimulus dimensions, then $d_T = (d_P^2 + d_I^2 + d_D^2)^{1/2}$. These distances were estimated in the present experiment by the measure $-\ln \eta$. The total

length of this discriminant function is also plotted in Fig. 4 for each of the three tasks. The correlation (cosine of the angle between the vectors) between the S's discriminant function and each of the three stimulus dimensions is equal to the ratio of distance along the particular dimension divided by the length of the discriminant function. Thus, we may evaluate the S's ability to obtain information about a particular stimulus dimension not only in terms of the "correctness" of his discrimination, but also in terms of the correlation between that dimension and the line that best discriminates between his two response categories. A S might make many errors in performing a particular discrimination as instructed but still apply all of his perceptual processing to that dimension and ignore the potential influence of other stimulus variables, as is illustrated by the results in the position task.

Figure 4 portrays several differences in the performance in the three tasks: (a) The RT at which discrimination on the relevant dimension began to rise above chance was roughly 140 msec for both the position and intensity tasks, but was about 200 msec for the duration task. (b) The rate of increase in discrimination accuracy with RT was much greater for the position task. (c) The regression of $-\ln \eta$ on RT was linear for the position task, but was negatively accelerated in both the intensity and duration tasks. (d) In the position task, the correlation between the S's linear discriminant function and the relevant position

dimension was above .90 for all RTs > 160 msec, whereas in the intensity task, the correlation between the intensity dimension and the S's discriminant function did not reach .90 until the RTs were about 330 msec, and in the duration task, a comparable correlation was not obtained until the RTs were about 440 msec.

Clearly, then, the intensity and duration of these stimuli exerted relatively little influence on the S's responses until the RTs were rather long. Inspection of the results in Fig. 4 for the intensity and duration tasks indicates the existence of three qualitatively different phases in the perceptual processing in both of these tasks: (a) From about 150 msec to about 250-300 msec, the position of the stimulus contributes most of the control over the S's responses, even when he is attempting to discriminate between the two intensities or the two durations. (b) From about 250 msec to 350-400 msec, the stimulus position has a declining influence and both the intensity and duration enjoy a jointly increasing control over behavior. (c) Finally, for RTs greater than about 400 msec, the irrelevant energetic dimension exerts decreasing influence and the relevant dimension acquires more exclusive control over the S's two responses. The time course of these trends is similar for both the intensity and duration tasks, although the intensity dimension is relatively more potent than the duration dimension in both tasks.

To obtain some idea of the reliability of the data points in Fig. 4, we can suppose that correct responses have a binomial distribution and then derive confidence limits for the $-\ln \eta$ scores from the binomial distribution, with standard deviation $\sigma(P) = \sqrt{P(1-P)/N}$. (The binomial model is not precisely appropriate, due to response biases and differences between Ss, but the effects of these deviations should be minimal.) At a $-\ln \eta$ value of 1.0 ($P = .731$), confidence limits corresponding to $\pm 2\sigma(P)$ range from .84 to 1.18, and at $-\ln \eta = 2.0$ ($P = .881$), the range is 1.79 to 2.25. Also, successive points on the same function are statistically independent.

DISCUSSION

The major concern of this experiment is with the temporal course of perceptual processing of stimuli varying in spatial position, intensity, and duration. The problem that originally motivated this study was the discrepancy between simple RT and various measures based on response choices as indicators of the perception of stimuli varying in intensity and duration: Although choice indicators have often demonstrated a dependence upon the integral of intensity over durations of about 100 msec, RT has been found to be more sensitive to the intensity than to the duration of stimulation (Kietzman & Gillam, 1972; Raab & Fehrer, 1962; and the position discrimination task in the present experiment).

The results of this experiment clearly demonstrate

that Ss can selectively attend to different attributes of the same stimulus and that the temporal characteristics of their perceptual processing depend upon the specific information which they are attempting to extract. Specifically, information about spatial position is shown to be acquired much more rapidly than is information about the intensity or duration of the stimulus. Two reasons for the discrepancy between choice and RT indicators of the perceptual process may be (a) that experiments employing RT measures have demanded attention to spatial and temporal changes rather than to energetic dimensions of stimulation as have experiments using choice indicators, and (b) that choices are usually recorded after unlimited RTs. RT tasks can alternatively reflect either a facilitatory effect from high intensities and a concurrent independence of duration, a mutual influence from both intensity and duration, or control by duration alone—depending upon the specific stimulus dimension to which S is required to attend and upon the specific value of RT.

A secondary aspect of this study concerns the use of the LOC (speed-accuracy tradeoff) as a means for tracing the temporal course of perceptual processing. The results, particularly in the intensity and duration discrimination tasks (see Fig. 4), demonstrate systematic temporal changes in the amount and form of the stimulus information that influences responses emitted at various times following the stimulus onset. These results are inconsistent with the common assumption that RT distributions reflect the distribution of latencies with which a given perceptual state is attained, because different states were attained at different RTs. Of course, this finding should not be surprising, since the Ss were instructed to respond so rapidly that they made errors. But the correlation between fast responses and various irrelevant stimulus dimensions (e.g., between stimulus position and responses of about 240 msec in the intensity discrimination task) is also contrary to the fast guess model (see Yellott, 1971), which postulates that RTs are either guesses or are appropriately controlled by the stimulus. In the duration and intensity tasks, RTs between about 200 and 400 msec were not purely guesses, but were systematically influenced by "incorrect" stimulus information. The fast guess model was appropriate for RTs of less than 150 msec. The use of confusion matrices constructed from several independent stimulus variables and fast responses seems to offer a technique for determining the kind of stimulus information that is available at various points in the perceptual process.

RT depends upon the information being processed, and the converse is also true.

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NOTES

1.

$$-1n\eta = 1/2 \log_e \left[\frac{p(r_1|s_1)}{p(r_2|s_1)} \cdot \frac{p(r_2|s_2)}{p(r_1|s_2)} \right]$$

where r_1 and r_2 , s_1 and s_2 correspond to the two alternative responses and stimuli, respectively. Both the scale values and underlying ROC of this measure are very similar to those of the signal detection measure, d' . This choice theory measure was preferred here because of its ease of calculation.

2. The simplifying assumption that the three component distances of this discrimination space are orthogonal is not precisely correct. The square root of the sum of three squared distances tends to be a slight overestimate of the total length of the linear discriminant function between the two response classes, because the eight alternative stimuli are not necessarily represented equally often in the confusion matrix for responses at a given RT. In other words, the sum of the information transmitted about each of the three component stimulus dimensions is an upper bound on total information transmitted from stimulus to response, because the three component dimensions are not always completely orthogonal. Although the eight alternative stimuli, composed of three independent binary dimensions, were presented equally often in each session, they were not responded to equally often at each value of RT. We have evaluated these constraints among the component dimensions and found them to be negligible. Additionally, the three component distances are not independent parameters, because the sum of the three distances is bounded—i.e., as the discrimination of one dimension becomes highly accurate, the responses must therefore be uncorrelated with the other dimensions. In terms of information theoretic measures, the sum of the information transmitted about each of the three dimensions cannot exceed the total response uncertainty. However, this constraint is not important in the qualitative interpretation of the data in Fig. 4. The sum of the information transmitted about each of the three component dimensions accounts for a maximum of 81%, 45%, and 45% of the total response uncertainty in Panels A (at median RT = 314 msec), B (at median RT = 398 msec), and C (at median RT = 496 msec), respectively. The analysis provided by Fig. 4 is intended as a qualitative description rather than as a rigorous and complete mathematical representation of the underlying process.

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