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THE FREQUENCY AND THE LATENCY OF RESPONSE IN RELATION TO THE RECIPROCITY LAW

by

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INTRODUCTION

There is little reason to doubt that visual reaction times can provide some useful information on visual-detection processes (cf. McGill, 1961, 1963). But latency data have not usually served as references for either the formulation or the evaluation of theoretical models on such processes (e.g., Blackwell, 1963). It is difficult to say to what extent reaction times can aid in reducing the uncertainties involved in interpreting visual-threshold data, because traditional determinations of reaction times and thresholds differ operationally, at least in terms of stimulus magnitudes and dependent variables. This paper is concerned with experiments which bridge certain of the operational gaps between the two types of determinations. The experiments may be regarded as comparative analyses of the respective dependent variables.

In studies of visual reaction time, subjects are usually instructed to respond ("Yes") as soon as they see a suprathreshold stimulus, their task resembling that of subjects in visual-threshold experiments. Often the latter are required to respond either "Yes" or "No," depending on whether or not they see a stimulus, the dependent variable being the relative frequency of "Yes" over trials, the "frequency of seeing" (e.g., Mueller, 1951).

In the present experiments, the frequency and the latency of positive response ("Yes") are recorded on the same trials, with stimuli for which the measures covary.

At the outset, it seems clear that the two dependent variables differ in various ways. In addition to the fact that frequencies and latencies are different kinds of measures, they also appear to reflect different aspects of stimulus processing. Frequencies of seeing indicate how often stimuli are adequate to occasion a positive response, but the latency of positive response presumably indicates how soon after stimulus onset a subject "decides" that a stimulus has occurred (cf. McGill, 1961, 1963). Reaction times also vary sytematically with stimuli for which the frequency of seeing is 100%: the stimulus ranges controlling the two variables are clearly different. Since latencies are clocked between stimulus onset and the response, their systematic variations could reflect processes which are not reflected by frequencies of seeing (cf. May, 1964). Nonetheless, certain investigators have indicated by experiment that Weber's "law" and the reciprocity law predict latencies of response to dim, but suprathreshold stimuli.

Steinman (1944) measured latencies of response to intensitive increments (ΔI), of 1-sec duration, in fields which are exposed initially at various intensities (I). The $\Delta I/I$ required to "determine" a relatively long mean reaction time decreased to a constant value with increases in I (Fig. 2, p. 17). Because the form of the constant reaction-time function was "in essential agreement" (p. 27), that is, was approximately parallel to, $\Delta I/I$

functions obtained in separate difference-threshold determinations, Steinman concluded that reaction time "is at least as informative as threshold determinations for studying discrimination" (ibid.). Considered in terms of the subjects' task, which required a discrimination, Steinman's conclusion is valid.

Steinman also inferred that "conclusions...drawn from the results obtained by the RT method concerning sensitivity are... consistent with, and in fact, complementary to those obtained by other psychophysical methods" (p. 59). While the anlysis suggested that "results obtained at the threshold level can be generalized to suprathreshold conditions" (Greenbaum, 1963, p. 10), the significance of the generalization is not clear. Moreover, one cannot be sure that the purported generalization is not fortuitous. A prior question to be answered is whether the $\Delta I/I$ values which determine a given frequency of seeing also determine a constant response latency. One should first indicate, at least, that Weber's "law" extrapolates to response latency under conditions for which the law holds, demonstrably. The present study is concerned with whether the reciprocity law extrapolates to response latency, but since the law is closely related to Weber's "law" of difference thresholds (cf. Keller, 1941), the results could have some bearing on whether the latter predicts latencies accurately.

Steinman's analysis was analogous to that performed by Lewis (1964), whose experiment was intended to indicate whether the reciprocity law predicts simple reaction times. The reciprocity (or Bloch's) law has been observed to apply in a variety of psychophysical contexts with various visually guided behaviors and different response measures (for references see Alba & Stevens, 1964; Kahneman & Norman, 1964). According to the law, a constant behavioral effect is determined by a given product of stimulus luminance and stimulus duration, that is, by a constant energy. In the context of a threshold determination, conformity with the law could be evidenced by a constant frequency of seeing (often 50% is chosen), for various luminances and durations of single, rectangular-waveform flashes, which contain a constant energy. The relationship holds, under given conditions, for durations which are briefer than a minimum that has been called a "critical duration" (e.g., Sperling & Jolliffe, 1965). Judging from results obtained with nonrectangular stimulus waveforms, such as single stimuli with various rise and decay rates (Long, 1951) and multiple stimuli spaced successively at various intervals (Bouman & van den Brink, 1952; Davy, 1952; van den Brink & Bouman, 1954; Blackwell, 1963, p. 155; Ikeda, 1965), the reciprocity relationship is an instance of a more general principle. The principle is that a threshold behavioral effect, such as a given frequency of seeing, is determined by the time integral of stimulus luminance, or stimulus energy, irrespective of stimulus waveform--if the energy is delivered within a sufficiently brief period of time after light onset (cf. Bartlett, 1965, p. 174; Graham, 1965, p. 77). Despite the broad parametric range of the reciprocity law, which is evidently an example of a more general rule in the case of thresholds, there is no obvious reason why it should predict constant simple reaction times for constant-energy flashes.

In Lewis' (1964) admittedly limited determination, two flash stimuli were equal in energy. A nonparametric test of differences led him to accept the hypothesis that "stimuli of equal energy yield equivalent reaction time distributions....For constant reaction time distributions, Bloch's law is valid" (p. 121). But inspection of the data discloses that the median reaction times from both subjects were ordered in conformity with the results of Raab and Fehrer (1962). Their data had provided Lewis' alternative hypothesis: "flashes of equal energy...produce different reaction time distributions, with the shorter flash yielding consistently shorter reaction times" (p. 109). It is of historical relevance that Froeberg's (1907, p. 31) observations were consistent with the alternative hypothesis; however, his procedures for controlling stimuli (daylight reflected from briefly exposed paper strips) and programming stimuli (nonrandom orders of flash durations; cf. Raab, Fehrer, & Hershenson, 1961) cause concern over the replicability of his results. Similarly, Lewis was concerned with possible biases in the results of Raab and Fehrer, because flash luminance was fixed during any session. Thus, to date, while inspection of the results of Froeberg, Raab and Fehrer, and Lewis suggests a consistent disproportionality between luminance and duration in governing reaction time, Lewis' experiment was the only one designed to evaluate the relationship in strict terms. Evaluated in a context where the frequency of positive response varies in accordance with the reciprocity law, the question of whether the latency of the response does too is relevant to: an understanding of response latency (cf. Raab, Fehrer & Hershenson, 1961; Raab, 1962; Raab & Fehrer, 1962; McGill, 1953; Robinson, 1956); and the theory of the reciprocity relationship.

According to Graham and Ratoosh (1962), "the significance of the critical duration...can be understood in terms of a hypothetical, probably idealized, experiment on reaction time" (p. 501). They considered a situation in which flashes of various luminances and durations are presented to a subject, who is instructed to respond as soon as he sees a flash. With the subject's reaction time clocked from flash onset, the expected result was a given reaction time for a product of the two independent variables. But for durations exceeding a critical duration, reaction time was expected to vary only with luminance. In this hypothetical context where reaction time obeys the reciprocity rule, the interpretation of critical duration evidently adopted was the one assumed in the "Graham formulation" (Blackwell, 1963, p. 154). The formulation (cf. Graham & Kemp, 1938) may be regarded as a qualitative explanation of critical duration, which presumably measures a storage period that is in effect for _all_ constant-energy flashes briefer than the critical duration. That is, "the effects of stimulation are accumulated during a storage interval with the neural activity corresponding to the effects of stimulation during the entire storage interval being initiated following a delay after the end of the storage interval" (Blackwell, p. 154; cf. Bartlett, 1965, p. 174). An essentially analogous description of the concept is "that a finite integration period, triggered by the first quantum of light absorbed, persists for some critical duration during which all quanta are 'counted,' with a response subsequently being produced in proportion to this number" (Boynton & Siegfried, 1962, p. 721). The concept of a constant storage interval has been questioned for reasons which are beyond the scope of the present discussion (Boynton & Siegfried, 1962; Blackwell, 1963; Kahneman, 1964; Kahneman & Norman, 1964). But the concept has a definite consequence in a simultaneous determination of the frequency and the latency of response.

Demonstrable reciprocity under given conditions is, in theory, sufficient evidence for the operation of the hypothetical storage process. The process is supposed to cancel the separate effects of the luminance, duration, and waveform of stimuli so that only stimulus energy delivered during the duration of the process, the critical duration, matters in response determination. Thus, the process, which is assumed to be the first in the sequence of events leading to a response, places constraints on the form of stimulus control that can be revealed by response variations.

The energy principle discussed previously is quite consistent with implications of the concept. Applied in the present experimental context, it implies that if the frequency of "Yes" for a given set of stimuli conforms with the reciprocity rule, then the latency of "Yes" should not vary systematically with either the luminance or the duration of the same stimuli.

The uncertainties about temporal aspects of stimulus processing in visual-threshold experiments have been recognized. For example, Blackwell (1963) pointed out that "the sensory effects of a momentary temporal stimulus spread out in an unknown manner in time" (p. 155). His discussion concerned thresholds which had been determined with two types of stimuli: single flashes of various luminances and durations; and a pair of successive flashes, which were equal in luminance and duration, and were separated by various intervals. Both types of stimuli were used in the present experiments, which were conducted in order to obtain a picture of the principal features of (1) the relationship between reaction time and flash duration at various luminances, and (2) the relationship between reaction time and the interval between two successive flashes, which are equal in luminance and duration. Such functions could disclose features of temporal processing which are not evident from the frequencies of seeing that are recorded with the latency measurements.

The primary difference between the present experiments and previous, similar reaction-time determinations (Raab & Fehrer, 1962; Lewis, 1964; Robinson, 1966), is that flash luminances here were low enough to determine frequency-of-seeing of psychometric functions over a wide range of flash durations (cf. Crozier, 1950). The previous work showed that simple reaction time varies inversely with flash duration, at fixed flash luminances. The present experiments can show whether or not an inverse relationship occurs with flashes that are detected on various frequencies of trials. Such an outcome is not an obvious concomitant of frequency-of-seeing variations. According to Swets, Tanner, and Birdsall (1961), "breaking up the observation continuum into Yes and No sections is a process that loses information. From a procedure forcing a binary response, one learns from the observer only that that observation fell above or below a critical value, and not how far above or below" (p. 326). It is conceivable that information on the grading of stimulus effects, beyond a minimum sufficient for a positive response, can be retrieved from the latency measures. In order to extract such information from the "Yes" response, it is necessary (cf. Swets, Tanner & Birdsall, 1961) to change an experimental parameter. The difference between previous visual-threshold determinations and the present experiments is that subjects are required to respond as soon as they see the stimulus light, as in reaction-time determinations.

Because of the dearth of information on experiments of the present type, they are regarded as exploratory ventures. The results are, nonetheless, relevant not only to the idea that visual-threshold relationships are generalizable to simple reaction times, but also to questions on the nature of processes which mediate the reciprocity and associated relationships.

APPARATUS

Flash stimuli were produced by a 4-w fluorescent lamp (Sylvania Deluxe Cool White, cf. Gerbrands & Stevens, 1964). The stimulus lamp was one of two lamps housed in the rear of a steel box. Each lamp was placed against the back of a fixture for neutral density filters, and the two lamp-filter combinations were separated by a metal partition that divided the rear of the box into two sections. Filtered light from either lamp passed forward into a single chamber that contained a third fixture for neutral filters, then through a plano-convex lens, and finally to the diffusing surface of a 'white' circular stimulus field. The 5/32-in. (diam.) field, viewed binocularly at a distance of approximately 21 in. from a head rest (no biting fixture), subtended approximately 0.5° of arc. A separate box, containing a shielded 929 phototube with shielded cable, was locked in position at the rear of the lamp housing so that unfiltered light produced by either lamp could be monitored.

Two fixation devices, at the same viewing distance as the stimulus field, were used. The first (in order of use) device was a dim, circular red light (a portion of a neon bulb) that was located approximately 3 degrees below the stimulus and subtended approximately 10 min of arc. This fixation condition is referred to later as the Peripheral viewing condition. For the Foveal viewing condition, two dim circular red lights, each subtending approximately 0.5° of arc, were located at equal horizontal distances (about 2 deg) from the center of the stimulus. The Foveal fixation device was a piece of glass to which a single neon bulb was attached. Light from the neon was reflected outward at the two fixation points, which were the only uncovered portions of the glass. The points were adjusted to equal brightness and the glass (with a central aperture for the stimulus field) was affixed to the front surface of the stimulus box.

The stimulus box was locked in position on a shelf attached to one wall of the subject's darkened booth, and, except for the stimulus field and fixation device, was covered by black cloth. Flashes were therefore viewed against a black, nonreflecting background. The head rest was located at the end of a table, on the left of which was a standard light switch for triggering a trial, and on the right of which was a normally open response switch (Unimax 2HBJ-1); these components were clamped to the table. Two electric fans in the booth circulated air and provided ambient noise. Shielded cables from the lamp housing (plug-in connections) and the switches ran outside of the booth to a rack on which control equipment was mounted.

The foreperiod, the silent interval between the subject's closure of the starting switch and flash onset, was controlled by two devices (silent for the subject). With the Peripheral viewing condition, an Amperite 115N02 relay was heated by a voltage adjusted so that closure occurred approximately 4 sec after the subject closed the starting switch. The switch was usually opened to permit cooling within about 3 sec after flash onset; intertrial periods of no less than 30 sec were employed. After a block of about 30 trials, the voltage setting was checked. A second foreperiod control, used with the Foveal viewing condition, was a Hunter interval Timer (Model 100C) that was set to close after 2.8 sec. The subject's task in operating the starting switch was the same with both foreperiod controls, each of which produced a gate voltage that remained in effect until the starting switch was opened at the end of a trial. The gate was differentiated to a positive spike that started all subsequent timing operations on a trial.

Stimuli were controlled by Tektronix pulse and waveform generators. One waveform generator controlled flash duration when it was an independent variable. Two pulse generators controlled flashes in experiments with two successive flashes. All stimulus times were clocked from the end of the foreperiod. In experiments involving two successive flashes, the second flash was synchronized to the 50% sawtooth voltage of a waveform generator, which was synchronized to the end of the foreperiod. The output voltages of the stimulus-control units passed through intermediate components (switches and resistances) and controlled a lamp pulsing circuit (e.g., Gerbrands & Stevens, 1964). One triode of a 6SN7GTB tube was biased to cutoff by a 45-v battery and the lamp (one filament at about 10 v DC) was in series with the plate circuit of the triode. A regulated power supply furnished 400 v DC.

Response latency was measured in the following manner. A waveform generator was synchronized to the end of the foreperiod and produced a 2-sec gate voltage. The gate operated another generator that produced pulses at a one/msec rate. On closure of the subject's normally open response switch, pulses were counted by a Hunter Klockounter, which clocked latencies to the nearest msec. On blank trials (when no stimulus occurred), the counter measured the time during which the subject continued to depress the response switch, up to a maximum of 2 sec.

The luminance of unfiltered flashes was monitored with reference to the output of the 929 phototube, viewed on a Tektronix 502A oscilloscope. Stimulus luminance was varied by inserting neutral density filters into the forward chamber of the light box. Absolute luminance calibrations were made with a Spectra meter. With the unfiltered luminance monitored and adjusted to experimental values, the lamp was pulsed continuously (equal light and dark periods) to yield meter readings in footlamberts (ft-L). Averages of these readings were doubled in accordance with Talbot's law (e.g., Le Grand, 1957, p. 295), with which the Spectra conformed for the conditions of measurement.

Absolute calibrations of flash duration were made by passing the output of the 929 tube across a low resistance at the input of the 502A oscilloscope, which was at a high sensitivity. Flash duration was measured by multiple observations of flash waveforms, and was defined as the width of the horizontal peak of the reasonably rectangular waveforms. Flash onset followed an approximately linear course to peak intensity and flash rise time (peak to peak) was less than 0.5 msec. Decay time (peak to peak) was on the order of 0.5 msec, but the decay was 80% complete within 0.1 msec after the decay commenced. In order to anticipate the analysis of data, it should be indicated that the present method of calibrating flash duration, which treats flashes as rectangular waveforms, results in significant errors when the product of luminance and duration (i.e., flash energy) is calculated for very brief flashes. The error occurs principally because the energy in the leading portion of such a waveform, that associated with the rise to peak intensity, is ignored. This problem arises in consideration of certain results from Experiment I, where the matter is discussed explicitly.

SUBJECTS and GENERAL PROCEDURE

After preliminary experiments with several subjects, formal experiments were conducted with three male subjects (H.H., M.R., and J.S.), who were paid by the hour. They worked approximately 3 hours per session and followed fairly regular schedules. None of them knew the purposes of the study and all were assigned the same task.

Following a signal, a subject initiated a trial when he was ready. Viewing was binocular from a head rest, responding was with the right index finger, and trial initiation was with the left hand. The subject's task was to release the button as soon as he saw the stimulus light, but to continue holding it if he did not (cf. Lewis, 1964). The latency of a positive response ("Yes"), a button release within 1 sec after the end of the foreperiod, was recorded. If the button was depressed continuously for 1 sec ("No"), then the trial was ended by a signal (vocally or with a clicking sound). During intertrial intervals (at least 30 sec), the subject was required to look away from the fixation light(s) and to rest.

Prior to formal experiments, subjects were trained not to respond in the absence of a stimulus light, but to respond as quickly as they could when the light was presented. During formal experiments, if a response occurred in the absence of a stimulus, the subject was informed. The next trial with a selected, relatively strong stimulus was regarded (unknown to the subject) as a practice trial. Responding in the absence of stimuli, on blank trials, was rare (cf. Lewis, 1964). When a formal experiment was completed, subjects were told and the periods between experiments were used not only to select stimulus values (constant stimulus programs), but also to reshape performance.

Detailed procedures differed among experiments and are described with the results.

EXPERIMENT I

Procedure

The frequency and the latency of positive response ("Yes") were recorded as functions of flash duration, at four flash luminances. This experiment was an initial, economical survey over reasonably wide ranges of the two stimulus variables. The independent variable was flash duration, values of which were presented in shuffled orders, with equal frequency, among trials. They were mixed with a few blanks. The parameter was flash luminance: (A) -2.82, (B) -1.81, (C) -0.81, and (D) -0.07 log ft-L, values of which were ordered over sessions in the sequence ABCDDCBAABCD.

Two subjects (H.H. and J.S.) participated, and the Peripheral viewing condition with a 4-sec foreperiod were used. At the start of each session, a subject was adapted to darkness for 30 min, and usually remained in the booth for an entire session; however, when he left it, dark adaptation was repeated. A series of trials contained each value of flash duration plus 3 blanks. Ten series, which were separated by rest periods, comprised one session. Each value of luminance was used in three sessions, and each stimulus (a luminance-duration combination) was presented on 30 trials.

Results

Tables 1 and 2 contain the number (N), median (Mdn), and semi-interquartile range (Q) of response latencies, for various flash durations (T in msec) at three luminances. Median latencies are reported for 10 or more responses (an arbitrary minimum) during the 30 trials with each flash duration. Table 3 contains the median and semi-interquartile range of latencies at the highest flash luminance, for which 30 responses to each flash duration occurred. Subject J.S. never responded to a blank, but H.H. responded once, with a latency of 630 msec, during a session at the highest luminance.

Figures 1 and 2 display the median latency (RT in msec) and the percentage relative frequency of response (%R), as functions of flash duration (log T in sec). Flash durations have been expressed in seconds, rather than in milliseconds, to follow the convention in previous visual-threshold experiments. The figures show that %R increased with increases of flash duration. It should be emphasized that they have been drawn to the briefest flash duration at which %R reached and remained at 100%. Since the approximate conformity of %R with the reciprocity rule is difficult to judge from Figs. 1 and 2, a better method of presentation is considered later. But the graphs do show clearly that RT was an inverse function of flash duration (except for one curve in Fig. 1), with no evidence of discontinuity in the range of durations that determined various %Rs. Moreover, the RT curves at -1.81 and -0.81 log ft-L appear similar to the curve for -0.07 log ft-L, where %R was 100% at all

Table 1

Number, median, and semi-interquartile range of response latencies (msec) for various flash durations (msec) at three flash luminances (log ft-L).

Experiment I. Subject: H.H.

	-2.82			-1.81			-0.81		
T	N	Mdn	Q	N	Mdn	Q	N	Mdn	Q
0.1	-			-			4		
0.3	-			-			7		
0.5	-			-			17	439	68
0.7	-			-			24	377	50
1.0	-			-			26	381	30
1.5	-			-			27	381	40
2.0	-			0			30	389	42
2.7	-			1			-		
3.5	-			2			-		
4.5	-			5			30	346	18
5.6	-			17	447	22	-		
7.5	-			22	417	50	-		
9.5	0			21	430	40	30	328	20
15	0			30	410	38	30	322	20
20	1			30	397	25	30	318	18
24	0			30	397	30	30	316	20
31	2			30	396	32	30	318	20
40	4			30	389	25	30	316	22
49	10	493	65	30	374	32	30	310	25
62	16	500	48	30	382	22	30	324	22
80	19	499	32	30	368	20	30	318	25
100	23	500	38	30	384	32	30	322	28
125	28	506	40	30	378	28	30	320	22
156	30	499	40	30	366	25	30	312	20
200	30	504	30	30	368	28			
250	30	490	28						

Table 2

Number, median, and semi-interquartile range of response latencies (msec) for various flash durations (msec) at three flash luminances (log ft-L).

Experiment I. Subject: J.S.

	-2.82			-1.81			-0.81		
T	N	Mdn	Q	N	Mdn	Q	N	Mdn	Q
0.1	-			-			7		
0.3	-			-			9		
0.5	-			-			17	459	60
0.7	-			-			26	428	43
1.0	-			1			29	435	31
1.5	-			-			29	419	30
2.0	-			5			-		
2.7	-			3			-		
3.5	-			9			-		
4.5	-			14	460	30	30	396	22
7.5	-			26	461	39	-		
9.5	1			28	453	32	30	374	36
15	1			30	419	25	30	366	20
20	5			30	412	25	30	362	18
24	6			30	412	19	30	377	22
31	6			30	404	24	30	362	22
40	17	540	48	30	406	31	30	354	22
49	21	523	42	30	402	20	30	361	29
62	26	503	39	30	392	28	30	350	18
80	25	493	38	30	396	18	30	348	23
100	29	500	38	30	404	18	30	357	18
125	30	500	29	30	406	20	30	349	18
156	30	489	25	30	398	14	30	360	21
200	30	500	30						
250	30	494	46						

Table 3

Median and semi-interquartile range of response latencies (msec) for various flash durations (msec) at -0.07 log ft-L.

Experiment I. Subjects: H.H. and J.S., N = 30.

	J.S.		H.H.	
T	Mdn	Q	Mdn	Q
0.1	405	29	348	20
0.3	396	19	354	30
0.5	382	20	342	30
0.7	372	22	330	25
1.0	362	10	326	20
1.5	370	26	320	20
2.0	356	20	314	20
4.5	344	24	298	15
9.5	318	17	283	20
15	326	19	265	18
20	324	26	274	18
24	317	22	272	18
31	316	16	270	25
40	310	23	268	15
49	321	20	272	25
62	328	24	272	18
80	310	23	276	22
100	307	19	270	22
125	302	22	272	22
156	310	13	268	15

Figure 1.

The percentage relative frequency of response, and the median latency of response, as functions of the logarithm of flash duration, at various flash luminances (log ft-L).

Experiment I Subject: H.H.

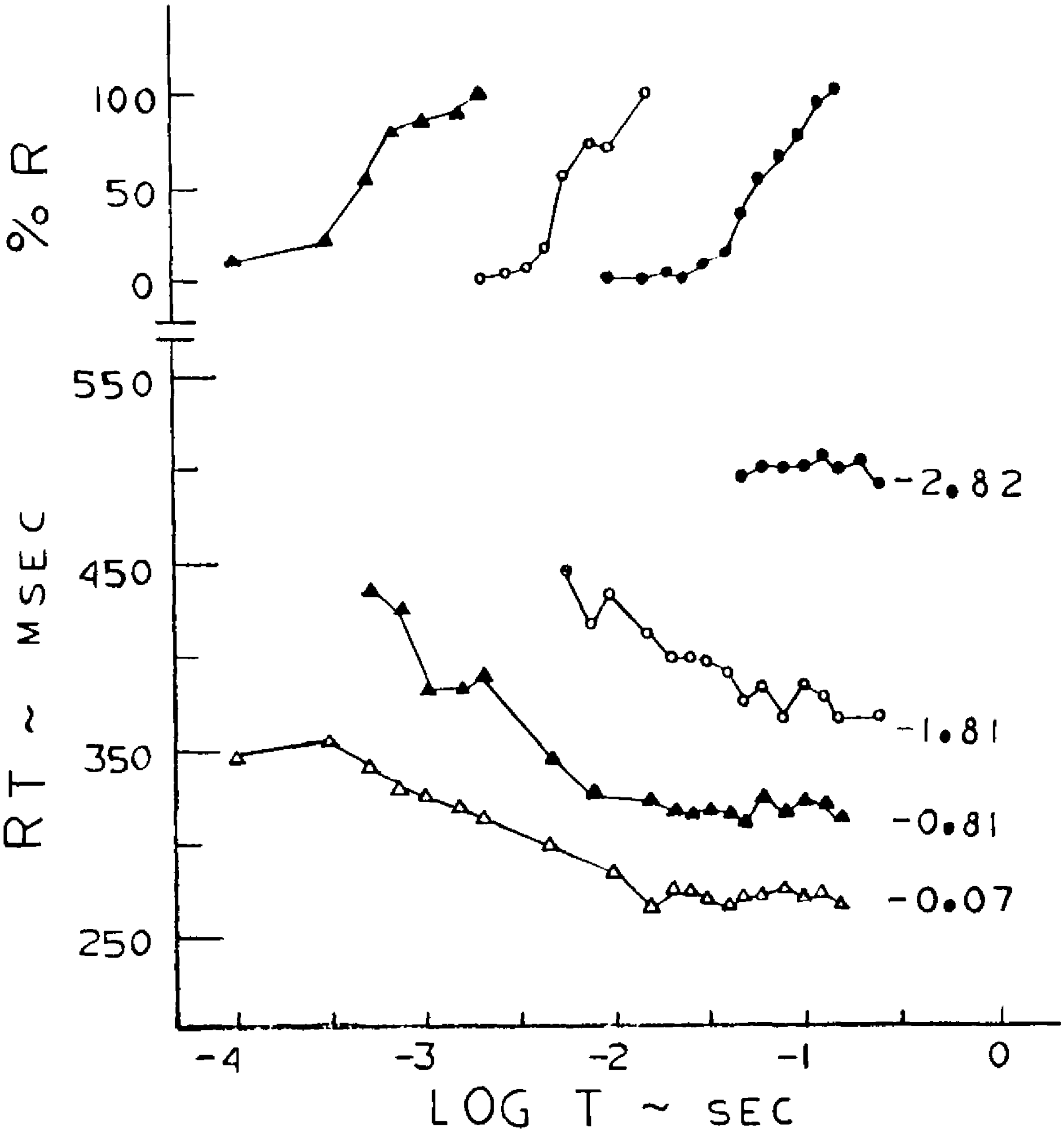
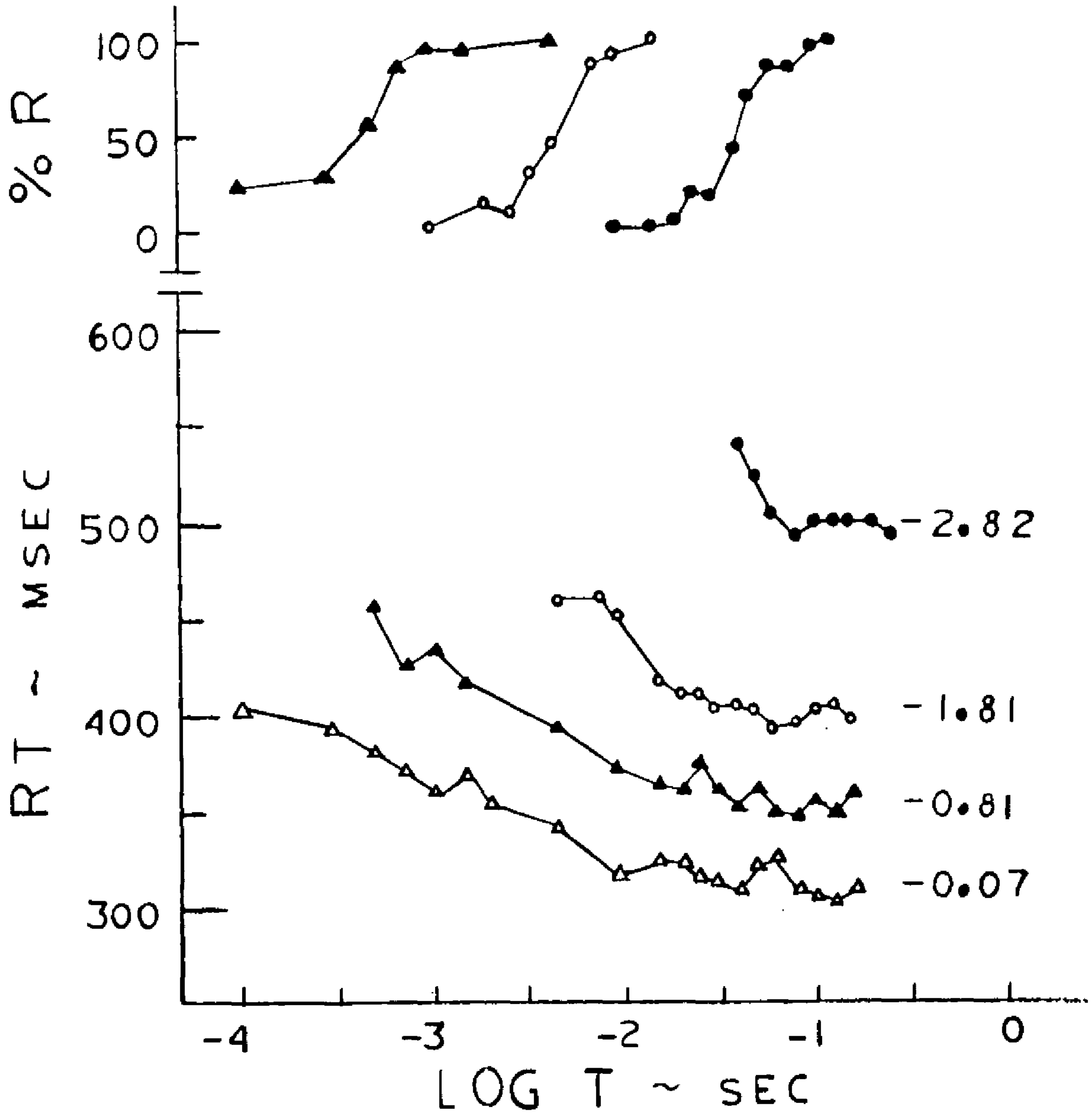

100
50
0
% R
550
450
350
250
RT ~ MSEC
-2.82
-1.81
-0.81
-0.07
-4
-3
-2
-1
0
LOG T ~ SEC

Figure 2.

The percentage relative frequency of response, and the median latency of response, as functions of the logarithm of flash duration, at various flash luminances (log ft-L).

Experiment I Subject: J.S.


100
50
0
% R
600
500
400
300
RT ~ MSEC
-2.82
-1.81
-0.81
-0.07
-4
-3
-2
-1
0
LOG T ~ SEC

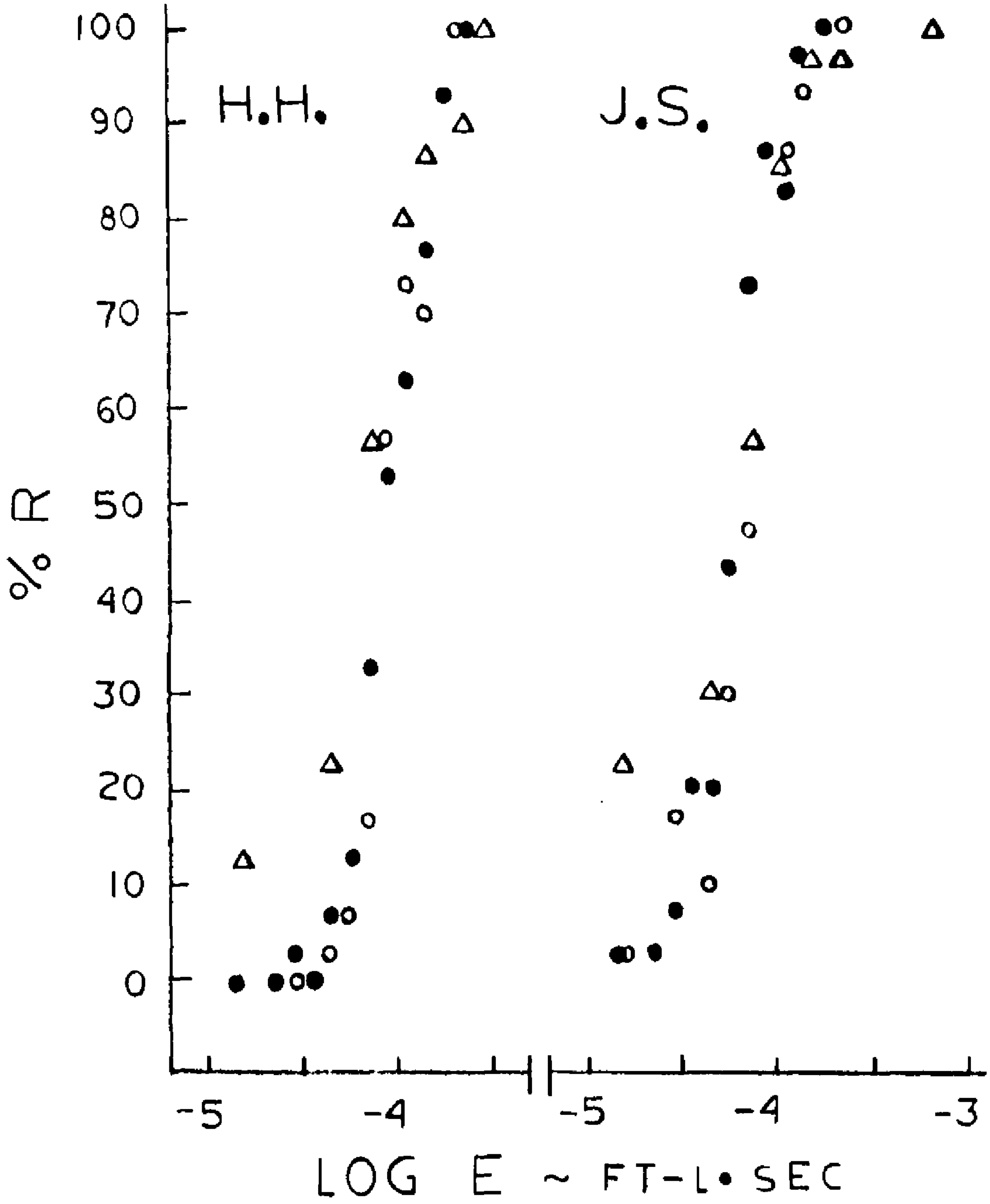
flash durations. It is also apparent that, with increases of flash luminance, the inverse relationship between RT and flash duration shifted to brieferdurations. However, the longest durations affecting RT tended to be longer than the durations at which %R reached 100%. It is relevant to add that the variability of latencies, as measured by the semi-interquartile range (Tables 1, 2, and 3), also tended to vary inversely with flash duration.

The role of flash energy in determining %R is indicated by Fig. 3, where %R is plotted as a function of the luminance-duration products, with luminance as the parameter. Conformity with the reciprocity rule is shown by the occurrence of a given %R for a given flash energy. The largest departures from the rule occurred with the 0.1-msec flash duration. At -0.81 log ft-L, the 0.1-msec flash determined a %R (about 13% for H.H. and 23% for J.S.) that was high in comparison with %Rs (about 0%) for the same nominal energy at the lower luminances, as if the energy in the 0.1-msec flash was effectively about 0.5 log ft-L-sec greater than its nominal energy. An analogous result occurred with the 0.1-msec flash at -0.07 log ft-L, for which %R was 100%, in contrast with the %R of about 50% that one might expect from its nominal energy (-4.07 log ft-L-sec), as if its energy was effectively at least 0.5 log ft-L-sec greater than the nominal energy. These "departures" are only apparent, resulting because the nominal energy (E_n) was less than the actual energy (E_a). In fact, the logarithm of the ratio, E_a/E_n, for both 0.1-msec flashes was close to 0.5 log

Figure 3

The percentage relative frequency of response, as a function of the logarithm of flash energy (i.e., luminance times duration), at various flash luminances (● -2.82, o -1.81 and Δ -0.81 log ft-L).

Experiment I Subjects: H.H. and J.S.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70
60
50
40
30
20
10
0
% R
H.H.
J.S.
-5
-4
-5
-4
-3
LOG E ~ FT-L• SEC

ft-L-sec. The quantity E_a was obtained by adding E_n and E_i, the latter being the energy in the initial portion of the flash waveform. Analogous computations for other flashes proved that the observed %Rs were all consistent with the reciprocity law, in that a product of flash luminance and flash duration predicted a given %R.

The role of flash energy in determining RT is particularly interesting for the range of flash energies which had determined %Rs in accordance with the reciprocity law. If a given energy determined a constant %R over flashes of various luminances and durations, did that %R correspond to a constant RT? The answer is no. In fact, the present findings are consistent with trends observable in previous results with simple reaction time (cf. Raab & **Fehrer**, 1962), where reaction times determined by a given flash energy were briefer for briefer and more intense flashes. This outcome is seen readily in Tables 1 and 2. For example, the means of the first four RTs tabled at each luminance in Table 1 are (from the lowest to the highest luminance) 498, 426, and 394 msec, and the associated means of Qs are 46, 38 and 47 msec, respectively. The analogous means from Table 2 are 515, 448, and 435 msec, with mean Qs of 42, 32, and 41 msec, respectively. Contrary to a prediction based on the reciprocity law, RTs for a given flash energy were an inverse function of flash luminance and, of course, a positive function of flash duration. On the other hand, the variability of latencies, as indexed by Qs, did not appear to vary systematically with the luminances of equal-energy flashes.

EXPERIMENT II

Procedure

Experiment II yielded results which were similar to those from Experiment I, however, there were a number of procedural differences between the determinations.

The Foveal viewing condition and a 2.8-sec foreperiod were used with J.S. Two values of flash luminance, (A) -1.77 and (B) -1.24 log ft-L, were presented during any session, in alternating blocks of trials. The sequence of blocks in the first session was AB/BA/AB/BA/AB, where each letter represents a block during which all values of flash duration occurred once in a shuffled order with interspersed blanks (3 per A block and 4 per B block), and slash marks indicate rest periods outside of the booth. The sequence was reversed in the second session and simple reversal continued during the experiment. Preceding each pair of blocks, the subject was adapted to darkness for 10 min. Since each luminance was presented in 5 blocks per session, over 14 sessions, a luminance-duration combination occurred on 70 trials.

Results

As in Experiment I, J.S. never responded to a blank. Table 4 is analogous to Tables 1, 2, and 3. Figure 4, analogous to Figs. 1 and 2, shows: %R increased with increases of flash duration; RT

Table 4

Number, median, and semi-interquartile range of response latencies (msec) for various flash durations (msec) at two flash luminances (log ft-L)

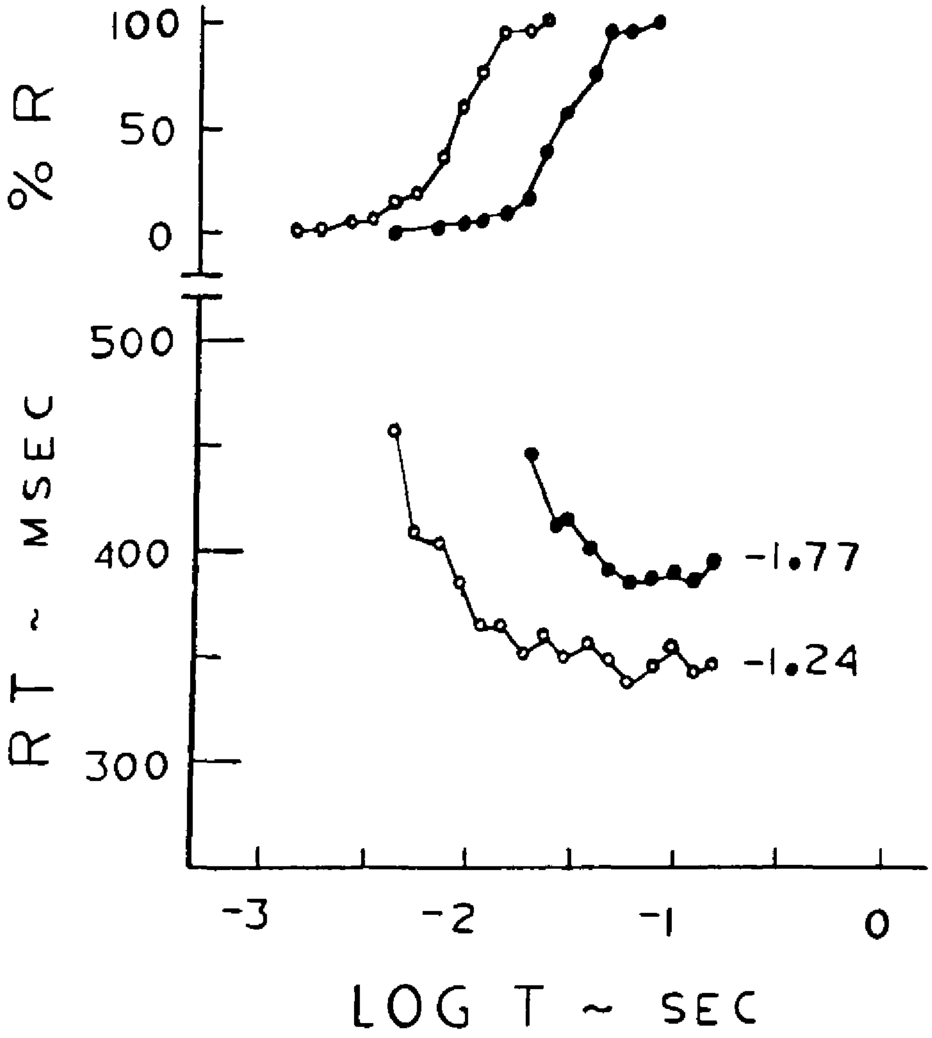
Experiment II. Subject: J.S.

		-1.77			-1.24	
T	N	Mdn	Q	N	Mdn	Q
1.5	-			1		
2.0	-			1		
2.7	-			5		
3.5	-			6		
4.5	0			10	456	77
5.6	-			13	408	55
7.5	3			26	402	40
9.5	4			42	384	40
12	5			53	364	38
15	7			66	363	28
20	13	445	40	67	352	22
24	27	411	48	70	360	28
31	40	416	50	70	350	28
40	52	402	38	70	357	20
49	65	391	30	70	348	22
62	67	387	30	70	339	18
80	70	388	30	70	346	20
100	70	391	32	70	354	28
125	70	386	30	70	341	30
156	70	394	32	70	348	22

Figure 4

The percentage relative frequency of response, and the median latency of response, as functions of the logarithm of flash duration, at two flash luminances (log ft-L).

Experiment II Subject: J.S.


100
50
0
% R
500
400
300
RT ~ MSEC
-1.77
-1.24
-3
-2
-1
0
LOG T ~ SEC

varied inversely with flash duration; and the longest flash affecting RT was longer at the lower luminance.

The role of flash energy in governing %R is indicated by Fig. 5, where %R is a single function of energy. Although the reciprocity rule accounts for the %Rs, it does not account for the RTs. Figure 6 shows that the RTs associated with a given %R were ordered as a function of luminance: the briefer and more intense flash of a given energy determined a briefer RT. The graph also shows that the semi-interquartile ranges (Q) of latencies were ordered to some extent with the luminance of flashes which had determined a given %R.

Figure 5

The percentage relative frequency of response, as a function of the logarithm of flash energy (i.e., luminances times duration), at two flash luminances (● -1.77 and o -1.24 log ft-L).

Experiment II Subject: J.S.

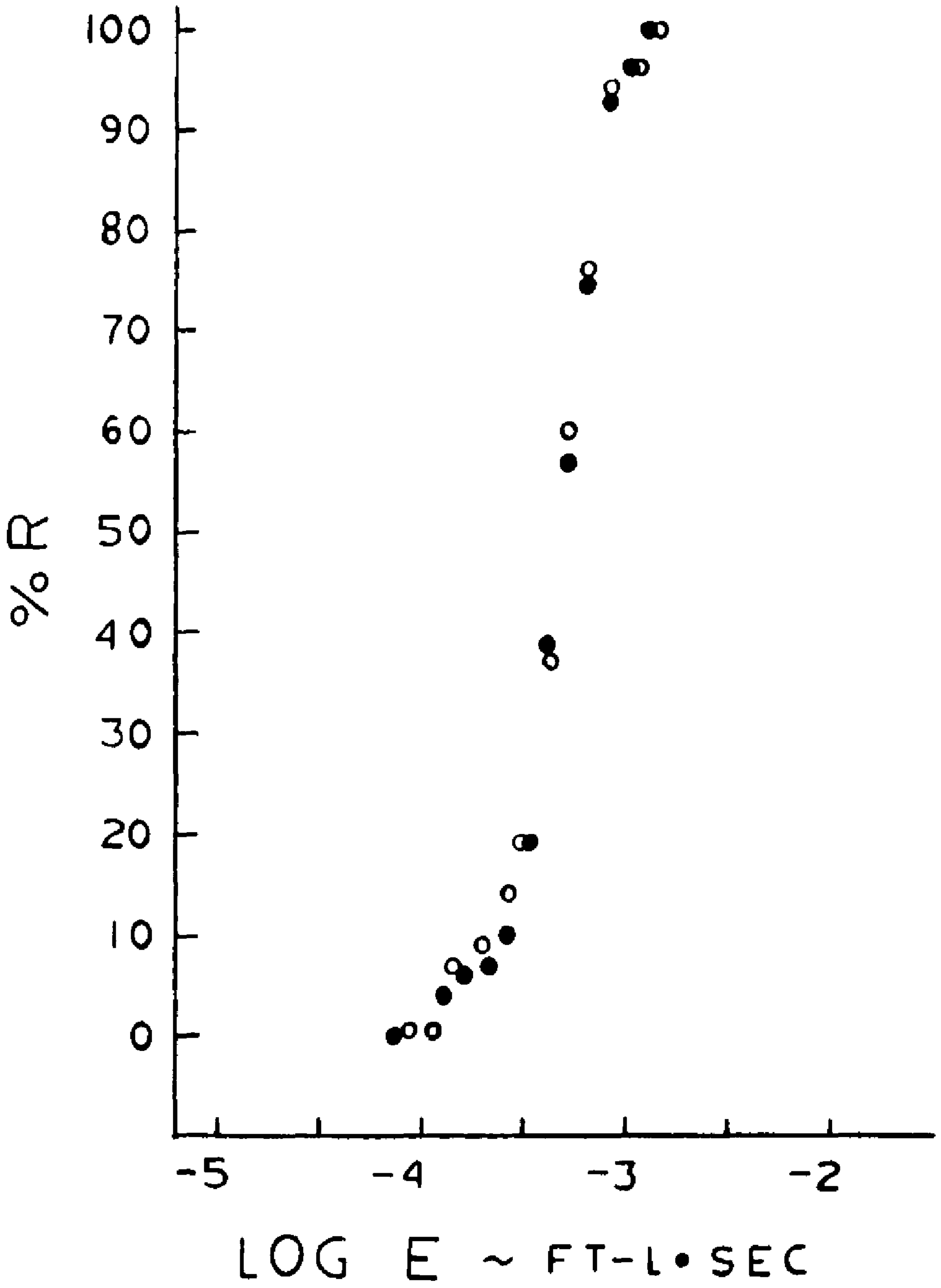
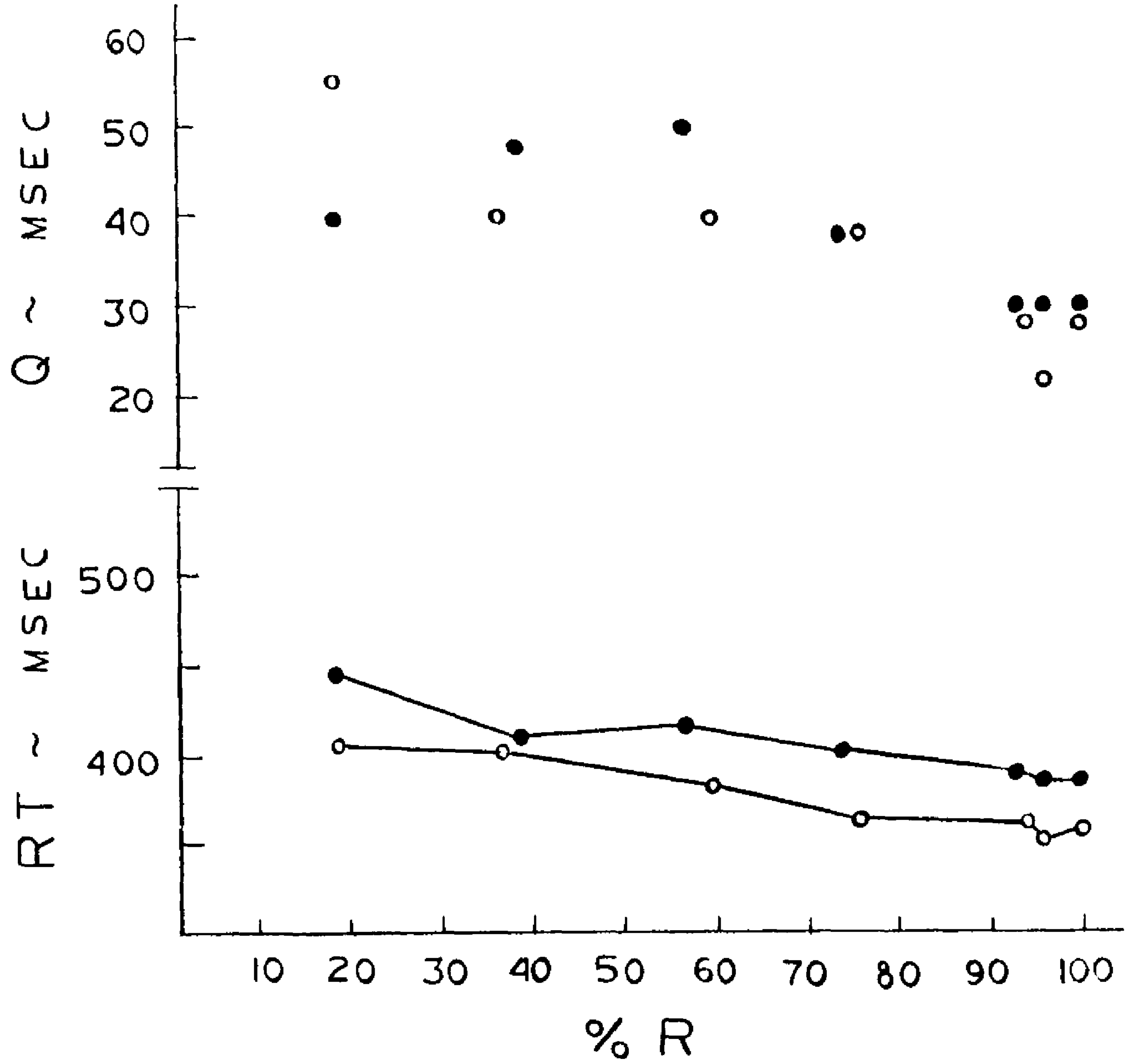

100
90
80
70
60
50
40
30
20
10
0
%R
-5
-4
-3
-2
LOG E ~ FT-L • SEC

Figure 6

The semi-interquartile range and the median of the latency of response, as functions of the percentage relative frequency of response, at two flash luminances (● -1.77 and o -1.24 log ft-L).

Experiment II Subject: J.S.


60
50
40
30
20
Q ~ MSEC
500
400
RT ~ MSEC
10
20
30
40
50
60
70
80
90
100
% R

EXPERIMENT III

Procedure

This experiment was the first of three in which a stimulus was composed of two successive flashes and the independent variable was the interval (ΔT) between flash onsets. As in Experiments I and II, the percentage relative frequency (%R) and the median latency (RT) were the principal dependent variables.

Two stimuli, each of which contained equal flashes, were presented. One stimulus contained two 2.5-msec flashes; each was at -0.74 log ft-L, with an energy of -3.34 log ft-L-sec. The other stimulus consisted of 25-msec flashes, each at -1.77 log ft-L, with an energy of -3.37 log ft-L-sec. (In terms of absolute luminance, the lower luminance was 9.3% of the other.) The Foveal viewing condition, a foreperiod of 2.8 sec, and 10 min of dark adaptation were used with subject M.R.

Somewhat different procedures were used to collect data with -1.77 log ft-L (L) and -0.74 log ft-L (H). The sequence of blocks during the first session was L/H/H, where slash marks indicate rest periods outside of the booth. This order was reversed during the second session and alternation of the block sequence was continued over 12 sessions.

During an L block, each ΔT occurred once in a shuffled order with 2 blanks, the cards were reshuffled, and the run continued without interruption for about 38 trials, when the subject rested in the booth. Then the run was resumed to completion. There were 75 trials in a block, with 5 trials for each ΔT. The designations, INF1 and INF2 (in Table 5), mean that there were 10 trials with the first flash alone (thus, INF signifies an infinite ΔT), and the numbers indicate the order in which the data were tabulated for a shuffled order of ΔTs. Each ΔT occurred on 60 trials over the 12 sessions.

During an H block, each series of ΔTs was a shuffled order within which 4 blanks were interspersed. In one block, two series of trials with each ΔT occurred without interruption before the rest period. The procedure with the second block was the same as with the first. Each ΔT occurred on 4 trials during each session, giving a total of 48 trials for the experiment.

Results

Table 5 contains the number (N) and median (Mdn) of response latencies for each of the two stimuli, at various ΔTs (in msec). The subject never responded to a blank. Figure 7 shows %R and RT as functions of ΔT (log sec). The abscissa has a value, INF, which denotes effects due to the first flash, when the second flash was deleted from the stimulus. In the case of %R, INF denotes the total frequency of response (INF1 plus INF2) during 96 trials at

Table 5

Number and median of response latencies (msec) for various intervals (msec) between the onsets of two, two-flash stimuli.

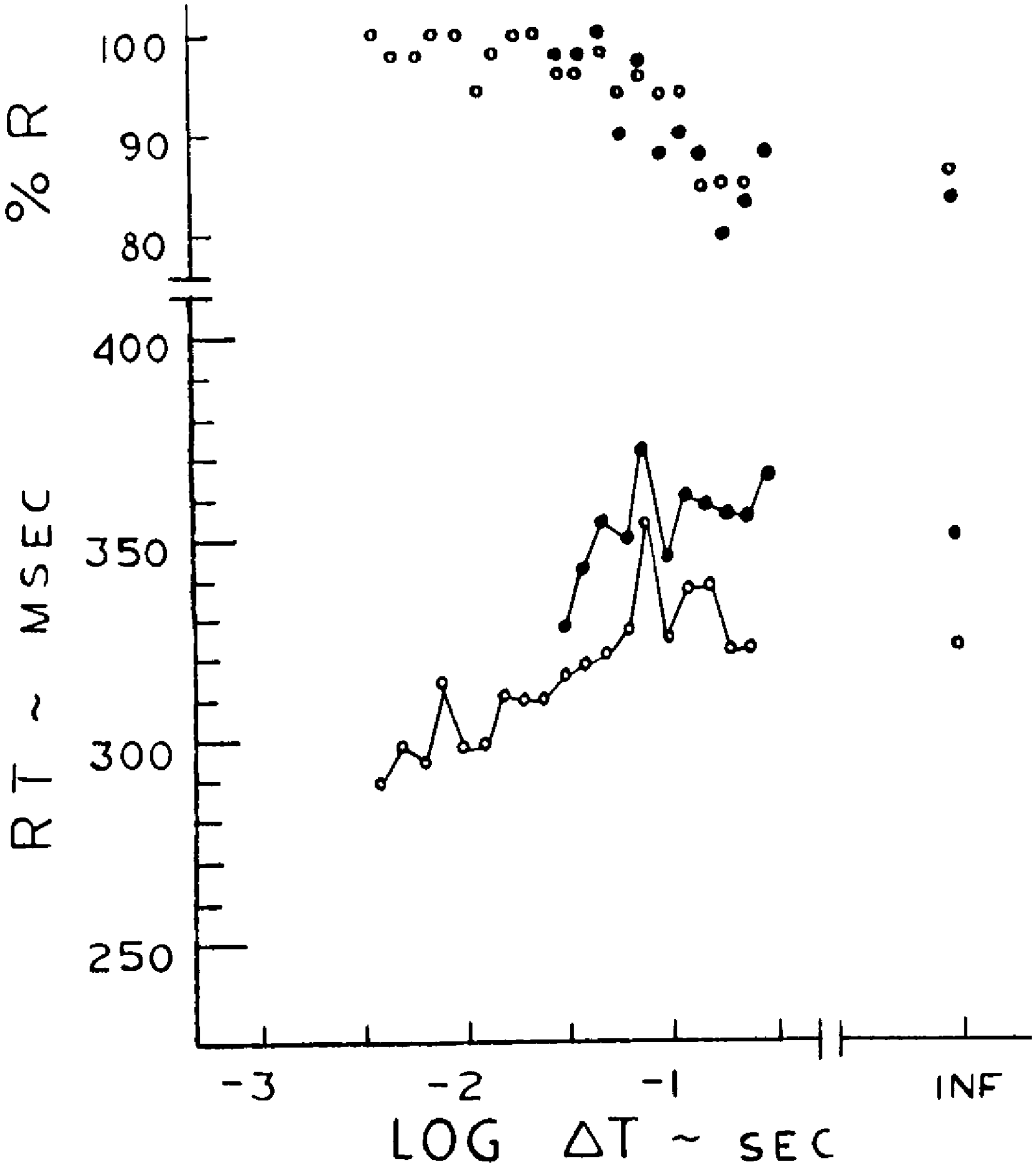
Experiment III. Subject: M.R.

	2.5 msec -0.74 log ft-L		25 msec -1.77 log ft-L	
ΔT	N	Mdn	N	Mdn
4	48	289		
5	47	298		
6.5	47	295		
8	48	314		
10	48	297		
12.5	45	298		
16	47	312		
20	48	310		
25	48	310		
32	46	316	59	327
40	46	318	59	342
50	47	321	60	354
65	45	327	54	350
80	46	354	58	372
100	45	325	53	345
125	45	337	54	360
160	41	338	53	358
200	41	322	48	356
250	41	323	51	355
315	-	-	53	365
INF1	44	320	48	342
INF2	39	326	52	357
Trials	48		60	

Figure 7

The percentage relative frequency of response, and the median latency of response, as functions of the logarithm of the interval between flash onsets in two, two-flash stimuli (● 25 msec at -1.77 log ft-L; o 2.5 msec at -0.74 log ft-L).

Experiment III Subject: M.R.


% R
100
90
80
RT ~ MSEC
400
350
300
250
-3
-2
-1
INF
LOG ΔT ~ SEC

-0.74 log ft-L and 120 trials at -1.77 log ft-L. In the case of RT, INF indicates the mean of the two median RTs (INF1 and INF2).

In agreement with the preceding experiments, single "equal"-energy flashes determined equal %Rs: the %R for 96 trials with the 2.5-msec flash was about 86%, while the %R for 120 trials with the 25-msec flash was about 83%. But the latency determined by the 2.5-msec flash, 323 msec, was briefer than the latency obtained with the 25-msec flash (350 msec). These findings are consistent with the previous results: a briefer latency was determined by the briefer and more intense of the equal-energy flashes which had determined equal %Rs.

Figure 7 indicates that the two, two-flash stimuli determined approximately equal %Rs at each ΔT that was common to both stimuli. The limited range of overlap between the two stimuli on the ΔT axis is due, of course, to the difference between flash durations. Also, %R was approximately constant for ΔTs up to about 50 msec (-1.3 log sec), then decreased with increases of ΔT until a ΔT of about 160 msec (-0.8). The lowest %Rs obtained with the two-flash stimuli were approximately equal to the %Rs determined by the first flashes alone (INF).

Figure 7 also shows that RT, while roughly constant at brief ΔTs, increased by about 15 msec between the briefest ΔTs and a ΔT of 50 msec. At 50 msec, RT for each two-flash stimulus was approximately equal to the RT for the first flash alone (INF). However, the longest RT for both stimuli occurred at a ΔT of 80 msec. In other words, RT was a nonmonotonic function of ΔT, between 50 msec and the long ΔT at which RT became equal once again to the RT for the first flash alone.

EXPERIMENT IV

Procedure

In Experiment III, functions relating %R and RT to ΔT were obtained at high values of %R (80% to 100%). Similar functions were determined in Experiment IV, but over a greater range of lower %Rs. Another purpose of this experiment was to provide an explicit bridge to Experiments I and II. Thus, two types of stimuli, single flashes of various durations, and a two-flash stimulus with 2.5-msec flashes spaced at various intervals, were presented. All flashes were at one luminance, -2.58 log ft-L. The Foveal viewing condition and a 2.8-sec foreperiod were used with M.R.

The luminance here was about 2 log units lower than in Experiment III with the 2.5-msec flashes. During preliminary runs with flashes yielding low frequencies of response, M.R.'s ability to detect such flashes improved considerably. After his behavior appeared to have become more or less stable, the stimuli used here were chosen. On 324 blank trials during the formal experiment, M.R. responded once with a latency of 252 msec.

A series of trials was a shuffled order of each value of flash duration (T), each interval (ΔT) between the onsets of the two, 2.5-msec flashes, and 6 blanks. Two series given continuously comprised a block of trials, after which a rest was taken outside the booth. Ten min of dark adaptation preceded each block. A session consisted of 3 blocks, hence, 6 trials with a stimulus. There were 9 sessions, which yielded 54 trials per value of T and ΔT, with one exception. The exception was the 2.5-msec flash (INF1 and INF2), which occurred on 108 trials.

Results

Table 6 contains the number (N) and median (Mdn) of response latencies for various values of ΔT and T (both in msec). As before, INF1 and INF2 refer to trials on which the first flash only (2.5 msec) of the two-flash stimulus occurred. Asterisks in the table indicate one point of physical identity between the two types of stimuli, the 2.5-msec flashes. The second point of identity is the energy in the two-flash stimulus and single flashes with durations between 4.5- and 5.8-msec.

Figure 8 shows %R and RT as functions of ΔT and T, that is, log TIME (sec) after light onset. The two data points (cf. Table 6) for the 2.5-msec flashes are plotted in terms of flash duration (-2.6 log sec). A horizontal dashed line marked INF (infinite ΔT) runs between the two points to denote their role in the ΔT function. In the case of %R, INF (about 22%) represents the total number of responses to the 2.5-msec flash over 108 trials. In the case of RT, INF denotes the mean (434 msec) of the two median latencies (INF1 and INF2) that were determined by the 2.5-msec flash.

Table 6

Number and median of response latencies (msec) for (1) various intervals (msec) between the onsets of two 2.5-msec flashes, and (2) various durations (msec) of single flashes.

Flash luminance: -2.58 log ft-L

Experiment IV. Subject: M.R.

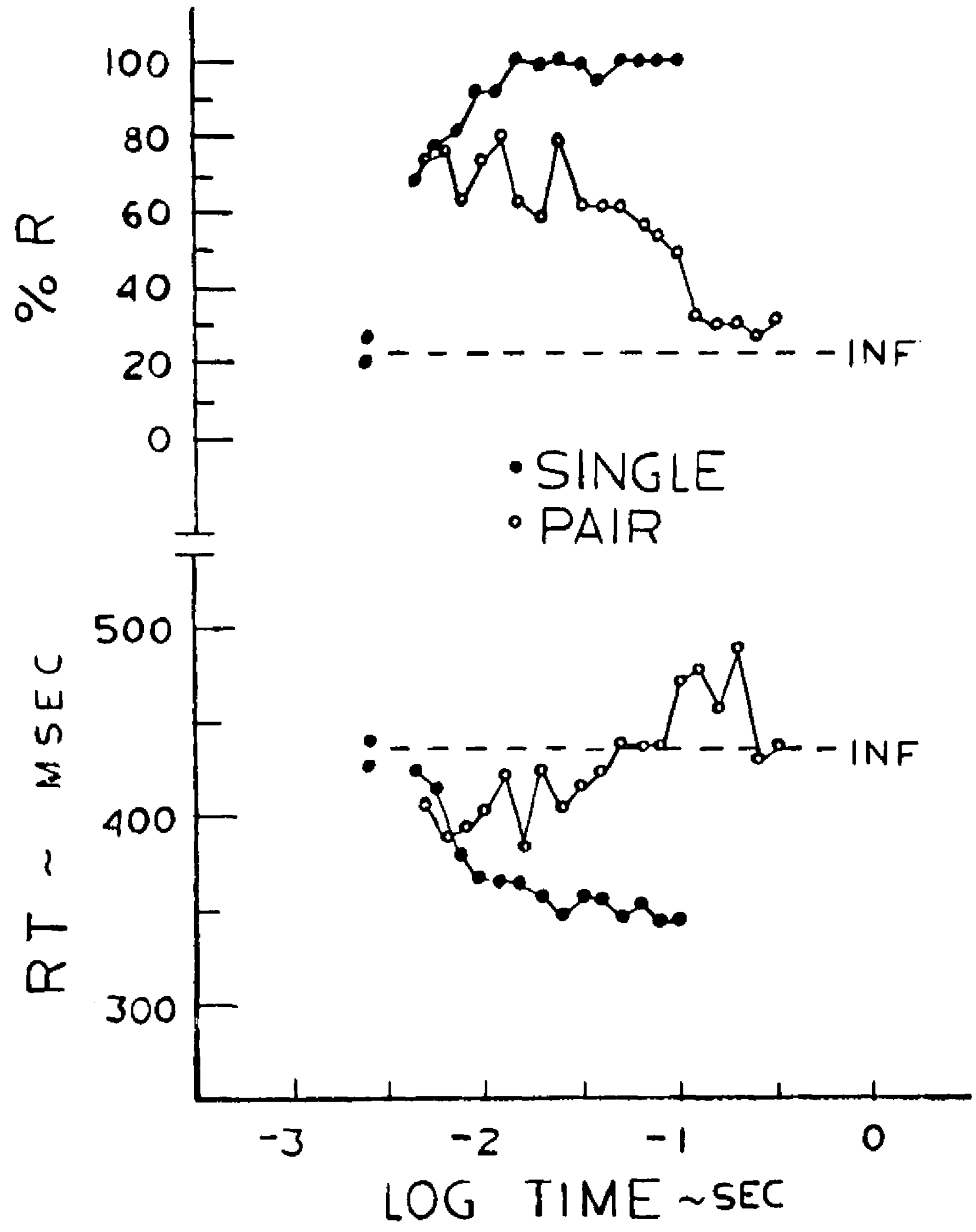
Two Flashes			Single Flashes		
ΔT	N	Mdn	T	N	Mdn
5	40	408	2.5*	10	440
6.5	41	389	2.5**	14	427
8	34	394	4.5	36	426
10	40	404	5.8	41	416
12.5	43	422	7.5	44	379
16	34	384	9.5	49	368
20	32	427	12	49	366
25	42	406	15	54	367
32	33	418	20	53	358
40	33	425	25	54	348
50	33	439	32	53	358
65	30	438	40	51	357
80	29	438	50	54	347
100	26	471	63	54	354
125	17	478	80	54	345
160	16	458	100	54	346
200	16	490			
250	14	430			
315	17	437			
INF1*	10	440			
INF2**	14	427			
Trials	54			54	

*, ** - See text

Figure 8

The percentage relative frequency of response, and the median latency of response, as functions of the logarithm of time after light onset: the _duration_ of single flashes (●); and the _interval_ between the onsets of two, 2.5-msec flashes (o). All flashes were at -2.58 log ft-L. The line, INF, indicates one point of physical identity between the two types of stimuli, the single 2.5-msec flashes.

Experiment IV Subject: M.R.



% R
100
80
60
40
20
0
INF
• SINGLE
∘ PAIR
RT ~ MSEC
500
400
300
INF
-3
-2
-1
0
LOG TIME ~SEC

In considering %R as a function of ΔT, one observes that %R was a fluctuating, but approximately constant function of ΔT up to about 32 msec (-1.5 log sec). At longer ΔTs, %R decreased to a ΔT of about 125 msec (-0.9) and, thereafter, was essentially constant. The low constant value of %R (about 30%) was slightly higher than %R for the first flash alone (INF: 22%). With regard to the fluctuating character of %R at brief ΔTs, it is noteworthy that similar fluctuations, but over a smaller range (10%), are observable in results of van den Brink and Bouman (1954; Figs. 5b and 5c). Fluctuations here had a range of about 20%.

In turning to RT as a function of ΔT (Table 6; Fig. 8), one observes that RT fluctuated, but tended to be constant at brief ΔTs. The latency then increased with ΔT until it equalled RT for the first flash alone (INF) by 50 msec (-1.3). Thereafter, RT remained constant until a ΔT of 80 msec (-1.1). Between ΔTs of 80 and 250 msec (-0.6), RT reached a peak and declined to equal RT for the first flash alone.

Results on %R and RT, as functions of flash duration (T), are relevant to the form of the summation between the two, 2.5-msec flashes at brief ΔTs. In Fig. 8, one observes that the T and ΔT curves intersect at a %R of about 70%. This value of %R was determined by the two 2.5-msec flashes at brief ΔTs and by a single flash of approximately a 5-msec duration (-2.3 log sec). Thus, the value of %R for ΔTs up to about 32 msec appears to be attributable to the combined energy in the pair of flashes.

There was an inverse relationship between RT and flash durations somewhat briefer than 32 msec (-1.5 log sec). The conformity of RT for brief ΔTs, with a prediction based on the energy in the two flashes, can be evaluated in Table 6. The mean of median RTs for ΔTs from 5- to 12.5-msec was 403 msec, 13 msec briefer than RT for the 5.8-msec flash. Thus, the energy fit is not obviously valid. This result must be checked, because preliminary data (%R equal to 100% at all ΔTs) indicated that RTs for brief ΔTs were accurately predictable on the basis of the summed energy in two-flash stimuli (with all flashes at one luminance).

EXPERIMENT V

Procedure

In this experiment, RT was determined as a function of ΔT, but here %R was 100% at all ΔTs. The luminance of the equally intense 1-msec flashes was -1.24 log ft.L. Values of ΔT (msec) were 3.2, 4, 5, 6.5, 8, 10, 12.5, 16, 20, 25, 32, 40, 50, 65, 80. 100, 125, 160, 200, 250, INF1 and INF2.

The subject, H.H., was adapted to darkness for 10 min. A series of trials comprised a shuffled order of each ΔT, plus between 4 and 6 blanks (so that blanks occurred throughout a series). Two uninterrupted series equalled a block, at the end of which the subject left the booth. Four blocks occurred in each session and there were 4 sessions; each ΔT occurred on 32 trials.

Results

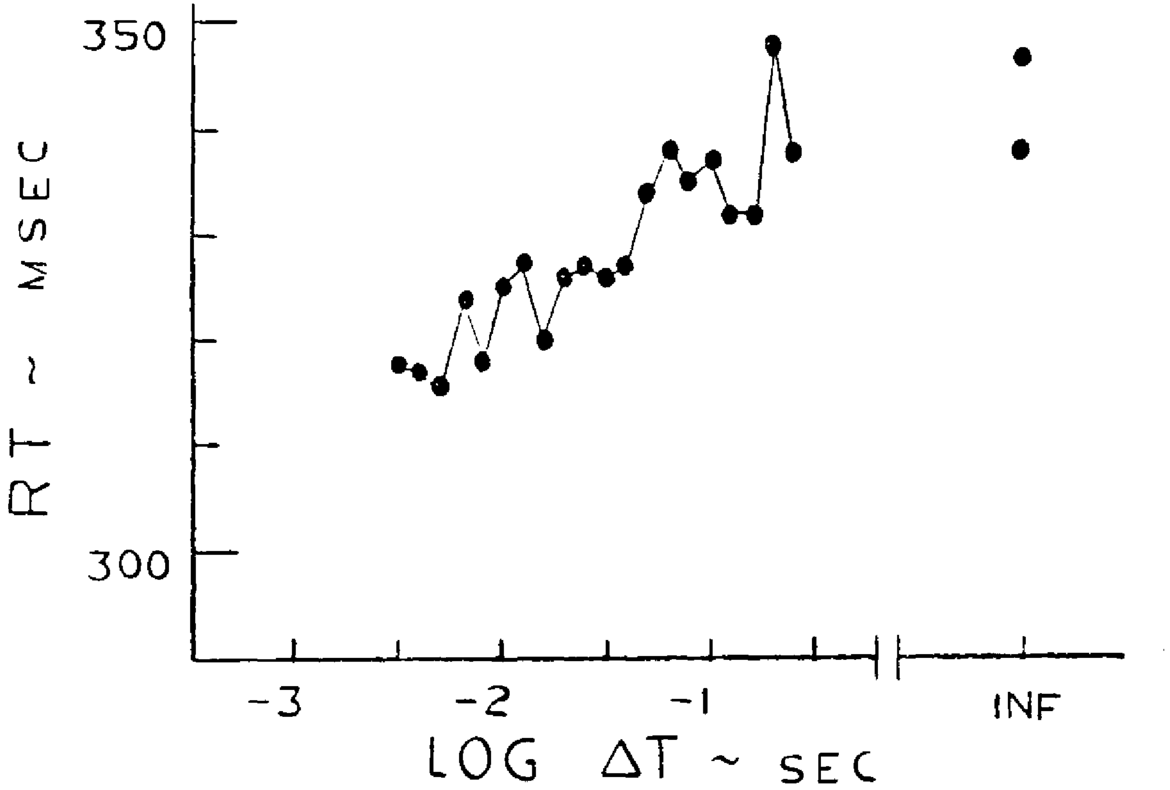
Of 153 blanks, H.H. responded three times with latencies of zero, 179, and 393 msec.

Figure 9 shows RT (median) as a function of ΔT (log sec). Both INF1 and INF2 are indicated (INF). Response latency was a positive function of ΔT, except at quite brief ΔTs, where RT tended to be constant. There is no suggestion of a nomonotonic trend at long ΔTs. Instead, the contribution of the second flash

Figure 9

The median latency of response, as a function of the interval between the onsets of two, 1-msec flashes, each at -1.24 log ft-L. A median was based on 32 responses. The value, INF, signifies that the first 1-msec flash was presented alone.

Experiment V Subject: H.H.


350
300
RT ~ MSEC
-3
-2
-1
INF
LOG ΔT ~ SEC

diminished gradually as ΔT was extended, until a long ΔT was reached, where RT was determined by the first flash alone.

DISCUSSION

Results with the two dependent variables, the frequency of seeing (%R) and the median latency (RT), were in reasonable accord with data obtained in previous, separate determinations of thresholds, on the one hand, and simple reaction times, on the other. And the latency data were obviously consistent and complementary to the frequency data (Steinman, 1944, p. 59). But the RT functions were not, by any stretch of the imagination, simple extrapolations of the %R functions.

The principle features of the frequency-of-seeing functions agreed with those which are either indicated in or implied by previous visual-threshold data (e.g., Long, 1951; Bouman and van den Brink, 1952; Davy, 1952; van den Brink & Bouman, 1954; Blackwell, 1963, p. 155; Ikeda, 1965). In general, the %R data conformed with the principle that a given stimulus energy, which is delivered within some period of time after stimulus onset, determines a constant %R (cf. Bartlett, 1965, p. 174; Graham, 1965, p. 77).

With the luminance of single flashes fixed, %R increased with increases of flash duration, describing a "psychometric" function. Such functions have usually been determined with flash luminance as the independent variable and with flash duration as the parameter (however, see Crozier, 1950). Nonetheless, the psychometric functions conformed with the reciprocity law, in that the product of flash luminance and flash durations was an adequate basis for predicting any %R.

In the case of the two-flash stimuli, %R was constant for some range of interflash intervals, and the constant %R was consistent with the rule of energy determination. Experiment IV showed that the %R for two 2.5-msec flashes was approximately equal to the %R determined by a single 5-msec flash, when all flashes were of one luminance. When the luminances and durations of flashes in two, two-flash stimuli were adjusted so that the two stimuli were approximately equal in energy (Experiment III), the stimuli determined constant %Rs which were approximately equal.

In turning to the RT data, one observes that RT varied inversely with flash luminance, as well as with flash duration. The longest durations which produced changes in RT were briefer at the higher luminances. But the shift in the position of the curves relating RT to flash duration (Experiment I) was not a reciprocal function of flash luminance, in contrast with the shift in position of the psychometric functions. Nor did the reciprocity rule account for RTs which were determined by single flashes of constant-energy content. Although RT varied inversely with both luminance and duration, indicating that the amount of stimulation was a controlling factor, the products of the two variables were not associated with constant RTs. For flashes containing a given energy that had determined a constant %R, the briefer and more intense flashes yielded briefer RTs. This systematic departure of RTs from a prediction based on the reciprocity rule was smaller at higher luminances (Experiment I). The trends observed here were similar to those which are observable in previous reaction-time data (cf. Raab & Fehrer, 1962). Since the reciprocity law is closely related to other visual-threshold relationships (e.g., Keller, 1941), one should be suspicious of future extrapolations, by formal substitution of dependent variables, of the exact laws of visual threshold to visual reactions times. In fact, the RT data disclosed features of stimulus control which were not evident from %R variations.

When a relatively low energy was sufficient to occasion a positive response, the latency of the response was relatively long and variable. With increases of energy, %R increased, and RT decreased, becoming less variable. The results suggest that a higher %R was due to a greater "magnitude" of sensory effect that was determined by a higher energy. But the processes underlying response were not just a function of energy, judging from the RT data. Briefer RTs occurred with the briefer and more intense flashes of a given energy. And the RTs for a given energy were a decreasing, decelerating function of flash luminance (Experiment I). Evidently, flash luminance was an important determinant of the speed with which flashes of a given energy were processed; however, luminance could not have been the only factor governing the time course of processing. The RTs determined with the two-flash stimuli, in which flashes were equal in luminance, tended to increase gradually with increases of the interflash interval. In fact, RT appeared to vary with brief interflash intervals for which %R remained constant, as if RT was the more sensitive index that stimulation (i.e., the second flash) was delayed with respect to stimulus onset. Constant RTs and constant %Rs occurred over different ranges of interflash intervals. And the two dependent variables were controlled by different ranges of flash durations. One might speculate on the reasons for such range differences, as well as on the other features of the results, but the data do not appear to provide enough information for a rigorous formulation.

In considering the covariation of %R and RT, it should be recognized that simultaneous determination of the two variables does not guarantee that their systematic variations represent identical underlying processes. The orderliness of the data indicates reasonably good stimulus control. This is also suggested by the fact that responses to blanks were rare. But the manner in which such control was achieved, during periods of time which exceeded 250 msec (all RTs were longer than 250 msec), is difficult to infer, even from two measures of stimulus effect. Moreover, existing theoretical formulations on visual detection (e.g., Blackwell, 1963), which are concerned with relative frequencies of response, are not readily extended to latencies of response. For example, the data are inconsistent with the storage-interval concept of critical duration, because systematic control of response, by flash luminance, was in evidence when %R conformed demonstrably with the reciprocity law (see the Introduction). It seems clear that the frequency of seeing (and probably other measures which obey the same laws), one of the traditional indices of stimulus effects in visual-threshold experiments, provides a rather incomplete picture of such effects.

The entire set of data, which is only a sample of an essentially unexplored territory, requires an explanation. Much more work is needed to gain a clearer picture of the functions and the underlying processes. In considering the processes responsible for latency variations, the latency measure itself requires attention. Informal discussions with a number of investigators have indicated their concern with whether latencies should be clocked from stimulus onset or from some other point(s) in time after stimulus onset. They noted correctly that if flash durations were subtracted from the associated RTs in Experiments I, II, and III, one would find that the rescaled RTs would conform more closely to a constant-latency for constant-energy prediction than the RTs did. Such an outcome suggests the need for a directed study of the latency measure, in order to provide a rigorously justified reference for process-oriented inferences. Of course, complex questions on the appropriateness of a measure are not unique to latency determinations (e.g., Blackwell, 1963). Judging from the present results, joint determinations of frequencies and latencies can provide more complete information on stimulus effects and subject factors than has been available from traditional separate determinations of the two variables. Since the covariation of the two measures is relevant to an understanding of each, one may well hope that future evaluations of visual detection will elaborate on the present results and, thereby, have greater scope than at the present time.

SUMMARY

Subjects in traditional determinations of thresholds, and those in determinations of simple reaction times, are required to discriminate, or detect, stimulus occurrence. While there is reason to believe that reaction time can yield information about detection processes, latencies have not typically served as references for either the formulation or evaluation of theoretical accounts on such processes. One good reason for the prevailing lack of regard is that the two types of determinations differ operationally, at least in terms of stimulus magnitudes and dependent variables. Thus, the meaning of latency data, when considered with reference to threshold data, is difficult to ascertain. The present experiments bridged certain operational gaps between the two situations and were essentially comparative analyses of frequencies of seeing and reaction times.

Subjects were instructed to respond ("Yes") as soon as they saw a stimulus light. The frequency and the latency of response were recorded on the same trials, with stimuli for which the two aspects of response covaried. The percentage relative frequency of response (%R), and the median latency of response (RT), were evaluated under conditions for which %R could vary in accordance with the reciprocity law and an associated relationship.

The reciprocity law accounted for %R determined as a function of flash duration, at various flash luminances. With luminance fixed, %R increased with increases of flash duration, describing a psychometric function. And the product of flash luminance and flash duration, i.e., stimulus energy, predicted any %R reasonably well, in accordance with the law. Although RT varied inversely with the luminance and the duration of flashes which determined various %Rs, RT was not predicted with reference to the law. Given products of luminances and durations, which had determined constant %Rs, failed to yield constant RTs. Instead, the briefer and more intense flashes of a given energy determined briefer RTs. And RTs determined by constant-energy flashes were a decreasing, decelerating function of flash luminance. Also, the longest flash durations affecting RT decreased with increases of flash luminance, but not as a reciprocal function of luminance.

In addition to experiments with single flashes of various luminances and durations, %R and RT were recorded as functions of the interval between two successive flashes (equal in luminance and duration). Variations of %R were consistent with the idea that a given stimulus energy determines a constant %R, if the energy is delivered within a limited period of time. With increases of the interflash interval, %R fluctuated about a given average for some range of brief intervals, then decreased monotonically to a low value that approximated the %R determined by the first flash alone. On the other hand, RT tended to be constant over a more limited range of interflash intervals, then increased to become equal to the RT determined by the first flash alone. Further increases of the interval yielded a further increase in RT to a maximum, followed by a decline until RT was equal once again to the RT for the first flash, when the second flash was absent.

Although the experiments were regarded as exploratory, because of their newness, the results with %R and RT were in reasonable agreement with those from previous, separate determinations of thresholds and simple reaction times, respectively. In the past, certain investigators appeared to have demonstrated that the laws of visual threshold generalize (i.e., hold) to simple reaction times (i.e., for suprathreshold stimuli). Such demonstrations were considered to have questionable validity in view of the present results with RT, the variations of which were not an obvious concomitant of %R variations. Indeed, the RTs disclosed aspects of stimulus control and effects which were not indicated by %Rs. For example, the systematic variation of RT, with the luminance of constant-energy flashes that determined constant %Rs, indicated that stimulus energy is not the only aspect of stimulation governing response in a threshold experiment. The control by luminance was regarded as being inconsistent with the influential, but questioned, idea that the reciprocity relationship reflects the operation of an initial storage process. It was also noted that other existing theoretical accounts on visual thresholds are not readily extended to the RT data. No theoretical interpretation of the results was offered. Instead, the need for further determinations of the present type was stressed.

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AUTOBIOGRAPHICAL STATEMENT

The author was born in New York, New York, on 8 December, 1937. He attended Stuyvesant High School from 1951 to 1955, then majored in Zoology at Cornell University, from which he received a B.A. in 1959. For one year thereafter he took additional courses (e.g., biochemistry, cellular physiology, and microbiology) at Columbia University.

He matriculated for the M.A. in 1960 in the Department of Psychology of Columbia University and the degree was conferred in 1963. At Columbia, his interest in response latency was first motivated by Dr. William McGill. This interest was amplified considerably by his experience at the Brooklyn State Hospital laboratories of Biometrics Research where his supervisor was Dr. Samuel Sutton. It was while working part- and full-time at those laboratories between 1961 and 1963 (with a Public Health Service Training Grant from 1962 to 1963), that the author was first exposed to questions on simple reaction time in relation to the reciprocity law.

In 1963, the author matriculated in the doctoral program of the City University of New York at Brooklyn College. As the research assistant of Dr. David Raab, he worked on a variety of psychophysical projects for about one year. A paper by Raab and Grossberg ("Reaction Time to Changes in the Intensity of White Noise", *J. exper. Psychol.*, 1965, *69*, 609-612) indicated that one type of generalization to response latency from threshold data is not valid. In 1964, the author was elected as an Associate of the Brooklyn College Chapter of Sigma Xi. From 1964 to 1966, he worked as a part-time research psychologist at an institution for retardates (Willowbrook State School). During the same period, he worked on the instrumentation, preliminary determinations, and tactics of the present experiments, which were sponsored by Dr. Eric Heinemann. Formal determinations were run in 1966, during the summer of which the author was a Lecturer on elementary statistics at Brooklyn College.

In the Spring of 1967, the author became a Staff Member in the Psychology Group at the Lincoln Laboratory of the Massachusetts Institute of Technology.