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DEPARTMENT of PSYCHOLOGY

PREDICTING HUMAN PERFORMANCE II: LAWS OF THE VISUAL REACTION TIME

WARREN H. TEICHNER
MARJORIE J. KREBS

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APRIL 1971

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13. ABSTRACT

The literature on the reaction time to a flash of light was reviewed and 14 studies published between 1896 and 1969 were selected as having provided sufficient methodological detail and data appropriate for a quantitative analysis of the effects of the following selected variables: Luminance, duration, size of stimulus, contrast, and background luminance, response to stimulus onset vs. offset of the signal, and monocular vs. binocular viewing. Conclusions were drawn about the effects of each variable and/or the status of the research literature concerning it.

Mathematical relationships were developed which can be used to predict binocular RTs over a wide range of luminance, signal duration and signal size. These relationships appear sufficiently reliable to be used for purposes of equipment design.

The data were also considered in theoretical terms. It was shown that the product of RT and luminance may be used to represent a response criterion in the sense implied by the theory of signal detection as developed in recent latency models.

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ABSTRACT

The literature on the reaction time to a flash of light was reviewed and 14 studies published between 1896 and 1969 were selected as having provided sufficient methodological detail and data appropriate for a quantitative analysis of the effects of the following selected variables: Luminance, duration, size of stimulus, contrast and background luminance, response to stimulus onset vs. offset of the signal, and monocular vs. binocular viewing. Conclusions were drawn about the effects of each variable and/or the status of the research literature concerning it.

The major findings of the study were the formulation of two classes of laws: (1) Laws of the distal stimulus and (2) Laws of the proximal stimulus. Both were formulated for conditions of a flash of light in a zero luminance background.

A. Laws of the distal stimulus.

$$RT = \frac{t}{bt - a} \qquad (1)$$

where t is the duration of the stimulus in seconds.

a is the duration at which $RT \to \infty$

$b = 1/K$ and K is given below.

This expression provides an acceptable fit over a wide range of durations and luminances. It cannot handle the monocular data available nor can it account for the very lowest luminance used (.0016 mL), nor the shortest durations (.00001 sec.). Within these limits it accounts for all available, acceptable binocular data regardless of signal size, luminance or duration reasonably well.

The second law of the distal stimulus developed is:

$$K = .302\ L^{-.04} \qquad (2)$$

or

$$K = .302\ L^{-.06} \qquad (2a)$$

and

$$K = .1799\ L^{-.02} \qquad (2b)$$

where K = asymptotic RT in sec.

L = luminance in mL.

Equation 2 is a general expression which ignores the relatively small effect of signal size. Equation 2a is applicable to signals $\leq$1 degree, and Eq. 2b to signals >1 degree. These equations apply only to binocular viewing.

B. Laws of the proximal stimulus.

Although a good deal of the data can be accounted for in terms of the distal stimulus laws, an important amount of it cannot be. By noting that the proximal stimulus has a duration = RT, and assuming that (1) the effect of luminance is to vary the rate of neural pulsing, and (2) that the individual's response criterion is a cumulated number of pulses, it becomes possible to identify the product, RT x L, as the theoretical response criterion. Plots of the data using RT x L as the dependent variable provided an orderly arrangement of <u>all</u> data including those not accounted for by the distal stimulus laws with only minor effects due to signal durations, size or viewing condition. The theoretical implications are discussed; the implications to equipment design are indicated, and a set of design principles stated.

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PREDICTING HUMAN PERFORMANCE II:
LAWS OF THE VISUAL REACTION TIME

This study was the second in a series intended to develop methods or models which maximize the use of the scientific literature as a basis for predicting human performance. The kind of performance to be reported is what we have called "switching" (Teichner and Olson, 1969). Switching is that performance involving a discrete response which is measured by the time elapsing between the onset of a signal and the initiation of a response to it. The most elementary, though not uncomplicated, kind of switching performance is the simple reaction time (RT), and it is RT with which this study was concerned. Our specific purpose was to use the data of the literature as a basis for developing a quantitative understanding of the visual RT. Primary interest was in the effects to be associated with the physical parameters of the stimuli.

Parameters other than those which describe the signal are also important (Teichner, 1954), but have been largely ignored in this study. Since our data were the absolute RT values of published studies, differences in the data among studies that might be associated with the effects of the ignored variables were assumed to be small and unsystematic. There were three exceptions. First, uncertainty in the time of arrival of the signal was assumed to be important, and only studies for which this uncertainty was thought to be minimal were selected for analysis. Secondly, position uncertainty was excluded by using only studies in which the signal's location was known in advance by the subject. Third, to reduce the scope of the effort, only studies involving foveal vision and signals of white

light were considered. In summary, interest was in (1) RT to a flash of white light having no positional uncertainty and little or no temporal uncertainty, and (2) the possibility of quantitative models for predictive purposes. The variables of concern were the luminance, duration, size, and contrast of the signal, whether viewing was monocular or binocular, and whether response is faster to the onset or the offset of a light. The data of all studies published between 1886 and 1969 considered acceptable for quantitative use were converted to common units of measurement and treated as the raw data of this study. Most of the studies which were not used were rejected for failure to provide information about all of the needed signal characteristics.

Theoretical interest in RT has been continuous, at least since Berger (1886) and Cattell (1886) showed that RT is inversely related to the intensity of the visual stimulus, and Donders (1889) proposed that RT is the sum of a series of component temporal intervals. The intensity relationship has since been demonstrated for RT to signals in other sensory modalities and may be considered to be well established, at least quantitatively. Less well-described are the effects of other signal characteristics.

Since Piéron (1920), theoretical approaches to the explanation of RT phenomena, especially the intensity relationship, have been concerend with one or more of three postulated kinds of RT components: (a) a very short delay required for neural transmission, (b) a delay which depends upon the intensity or energy characteristics of the signal, and (c) as emphasized recently by Grice (1968), a delay which depends upon attentional, perceptual, cognitive and motivational factors. Investigators variously interested in

psychophysics, sensory processes, central information processing functions, conditioning and learning, the concept of psychological time, the intermittency of the human operator as a component in a control system, and stress have been concerned with the relationships between RT, or one of its three postulated components, and the variables on which it depends. For these reasons and because of the long history of research associated with it, an understanding of RT may be considered to be one of the primary problems of psychology in both its fundamental and applied aspects.

The first, formal, mathematical proposal was made by Piéron (1920). Using visual stimuli in a wide variety of experimental conditions, Piéron found that RT could be fitted by a hyperbolic function which he expressed in terms of the first two postulated components noted above. Specifically, Piéron proposed that:

$$RT = \frac{a}{I + b} + K \qquad (1)$$

where a and b are empirical constants.

I is stimulus intensity expressed in multiples of threshold intensity, e.g., in multiples of threshold luminance for visual signals.

K is an "irreducible minimum" neural delay which is constant, at least for a given sensory modality and a given effector system.

The fraction, $a/(I + b)$, was proposed as the "reducible margin", a quantity which decreases with intensity and is asymptotic to K as a limit. Although Piéron found that Eq. 1 could be fitted nicely to a variety of sets of data obtained in his laboratory, as Welford (1960) has noted, the constant, b, in those curve fits varied from zero to large magnitudes.

That is, b was unique to each set of data fitted. While Welford suggested that this may have been due to the difficulty of obtaining high precision data, it is also plausible that either some other function may be more appropriate for providing a general law, or that the general form of the relationship used by Piéron may be appropriate, but may not include all of the critical factors.

Piéron (1936) extended Eq. 1 to luminance contrast by expressing I as a multiple of the difference threshold. With adaptation to different background luminances Piéron found that Eq. 1 provided an acceptable fit. Bartlett and MacLeod (1954) have extended Piéron's work with the effects of contrast over a wide range of flash luminances using both foveal and peripheral vision. On the basis of their results, these authors developed a hyperbolic expression which scales the stimulus logarithmically rather than arithmetically:

$$RT = \frac{1}{b\ (\log I - I/I_o)} + K \qquad (2)$$

where I_o is the flash luminance at which RT approaches infinity, a quantity which varies with background luminance.

I is the flash luminance.

b is a slope constant.

K is the irreducible minimum.

Bartlett and MacLeod also found a greater acceleration of the RT function with foveal as compared to peripheral vision and, of considerable relevance, that K increased with the logarithm of the background luminance. The latter suggests that the irreducible minimum is not a constant for vision, but itself depends upon stimulus intensity factors.

Using an intense flash luminance (1500 mL), Bartlett and MacLeod (1954) also found that RT was short and was constant over the entire range of background luminances from just visible to maximum tolerable that could at the same time be discriminated from the flash. Under those conditions contrast was high throughout. With lower flash luminances these investigators found a very rapid increase in RT beginning just before threshold contrast. The last result is not in close agreement with earlier data of Hovland (1936), which suggested a continuing, though not monotonic, change in RT with variations in contrast, nor with the very extensive study of Steinman (1944), who found a more gradual, monotonic change in RT with contrast.

Hull (1949), concerned with the effects of stimulus intensity on response strength, particularly on the strength of the conditioned response, turned to RT as a means for developing a concept of "stimulus intensity dynamism". A presumed assumption on his part was that RT provides a latency measure relatively uninfluenced by learning factors and, therefore, that it represents a more nearly pure intensity function which might serve as a nonlearning factor determining excitatory potential. Using the data of Berger (1886) and of Cattell (1886), he obtained a good fit with an exponential of the form:

$$RT = ab^{I} + K \qquad (3)$$

where I is luminance, K is again the asymptote or irreducible minimum, and a and b are constants.

Woodworth and Schlosberg (1954) applied Eq. 3 to the auditory data of Chochell (1945) and found that it provided a good representation, but they found it necessary to fit two curves, i.e., a single curve did not fit over

the entire range of the data. One curve dropped steeply over a short range of very low signal intensities; the other, extending over the remaining greater intensities decreased slowly. Woodworth and Schlosberg hypothesized that the two curves required by the data might represent a sensory delay factor operating at low signal intensities and a motor delay factor at higher ones. More recently, Vaughan, Costa, and Gilden (1966) have made a similar distinction, but have proposed a retinal process which is a power function and a second process related to efferent variability. They have also shown that a power function describes the visual evoked response latency, and that a power function describes the estimated reducible portion of a variety of published behavioral RTs, as well as their own data. It is important to note that they were concerned with relative luminance as the measure of intensity, whereas we shall be concerned with the absolute luminance of the stimulus.

In response to Hull's treatment of the problem, Logan (1954) pointed to the importance of inter-trial sequential effects in determining the RT to an intensity present on any particular trial in a series. Grice and Hunter (1964) explored this problem in terms of a single intensity between groups versus a multi-intensity within subjects experimental design, and concluded that there is an adaptation effect which reduces the sensitivity of the between-groups design.

Stochastic models of RT (e.g., Luce and Green, 1970, McGill, 1963; Restle, 1961) have been concerned with the distribution of RT within an individual over a series of trials. McGill (1963) has assumed that: (1) the rate of neural impulses associated with a stimulus increases as stimulus intensity increases and is a random variable, (2) the subject's response

criterion can be expressed as a criterion number of impulses. On this basis an inverse relationship between RT and intensity may be derived. Grice (1968) has questioned the validity of McGill's model as proposed, since it requires that the subject's response criterion remain constant over a large block of trials. Instead, he offered an alternative model in which the criterion, but not the signal intensity, is assumed to vary from moment to moment or trial to trial. Both models make predictions about the RT-density function as well as the mean of the distribution. Both assume random, normal distributions.

Luce and Green (1970) have also provided a mathematical theory which attempts to predict sensory decisions and their associated latencies. The underlying density function is assumed to be Poisson, although that is not a critical requirement of the approach. These authors compared a variety of possible models for each of a number decision rules for a variety of experimental situations. In general the experimental conditions impose requirements which are different from the conventional RT situation, e.g., the requirement for a discrete secondary stimulus which acts as a marker for termination of the primary stimulus.

The difference between assuming a stable criterion with probabilistic stimulus input vs. a probabilistic criterion with a stable input is analagous to the differences in assumptions between classical psychophysics and that based on the quantum theory of vision, i.e., both appear to be equally good predictors of the same data. With regard to the sequential effects of varied intensities, one of the most obvious considerations is sequential sensory adaptation effects. Investigators who have studied variable intensities in terms of the concepts of McGill and of Grice have not controlled

sensory adaptation since they did not allow a recovery time between trials which could be demonstrated as sufficient to return the subject to his previous level of adaptation. As Murray (1970) has observed in this regard, both his results and those of John (1967) using intertrial intervals of 7.0 and 6.5 sec. show sequential effects with varying trial intensities, whereas Kohfield (1969), using a 15 sec. interval, did not obtain sequential effects. The problem, however, is that, given sequential effects, it is not possible to distinguish between a changing response criterion and a changing stimulus intensity level, especially since the former would appear to vary with the latter when it changes (Grice, 1968).

Another point deserves comment. Both McGill and Grice would agree that the subject's response criterion depends on factors other than stimulus intensity. Stimulus intensity determines how rapidly the criterion will be reached. But, RT appears to vary systematically not only with the flash luminance, but also with the background luminance to which the subjects are adapted. Furthermore, Bartlett and MacLeod (1954) found that the asymptote of the RT—intensity function was systematically related to the adapting luminance level. Thus, if the concept of irreducible minimum is useful, it may be necessary to distinguish between a minimum transmission lag below which no RT can fall and a series of minima which are asymptotes or limits for particular sets of intensity factors, and below which no RT can occur with those factors present. Taylor (1965) has even suggested that the irreducible minimum varies with each trial although its expected value may be constant for a fixed set of experimental conditions. On the average, however, since RT decreases with a number of experimental conditions and since the asymptote of the decreasing curve is apparently determined by

the intensity of the stimulus, the irreducible minimum may be simply the asymptote of the curve for the greatest effective intensity. Thus, if there is an interest in subtracting the irreducible minimum from an obtained RT in order to deal with the "reducible margin" (a common practice), perhaps what should be subtracted is the asymptote of the curve for the particular experimental conditions rather than the smallest possible asymptote, as is usually done. In any case, if an irreducible minimum or minima and a reducible margin are distinguished, it may be necessary for stochastic models to account for the oscillation of each. Later we shall question the utility of such a distinction as well as the lags-in-series concept of Donders (1889).

Stimulus Duration:

The stimulus duration variable deserves special mention since its effects have never been clear. In reviewing RT in 1954, Teichner noted the wide variations in results among available studies in regard to the effects of stimulus duration. As seen then, it was difficult to understand why RT should be affected by the duration of an easily detected stimulus since RT is measured as the onset of the response. Raab, Fehrer, and Hershenson (1961) have made a similar comment more recently. The only possible way by which durations equal to or longer than RT might influence the observed RT seems to be by affecting the speed of movement following response onset. Some of the conflicting results obtained among the various studies might reflect different degrees of inclusion of that possible effect in the measured value. On the other hand, it is not difficult to see why RT should vary with the duration of a less than perfectly visible stimulus. Regardless, studies which use an experimental arrangement in which the stimulus remains on until

the subject responds do not allow for any way to determine the required stimulus duration for the RT which occurs. In fact, a number of authors have left the stimulus on for a prescribed duration which is longer than the RT, and have reported their durations as the prescribed times. Clearly, the length of time that the signal light is on after the subject responds should have no effect on the response latency.

After reviewing the available literature, Teichner (1954) was unable to draw a conclusion about the effects of duration. He did hypothesize that RT is a rapidly decreasing function of duration to an asymptote which itself is a function of stimulus intensity. Since that hypothesis was stated there have been a number of studies of the duration variable, especially with an interest in the applicability of Bloch's Law (It = C) to the visual RT. Raab and Fehrer (1962) concluded from their data at high luminance (>300 ft-L) that RT decreases as duration increases up to a "critical" duration of .5 msec., and that as luminance decreases, the "critical" duration increases to at least 10-20 msec. at .3 ft-L, the lower limit of their experiment. On the other hand, in an earlier study Raab, Fehrer, and Hershenson (1961) found no significant duration effect at all over the same range of luminance. In both studies duration was varied randomly within sessions.

Pease (1964) found RT to decrease with increased flash duration and a "critical" duration which was dependent on luminance. Similarly, Sticht (1964) reported data which he interpreted as evidence of temporal summation at low luminance. Grossberg (1968), on the other hand, found that rather than being constant, RT decreased with the product of luminance and duration as well as with duration alone. Interesting, but difficult to interpret,

was Grossberg's observation that Bloch's Law did appear to hold approximately for his data when the RT was measured from the termination of the flash rather than its onset. However, he did not provide data to support that observation. Finally, Lewis and Mertens (1967) failed to find any evidence of a duration effect over a wide range of stimulus luminance, and along with Raab, Fehrer, and Hershenson (1961) concluded that apparent duration effects, when reported, are experimental artifacts which result from a failure to control inter-trial sequential effects.

Experiments on the effects of stimulus duration are more plentiful now than they were in 1954, but they do not seem to be more conclusive. The hypothesis made then (Teichner, 1954) has received what appears to be both strong support and strong rejection. To the degree that it is supported, it seems that RT might be inversely related to duration up to some limiting duration below some limiting luminance.

Area:

Size of the stimulus has received very little study in regard to RT. As reported earlier (Teichner, 1954), Froeberg's (1907) data indicated that RT decreases as the retinal area stimulated increases. More recently Hufford (1964) has reported an interaction between the effects of area and luminance in the peripheral retina. Signal size, then, can be expected to be an effective variable, but its limits have not yet been determined.

Monocular vs. Binocular Viewing:

Although the data have not always been consistent, the working belief held by most investigators is that binocular visual detection is slightly

better than monocular detection (e.g., Teichner and Krebs, 1970). Thus, if RT is viewed as related to the sensory process, it should be slightly faster with binocular viewing. Poffenberger (1912) reported RTs about 0.015 sec. shorter for three subjects under binocular conditions. More recently Minnucci and Conners (1964) have also reported evidence for binocular summation with RT. Thus, there is some evidence suggesting that binocular RTs may be shorter than monocular ones, but the data are not extensive.

Onset vs. Offset of the Stimulus:

A number of the older studies reviewed by Teichner (1954) reported a faster RT when the subject was required to respond to the cessation of a light or tone as compared to responding to the onset of the stimulus. Others of those reviewed found no difference. More recently, Pease and Sticht (1965) and Sticht (1969) reported a faster RT to the offset, but in neither study was the difference statistically significant. This factor was not one of major interest to the present study and, in fact, all of the data to be reported, except for those of Sticht (1969), are for response to the onset of a light. Nevertheless, because the question has important implications, onset and offset will be considered to some degree.

Probability of Detection:

For conditions under which the visibility of the signal is somewhat less than 100 per cent, it can be said that there is uncertainty about the presence or absence of the stimulus. The lower the probability of detection, the greater the uncertainty. Similarly, the greater the uncertainty, the longer RT might be expected to be. This assumption underlies all attempts

to use RT as a psychophysical measure and it has support in the work of Grossberg (1968) and of Steinman (1944). In a different context, Teichner (1962) has reported that with increasing time of vigil in a watchkeeping task, using a flash of light as the signal, the probability of detection decreases and RT increases with time. However, RT at any time during the vigil was consistent with the probability of detection before the vigil started. It appears, therefore, that a relationship between RT and detection probability may be a general phenomenon. In fact, Teichner and Olson (1969) proposed a speculative relationship between the two.

The first study of the present series (Teichner and Krebs, 1970) was an attempt to develop methods for estimating the probability of detection of light signals for which visibility has not been determined. One intended application was that of estimating the probability of detection of the signals used in reaction time studies. That probability is almost never estimated; in fact, most authors appear to have assumed a perfectly visible stimulus. One of the purposes of this report, therefore, was to determine the relationship between RT and detection probability from the available literature using the Teichner and Krebs (1970) method.

METHOD

An attempt was made to find and evaluate all studies published in English which used RT as a dependent measure. A few unusually important papers in French and German were also included. The following restrictions were then imposed on the papers before they could be accepted for further use:

1. Viewing was restricted to central vision. Studies which did not specify either monocular or binocular viewing were assumed to have been binocular.

2. The spatial position of the signal had to be constant and known by the subject.

3. The time of arrival of the signal had to be known by the subject within close tolerance. Studies using both random and non-random fore-periods were accepted if it could be assumed for the former that the subjects were well-practiced.

4. There could be only one possible signal and one possible response.

5. Except as noted, response was always made to the onset of the light.

6. The report had to provide either the actual values of luminance, duration, visual angle, background luminance, and contrast, or information with which those values could be derived.

7. The procedures and experimental design had to meet the quality requirements of the authors.

On this basis a total of 14 studies were accepted as providing usable data. Those data were converted to common units of measurement of the stimulus parameters and of RT, viz. luminance in millilamberts, size or "area" of stimulus in degrees of visual angle, contrast in terms of the relative difference ratio, stimulus duration and RT in seconds. All data will be reported in those units.

The general approach was an iterative one intended to reveal trends across studies. This was done by plotting the data of the various studies on common ordinates and then replotting according to hypotheses suggested by inspection of the graphs. The only distinction made at first was between

those four studies involving contrast and those ten for which the background was dark. This distinction will be maintained in presenting the results.

RESULTS AND DISCUSSION

I. Zero Background Luminance

The first step was to plot the data of all studies together as a function of stimulus luminance in the hope that at least the strongest effects would be discernible. On this basis it seemed that luminance, duration, and area interacted in a very complex way, and that the variable of greatest effect was probably luminance. A second step was to manipulate the dependent variable in the hope of separating phenomena which might be components of the total RT. In particular, attention was given to the question of processes which might be going on during the presence of the stimulus and those which might follow its offset. One approach to this distinction was simply to subtract the stimulus duration (t) from RT and to compare RT with (RT-t). If RT does not depend upon t, or if Bloch's Law holds for latencies measured from the offset of the stimulus (Grossberg, 1968), then a comparison of these two dependent measures might yield different functions. However, they yielded the same trends except at relatively long durations and large luminances where RT was essentially constant and, therefore, where (RT-t) dropped rapidly toward very low values. This suggested only that RT does decrease with increasing t.

Another dependent measure which was considered was the fraction, t/RT, which represents the proportion of the total RT in which the stimulus was present. The quantity, 1 − t/RT, then, represents the proportion of the

total RT during which the stimulus is absent. These ratios tended to smooth out the data in very interesting ways, but ultimately it was decided that they provided no more information than was available in the conventional RT measure. Therefore, they were not pursued further. The data to be reported are all in terms of the conventional measure.

Effects of Area:

Figure 1 compares the effects of area for different, but comparable values of duration as a function of luminance. The foveal-sized data of Grossberg (1968) covers the lower luminance range; the data of three other studies using larger stimuli represent higher luminances. In both cases, RT is a decreasing function of luminance. It may also be seen that duration is generally an effective variable and that the larger areas were associated with smaller RTs.

Although Fig. 1 suggests that RT is inversely related to size of stimulus, not enough data are shown to suggest the nature of the area function. This is characteristic of the foveal data which we were using. That is, with the exception of a single data point from Poffenberger (1912), who used one degree, all of the studies used employed stimuli which were well within foveal dimensions, actually .5 degrees of arc or less, or which exceeded foveal dimensions within the range of 1.1 - 4.0 degrees of arc. Not enough variation within these limits was available for developing an area trend. For that reason, some of the analysis to follow will distinguish only between foveal-sized ($\leq$1.0 deg.) and extra-foveal-sized (>1.0 deg.) stimuli. That is, the data will be treated within each of those categories

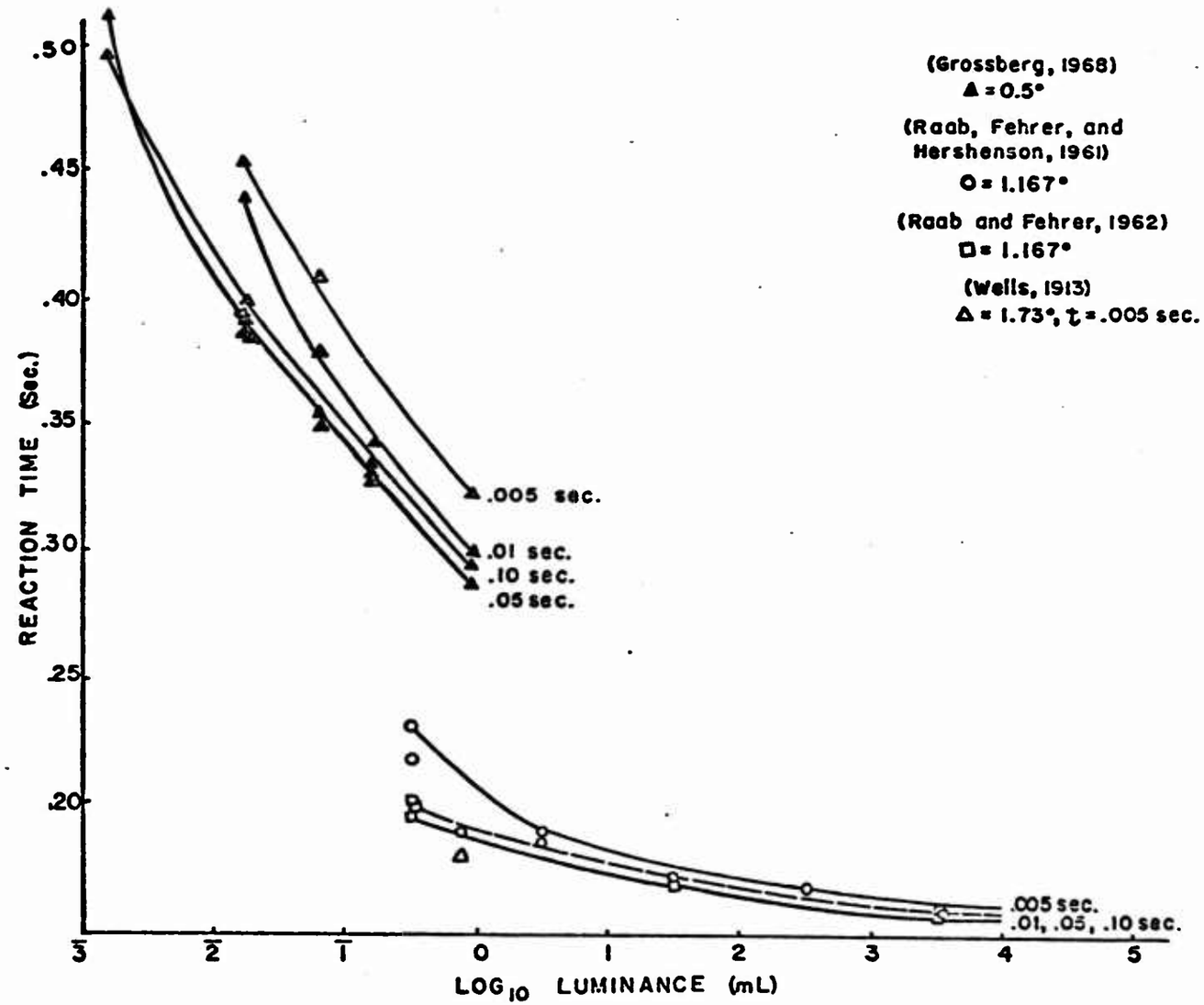

Figure 1. Effects of signal luminance, duration and size on RT. Viewing was binocular. Lines drawn by eye.

as if area has no effect on RT. We conclude that there is an effect between categories, but that not enough data are available to determine what effects, if any, exist within these two categories.

Luminance, Duration, and Onset-Offset:

The durations used varied from reported t = .00001 sec. to durations which nominally exceeded RT. An attempt was made to view the luminance function in an uncomplicated way by grouping the durations used into class intervals and treating all data within an interval as the same in duration. An example is shown in Fig. 2 using the interval, .200 - .010 sec. The figure also provides a comparison of the use of stimulus onset with offset as the signal for the data of Sticht (1969). Regarding that comparison, stimulus onset is shown to be associated with a faster response. This was not a consistent result, however, even for the other data of Sticht, not shown here. In any case, the offset data are easily included within the onset data, which suggests that if there is a difference, it represents the effects of a minor variable. As a precaution, however, the data to be reported below are only for the case in which stimulus onset was used as the signal.

As in the previous figure, Fig. 2 shows that extra-foveal target sizes produced faster RTs. There is an indication again that short durations tend to be associated with longer RTs. As before, RT tends to decrease with luminance. This is certainly the case within studies. Between studies, duration and size appear to interact. A variety of other plots using different duration intervals provided essentially the same trends except, as noted, they were inconsistent about the effects of onset and offset.

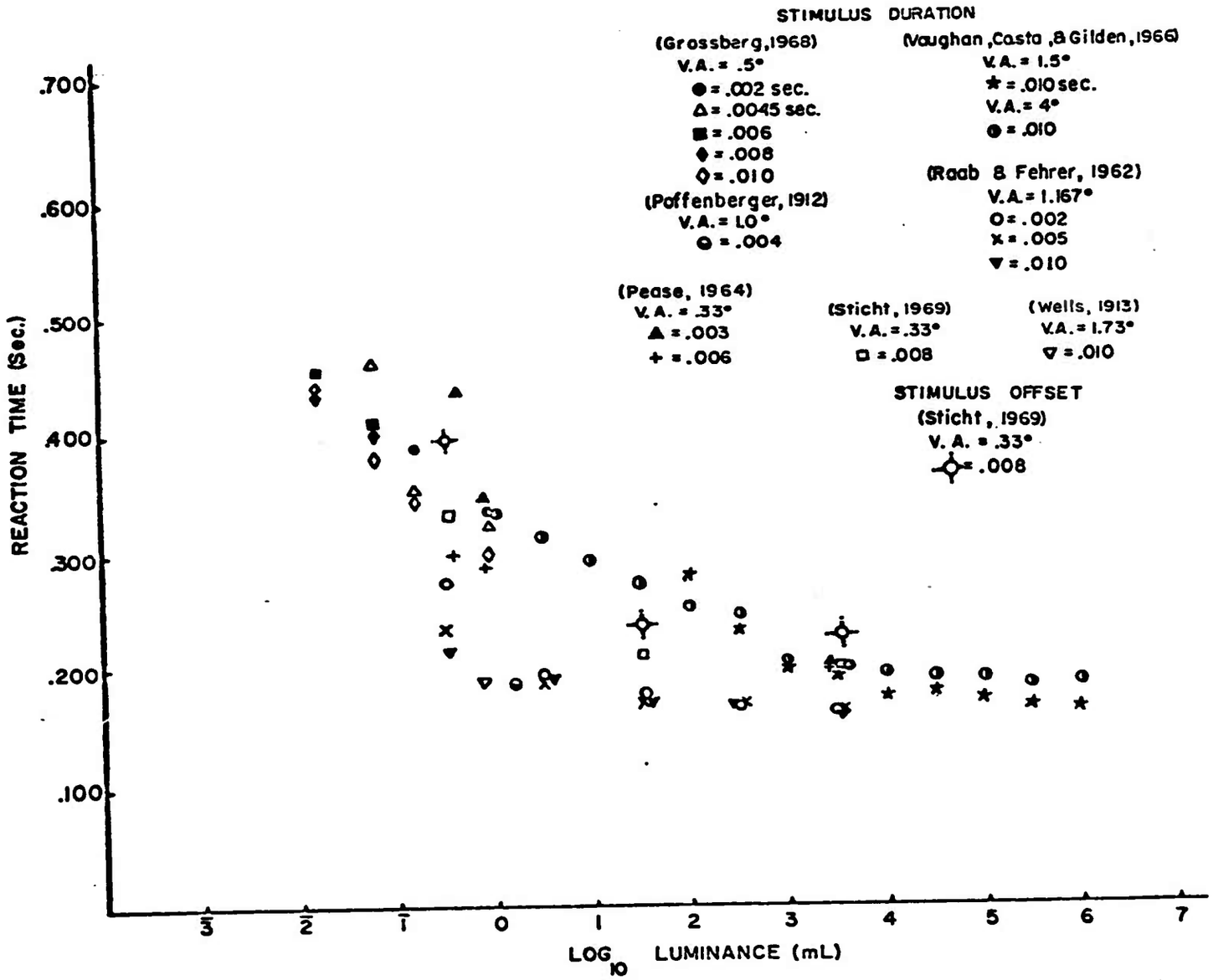

Figure 2. RT as a function of luminance for varying signal sizes and durations varying within the range, .002-.010 sec. Data from both monocular and binocular viewing conditions are included. All data are from response to stimulus onset except the three points indicated from Sticht (1969).

Although plots of the sort shown in Fig. 2 were informative, they were considered to be too confounded by the effects of area and not really clear about the effects of duration. All of the data, therefore, were plotted as a function of duration with luminance as the parameter. This was done separately according to the following conditions: Foveal-Size-Monocular, Foveal-Size-Binocular, and Extra-Foveal-Size-Binocular. The results are shown in Figs. 3, 4, and 5 respectively. No monocular studies of signals of extra-foveal size were available.

Comparison of Figs. 3, 4, and 5 indicate that RT is a negatively accelerated decreasing function of stimulus duration and that RT decreases as luminance increases. From Figs. 1 and 2 it was already seen that the luminance function is negatively accelerated and decreasing. It is also apparent that the separation of the data into the three figures according to size and monocular vs. binocular viewing resulted in a considerable gain in ordering of the data. In all three cases the early hypothesis about the effect of duration and of luminance (Teichner, 1954) was supported. Since the data fell most systematically when plotted as time functions with luminance as a parameter, it was decided to attempt a formal expression for the data in that form.

When the data of Figs. 3 and 4 were plotted on one graph, it was found for approximately comparable luminances and sizes that the monocular RTs were smaller in general than the binocular ones. This violates any reasonable explanation. The monocular RT should be larger than or equal to the binocular RT; it should not be smaller. Nothing in the published reports suggests that one or the other data sets should be considered less reliable. The decision that the monocular data were probably less reliable was made

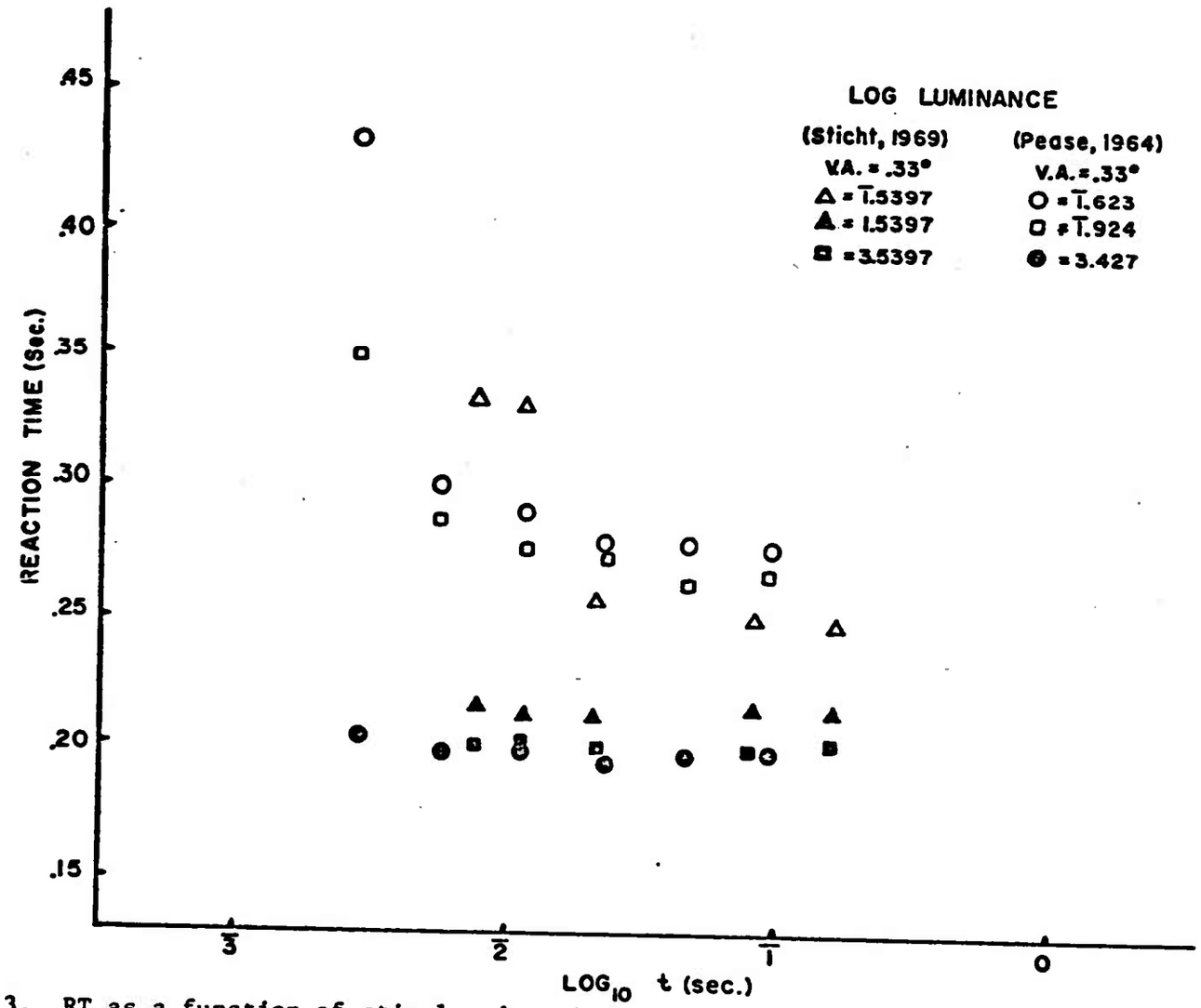

Figure 3. RT as a function of stimulus duration and with luminance. Viewing was monocular; signal size was .33 degrees. Data from Sticht (1969) and Pease (1964).

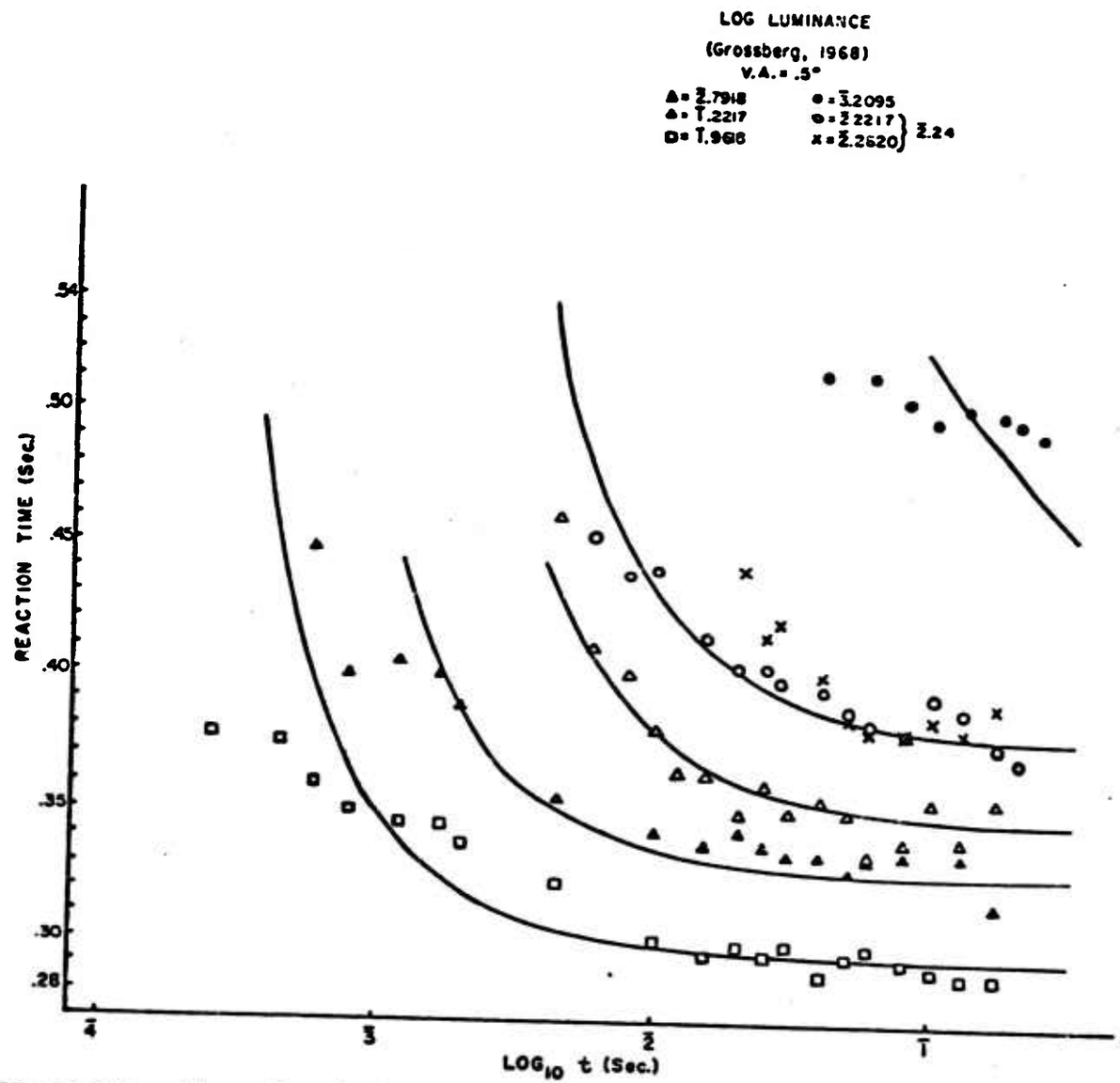

Figure 4. RT as a function of stimulus duration and luminance. Viewing was binocular; signal size was .5 degrees. Data from Grossberg (1968). Curves calculated with Eq. 4a and 5 as discussed in the text.

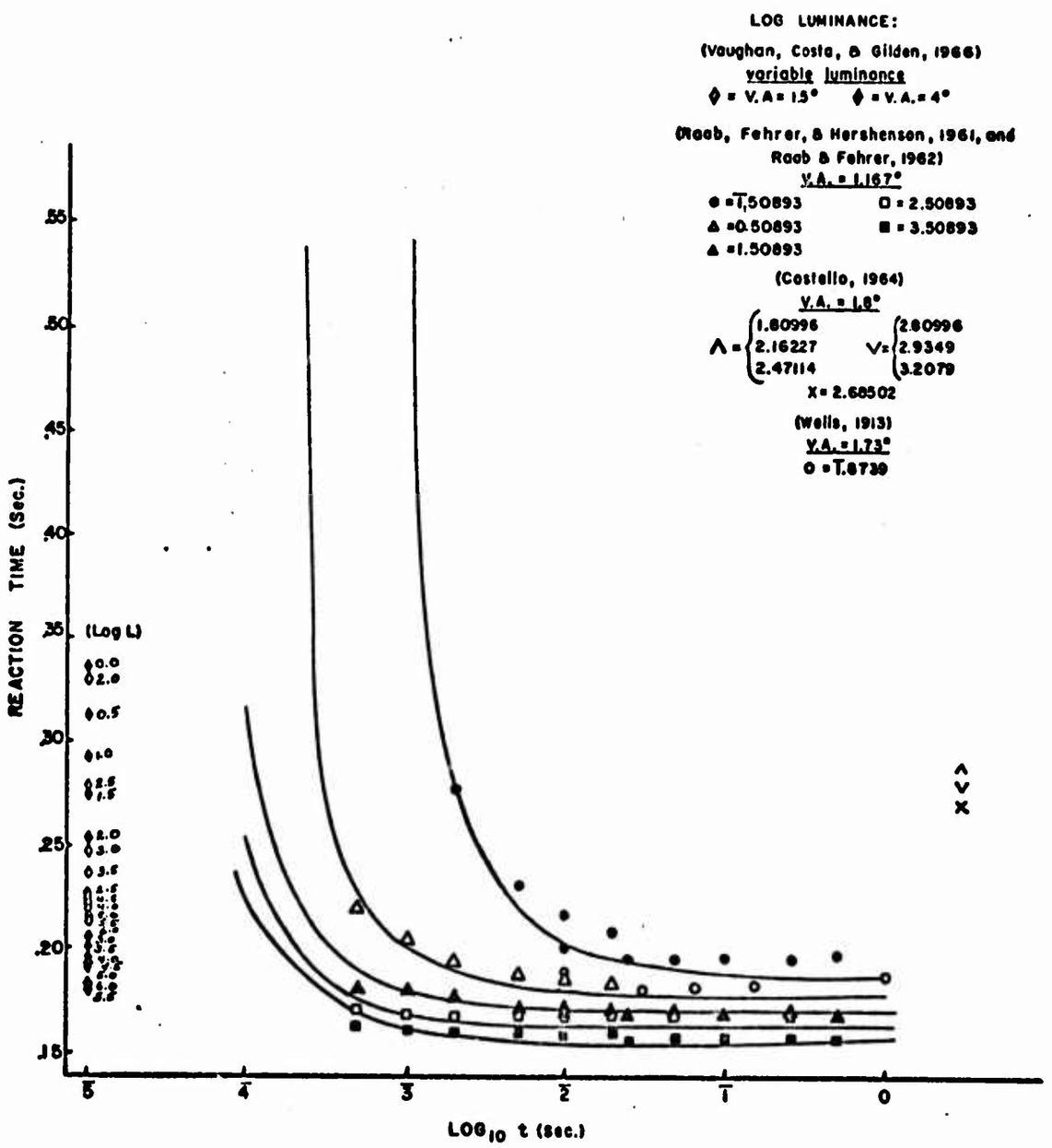

Figure 5. RT as a function of stimulus duration and luminance for extra-foveal signals viewed binocularly. Curves calculated with Eqs. 4 and 6 as discussed in the text.

on the basis of a comparison of inversions within the two figures and on the greater comparability of time and luminance trends of the data of Fig. 4 to those of Fig. 5, which represents binocular data for the larger areas. The differences between the monocular and binocular data will be reconsidered later in a different context. Meanwhile, the nature of the curves shown in Figs. 4 and 5 will be explained.

Inspection of Fig. 4 at the two higher luminances suggests that perhaps two time functions may be required, one for very short durations and one for higher ones. Although that possibility is not consistent within the figure, an attempt was made to treat the data at each luminance as a two-factor system. This not only could not be done consistently for the family of relationships in the figure, but even for the two higher luminances, it could not be done well with consistent functional forms. The possibility was abandoned, therefore.

Of the various functions which might have described the data of Figs. 4 and 5, the expression found to be most consistently adaptative within and between the figures was:

$$RT = \frac{t}{bt - a} \qquad (4)$$

In this expression the constant, a, depends on the value of duration at which RT approaches infinity (t_∞), and the constant, b, is a function of the asymptotic value of RT. The latter can be seen in the figures as depending upon luminance. The first steps, therefore, were to estimate both kinds of asymptotes for the data of Fig. 4. This was done visually except for t_∞ for the lowest luminance where t_∞ was determined from $t_\infty = -a/b$. The constant, a, for that luminance was determined iteratively.

Obtaining b required first that the luminance function be developed. Asymptotic values were estimated for each curve of Fig. 4 with the exceptions of $\bar{2}.22$ and $\bar{2}.26$, which instead were treated together as $\bar{2}.24$. The estimated asymptotic values were then plotted as a function of luminance in various transforms. The best fit was clearly a power function. That relationship in the form of the reduction line is shown in Fig. 6. The equation was fitted graphically. Its antilogarithm is:

$$K = .302\ L^{-.06} \qquad (5)$$

where: K is the asymptotic value of RT in sec. at a given luminance.

L is the luminance in mL.

.302 is a constant.

No attempt was made to add a constant to Eq. 5 which would impose a limit on it.

The value of b at any luminance was obtained for Eq. 4 by solving Eq. 5 for K at that luminance and using the relationship, $b = 1/K$.

Figure 7 presents the values of t_∞ used as a function of luminance. The smooth line, drawn by eye, suggests a power function for this signal size. Using Eqs. 5 and 6 and the relationship, $-a = bt_\infty$, the constants required for Eq. 4 may be obtained for any luminance. When this was done for the data of Fig. 4, the curves obtained tended to overestimate slightly, so a subtractive constant of fit was introduced. With this constant, Eq. 4 as applied to Fig. 4 becomes:

$$RT = \frac{t}{bt - a} - .01 \qquad (4a)$$

It may be seen in Fig. 4 that the fit is poorest at the lowest luminance (uppermost set of points). Whether it would improve were more data available there cannot be stated. At the two highest luminances (lowest

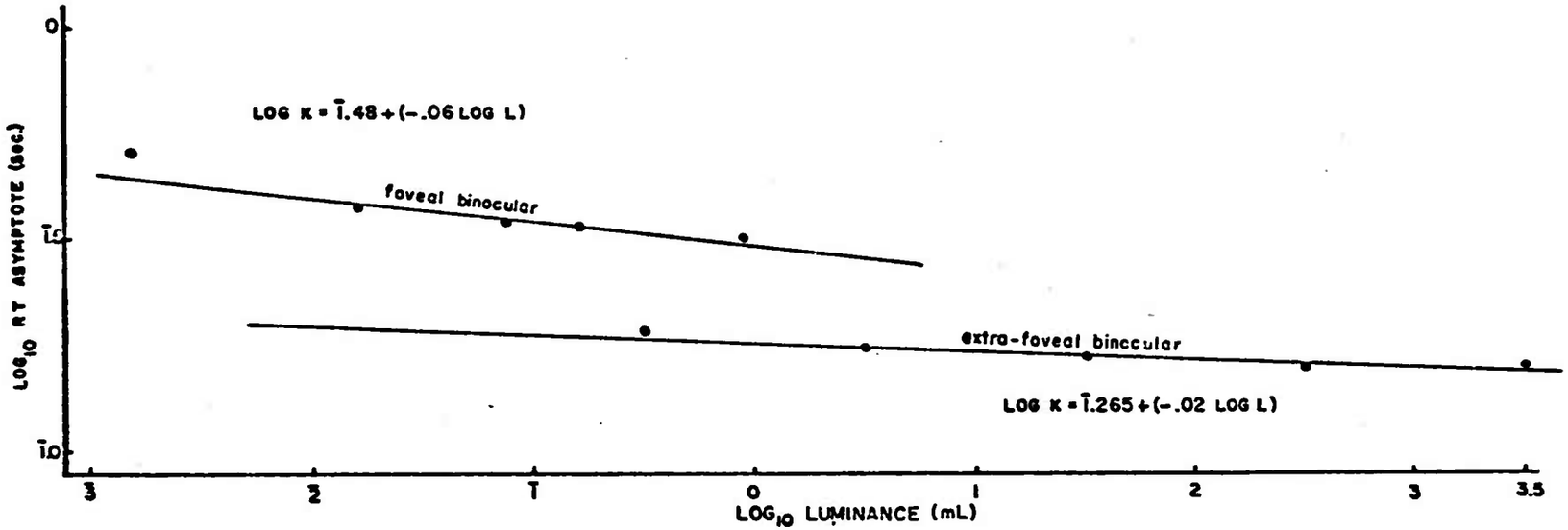

Figure 6. Log-Log plot of asymptotic RT vs. luminance for binocular viewing.

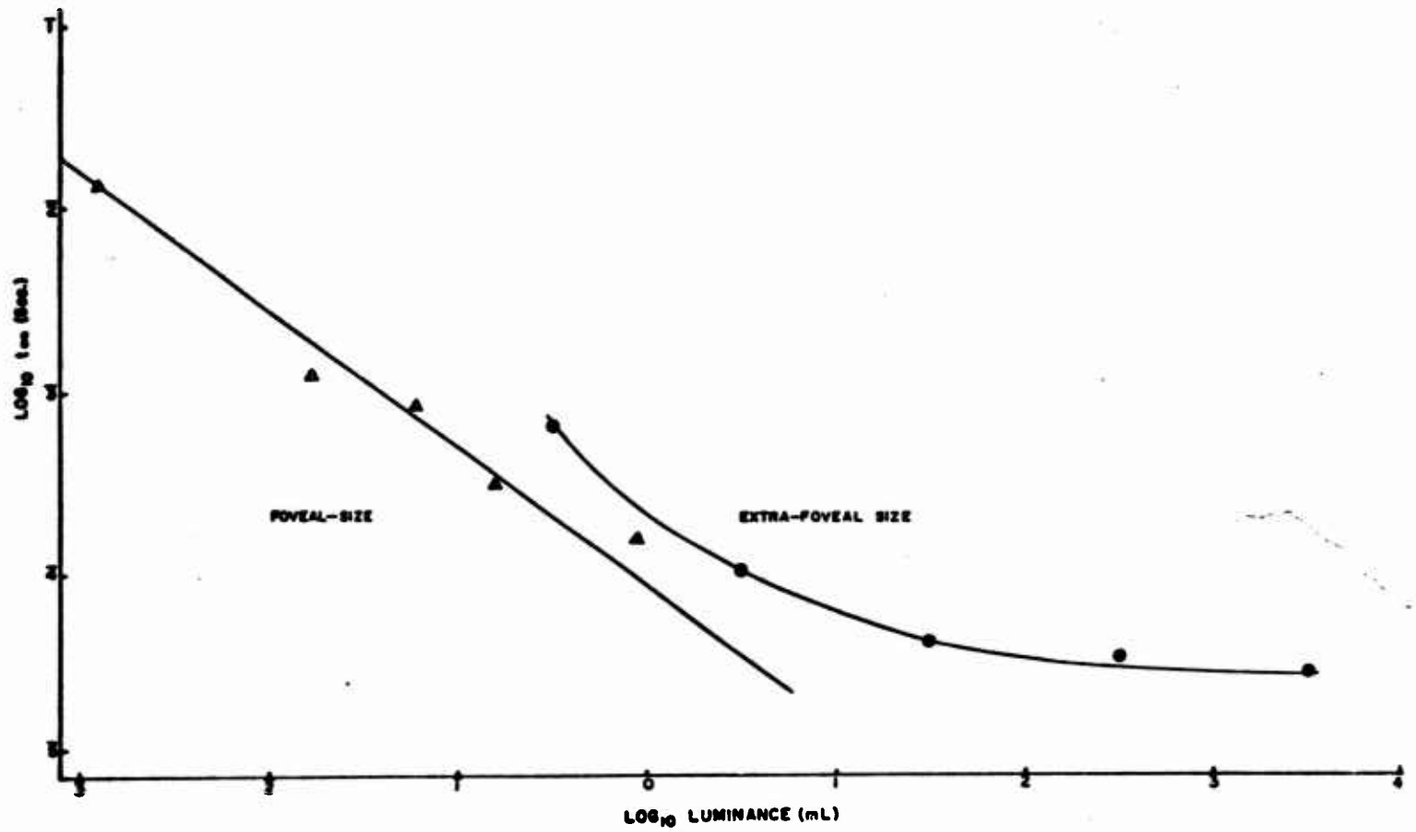

Figure 7. Log-Log plot of t_∞ vs. luminance for binocular viewing.

curves), the fit misses the points representing the shortest durations. This does not seem to be too serious since those points are close to t_∞ and, therefore, represent very low visibility levels. They may, therefore, be expected to be the least reliable of the points and, in fact, this is suggested, since they can be viewed as not in line with their own trends.

Using the methods described above, Eq. 4 was also fitted to the data of Fig. 5. The equation for the antilogarithm of the asymptotic luminance function shown in Fig. 6 is:

$$K = .1799\ L^{-.02} \qquad (6)$$

Shown in Fig. 7 are the values of t_∞ obtained. The smooth line was drawn through the points by eye. It suggests that a different function describes the dependence of t_∞ on luminance for the larger stimulus sizes than for the smaller ones. The difference may be the result of the fitting process since it was possible to estimate t_∞ graphically for more curves at the smaller sizes than for the larger ones. On the other hand, the difference in functions could be a genuine difference between within-foveal and extra-foveal viewing conditions. In applying Eq. 4 to Fig. 5, no fitting constant was used.

The curves shown in Fig. 5 provide a not unreasonable first approximation of the data reported over the range of stimulus durations, $RT > t \geq .0005$ sec. The failure to describe the data of Costello (1964) is to be expected since there is no way to estimate a value of the abscissa except that it should be no greater than the RTs reported and, undoubtedly, less. The microsec. duration data were also not accounted for by Eq. 4.

Attempts to fit other functions to the data of Figs. 4 and 5 were less successful than Eq. 4. As noted, the data of Fig. 3 for monocular viewing

were not sufficiently consistent to allow for the fitting of a single function. The inconsistency lay not so much in the shape of the duration functions shown in the figure, but in the function to be used to predict the asymptotic RT, i.e., K; the luminance trend obtained did not make sense when compared to the relationships found for the other two figures.

Energy Relationships:

If RT is a constant value for a constant stimulus energy, then Bloch's Law holds for the visual RT. If so, at least within the limits of application of the law, RT may be viewed as largely, if not entirely, dependent upon the same retinal process as that on which visual sensitivity depends. If the law does apply, Figs. 4 and 5 suggest critical durations which depend upon luminance. On the other hand, if RT does not behave like a visual threshold by following Bloch's Law, questions about the relative importance of peripheral and central processes must be raised.

In the visual literature, Bloch's Law is tested by plotting the product of luminance and duration at threshold as a function of duration. The constant dependent measure in that case is the threshold which is defined independently of both luminance and duration. A comparable procedure cannot be employed in evaluating the law for RT since the dependent measure, RT, includes duration as a component value. That is, for this purpose the independent and the dependent variables are completely confounded so that the duration quantity would appear on the abscissa, in the product on the ordinate, and in the referent constant RT.

To circumvent the problem, RT investigators have attempted to make use of the finding that the critical duration up to which a constant energy

is found at threshold varies with other parameters of the visual stimulus. Since the critical duration of the RT curve varies with luminance as shown in Figs. 3, 4, and 5, investigators have used that phenomenon to support the applicability of Bloch's Law. This of course is a non-sequitor. The test may be made, however, simply by plotting RT as a function of the product of luminance and duration and observing whether or not RT is a constant for constant ordinate values of the graph. This has been done in Fig. 8 using all of the data of Figs. 3, 4, and 5 except those reported with t>RT. It is clear that Bloch's Law does not hold. The same conclusion was reached by Grossberg (1968), whose data are included. Figure 8 shows that the conclusion is general.

Figure 8 also shows that as It increases, RT decreases in a negatively accelerated manner. There is also some suggestion that at larger RT values, there is a family of curves whose asymptotes vary with luminance while for the smaller RTs in the lower portion of the figure, another family of curves might possibly depend upon area. The smooth lines, drawn by eye, are intended to represent the minimum RT for the binocular and the monocular data. A comparison of those curves suggests that the monocular condition did, in fact, tend to produce longer RTs. The smooth curve for the binocular condition, then, defines an envelope within which all RTs are likely to fall when It is the independent variable. The monocular curve may be interpreted similarly. These lines may be used to estimate the fastest RT to be expected at any It regardless of other stimulus or viewing conditions.

Whereas the product of duration and luminance represents the energy rate per unit area, the product of luminance, duration, and area represents the total energy. A plot of RT vs. LtA was so similar to that of Fig. 8,

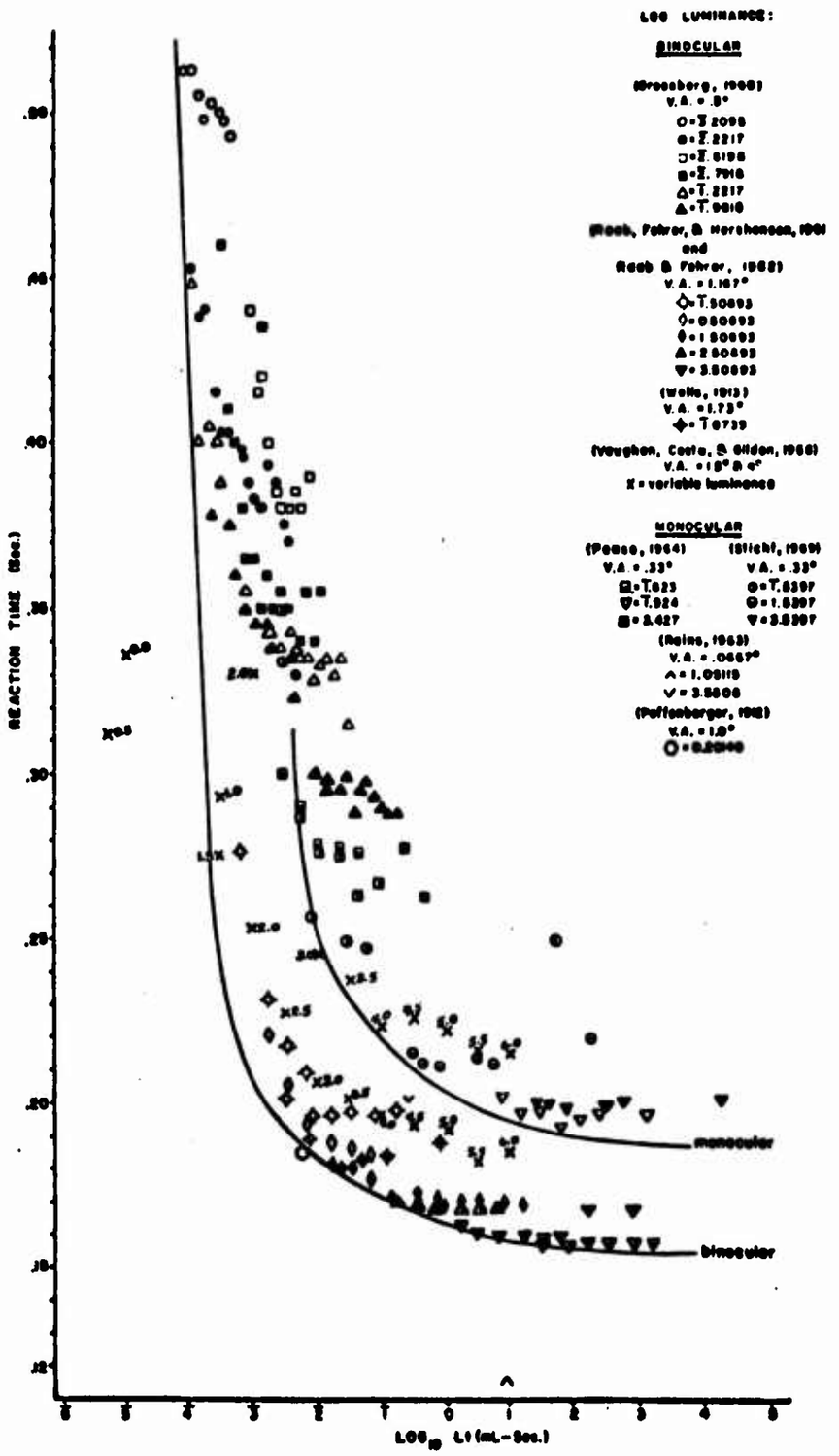

Figure 8. RT as a function of log stimulus energy.

that it is not shown. Of additional interest in that plot, as well as in Fig. 8, was that the RTs obtained at microsec. durations were much more in line with the remaining data than they are in Fig. 5.

Redefinition of the Stimulus:

So far we have presented an analysis of RT based upon a conventional definition of the stimulus as an energy applied for a period of time, and a conventional view of the response as an event which occurs when a necessary amount of energy has been applied. RT is defined as the latency of the response measured from the onset of the stimulus. A critical underlying assumption is that when the external stimulus energy is removed, stimulation stops and that the temporal lag observed before onset of the response is due to lags in the nervous and muscular systems. With these assumptions it is clear that a reasonably consistent, quantitative literature has developed and that it can be organized within limits into a simple mathematical framework.

On the other hand, the assumption that stimulation ends as defined by its externally controlled duration is unacceptable. A distinction between the distal and proximal stimulus seems particularly pertinent here, as well as in studies of visual detection, because it has become apparent in the last few years that there is a persistence of the visual input after the external energy is removed, which lasts under ordinary stimulating conditions for at least .25 sec. (Sperling, 1960; Mackworth, 1963), and under conditions which produce after-images for several sec. (Teichner and Wagner, 1964), during which information can be extracted by the individual. Whether this information store is actually retinal or at a stage beyond, or both,

is very important for many reasons. It is not, however, critical to our present interest, which is in the question of when the proximal stimulus should be considered to have terminated. The simplest, if not the only, answer which appears to be available is that the proximal stimulus is effectively terminated by the individual at a duration which is equal to his RT.

Response Criterion Model:

As reviewed earlier, a number of mathematical theories of RT have been developed which have some relationship to the theory of signal detection. Figure 9 presents the fundamental relationships which these theories appear to have assumed in common. Individual approaches have postulated one or another kind of input density function or of distribution of the response criterion. We shall not be concerned with those possible distributions, but rather we shall assume that if either the input or the criterion (or both) is not constant from moment to moment or trial to trial that their averages are, and it is the average values with which we shall deal. On this basis, Fig. 9 assumes that the individual's response criterion is represented by a cumulated number of neural impulses so that the greater the luminance, and therefore the greater the pulse rate, the sooner the criterion is reached.

Figure 9 provides no information about the role of duration and size of the distal stimulus. Nor have the authors concerned made assumptions about how these variables are to be incorporated into the model. A requirement of the model of concern to such assumptions is, as shown, that the pulsing rate is constant over time. This requirement has implications for the nature of the underlying neural pulsing, whether it decreases with time and what

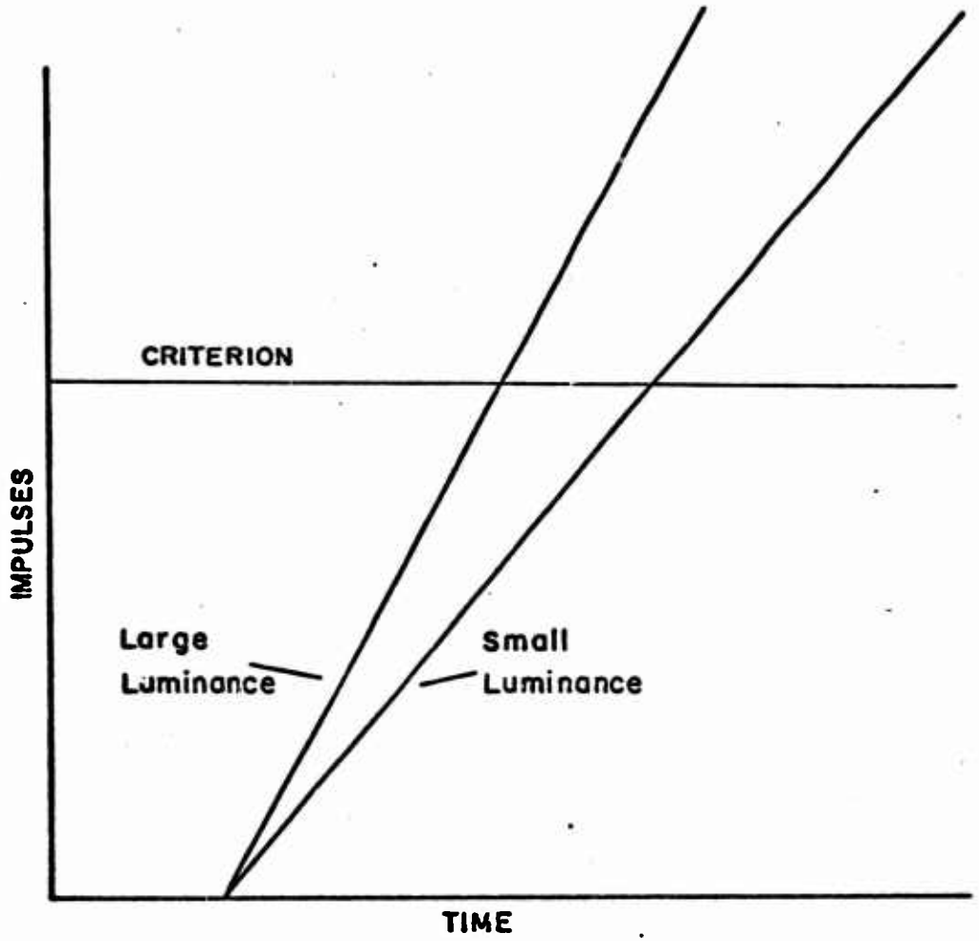

Figure 9. Graphical representation of Grice's RT model without distribution functions. Adapted from Grice (1968).

kind of mechanism might do one or the other, consistent with what is known about the nervous system. A simple linear system such as is shown in Fig. 9 has many advantages as a model. It will be our hope, therefore, as we develop the model further, to retain it.

The data of Vaughan, Costa, and Gilden (1966) as shown in Fig. 8 indicate that RTs which are reasonably located within the range of other RT studies may be obtained with distal stimuli having durations of as little as one microsec. Thus, if the luminance is sufficient for detection of the stimulus at all, all that is needed is a distal stimulus which for all practical purposes is instantaneous.

In Fig. 9 luminance determines the rate of pulsing for response to a visual stimulus and RT represents the duration of pulsing required to reach the response criterion. Assuming that pulsing rate and luminance are directly related, it follows that the criterion number of impulses is represented by the product of luminance and RT, i.e.,

$$\text{Response Criterion} = RT \times L \qquad (7)$$

We do not know if the authors of the neural pulse model had it in mind, but the model is exactly analagous to:

$$\text{Distance}_c = \text{Rate} \times \text{Time} \qquad (8)$$

where Distance_c is a fixed or criterial distance.

The difference between Eq. 7 and Eq. 8 is that, although in both cases the left hand term is operationally defined as the product of the other two terms, Distance_c can be measured by procedures which are independent of the measurement of the other two quantities, whereas Response Criterion, in addition to being an hypothetical concept, albeit operationally defined, is also measured on a scale of number of neural impulses, and that scale

is both hypothetical and undefined. In an effort to get around the problem in dealing with the data of Kohfield (1968), where intensity was given by sound pressure level in db, Grice (1968) constructed a scale for the ordinate of Fig. 9 in arbitrary units and then located the response criterion at positions on this scale which were proportional to the db levels involved. Thus, sound pressure level determined impulse rate and, at the same time, represented number of impulses. Unfortunately, use of an arbitrary scale does not alter the fact that the independent variable is being used to determine itself as if it were also the dependent variable.

Equation 8 is useful to keep in mind because anything that should happen with the distance relationship should also happen with the response criterion relationship. For example, RT x L should be linearly related to both RT and to luminance. In other words, we can use RT x L in the same ways with which Rate x Time may be used, and ask if the data can be predicted from the relationships involved, and in what ways variables not included affect those relationships. In this way RT x L may tell us about the response criterion even though we have no independent measure of it.

Figure 10 relates RT x L to duration of the external stimulus with luminance as a parameter. The lines in the figure were drawn by eye. The first thing to observe about this figure is the enormous range of the ordinate value. Considering that the quantity, RT, varies within less than one log unit, it is apparent that the vertical arrangement of the lines is due almost entirely to luminance. Looking over this arrangement it is clear that all of the data which were previously unordered are now systematically ordered by luminance, with minor exceptions. Differences between signal size and monocular vs. binocular viewing are also minor except at the shortest

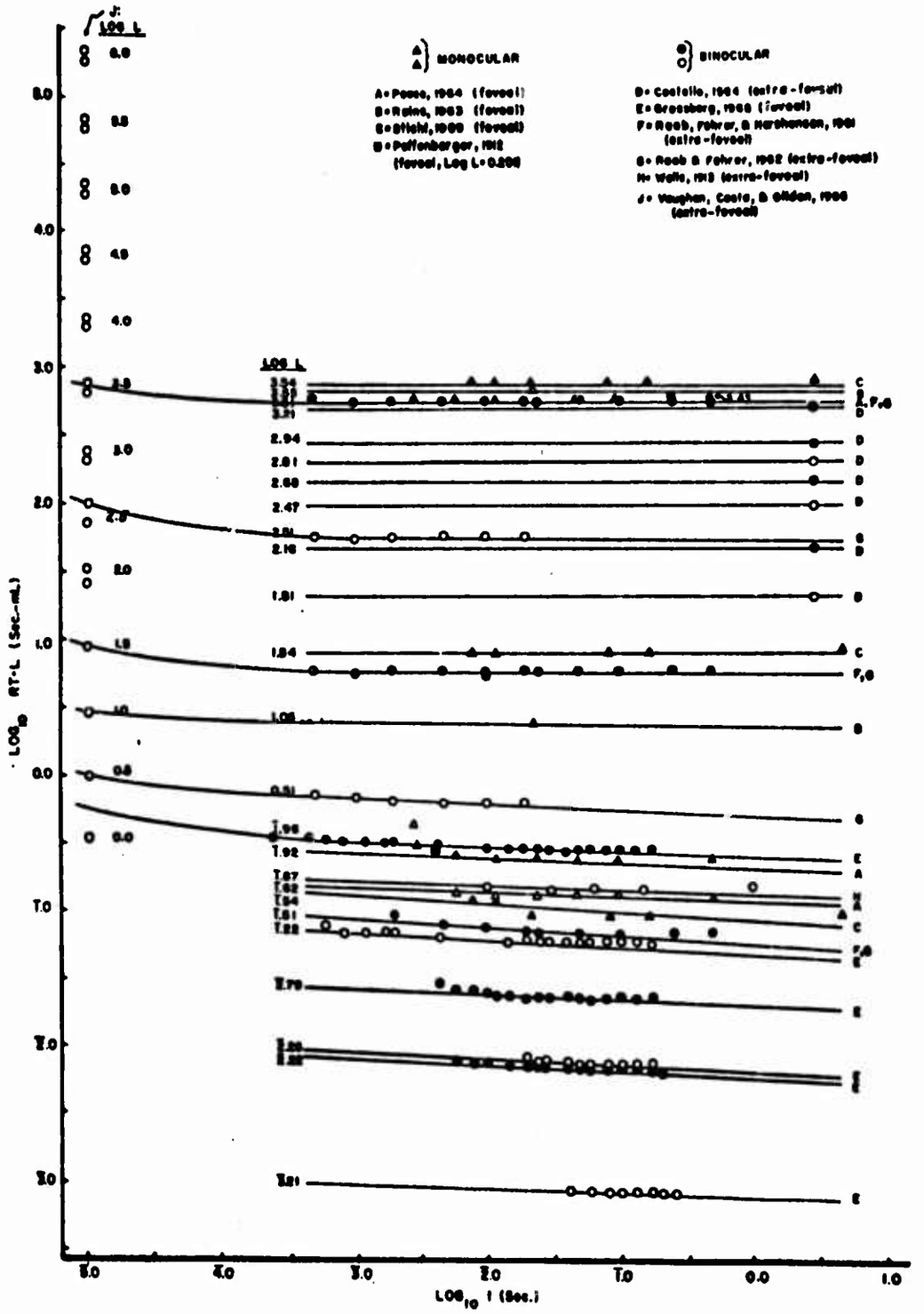

Figure 10. Response criterion expressed as log (RT x L) as a function of log stimulus duration and log luminance. Smooth lines drawn by eye. For all pairs of points at log t = $\bar{5}.0$, the upper point is based on a stimulus of 1.5° visual angle, the lower of 4.0°; the single points at this duration for luminances below log 2.0 are based on the 4.0° stimulus.

duration. Although the large range of RT x L reflects good experimental coverage of the luminance variable, it is unfortunate that more comparisons are not available where the luminance differences are small. However, for those few cases where the differences are small, especially for those smaller than the RT range, luminance is still the major factor. If, using Eq. 8, Rate x Time were plotted with rate having a very large range, and time having a very small one, the same kind of graph would be obtained. We would have to conclude that the arrangement of the trends was meaningful both mathematically and physically. We conclude, then, for Fig. 10, that luminance is the primary variable determining the response criterion and that the relationship shown is meaningful.

Figure 10 also shows that the effect of duration of the distal stimulus was to decrease RT x L as duration increased. Data which could not be handled in Fig. 5, may be seen here to fall on single trends. The data of Costello (1964) are incorporated in this context since now it is RT which defines the effective stimulus duration so that even though those data are at large values on the abscissa, they are meaningfully placed in terms of the ordinate. They may be seen simply to be at the asymptote of the duration function. All in all the figure shows that duration affected RT x L systematically, though not with a large effect, at low to moderate luminances and little or not at all at higher luminances. In the sense that RT x L represents the response criterion, the figure shows that the response criterion varies widely with luminance and to a small degree with exposure time.

Figure 11 provides a plot of RT x L as a function of luminance. The points were obtained from Fig. 10 as single-point estimates of the asymptotes of the t-function where t-functions are available. Where only one point was

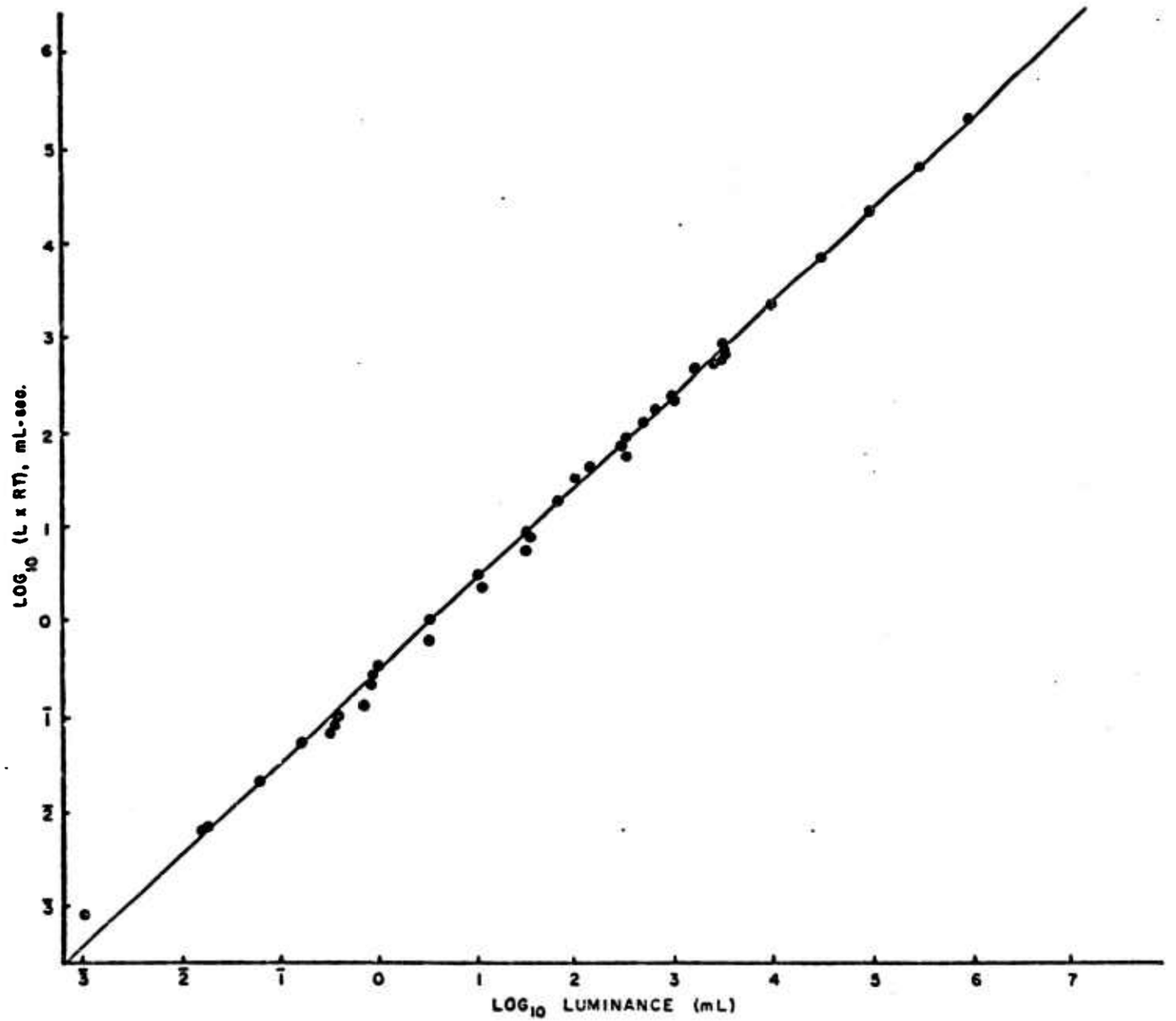

Figure 11. Log (RT x L) as a function of log luminance.

available to represent a given luminance or size that point was used as if it were the asymptotic value. Where two points were available, an average value was used. The figure shows that RT x L is proportional to luminance. The antilogarithm of the equation for the line which was drawn by eye is:

$$RT \times L = .302\ L^{.96} \qquad (9)$$

which indicates that RT x L is almost entirely determined by luminance. Dividing by log L in Eq. 9,

$$RT = .302\ L^{-.04} \qquad (10)$$

for which the exponent is midway between that of Eqs. 5 and 6 and the other constant is identical to that of Eq. 5. Thus, Eq. 10 provides a general luminance function for RT which can be used with Eq. 4 if factors other than luminance are ignored.

A three-dimensional plot of RT x L vs. RT vs. luminance verified the implications of Eq. 9. The effects of stimulus duration and of size were very, very small. To show that there are such effects it was necessary to expand the RT range (less than one log unit) so that it was almost equivalent in linear space to the luminance range. The deviations from absolute linearity of the points of Fig. 11 are very much due to the minor effects of duration, size, and manner of viewing. It is apparent that they are negligible compared to the effects of luminance.

Probability of Detection:

We had hoped to test the hypothesis that RT and the probability of detection of the stimulus were related by evaluating the stimuli used in the literature with regard to their probability of detection. A method for

estimating such probabilities has been developed by Teichner and Krebs (1970). In using the method, it was discovered that the estimated probabilities for most of the data were at least .98. A few data points fell at very low levels and fewer yet at intermediate values. What was available was considered inadequate for testing the hypothesis. That it is still a good hypothesis is suggested not only by the very small literature about it, reviewed above, but also by the analysis just described. That is, it is very reasonable to expect that if the latency of response to a signal is dependent upon the individual's response criterion, the relative frequency with which he will report seeing the stimulus depends upon that same criterion. This particular question of signal detection has been considered in great detail by Swets (1964) and Swets, Tanner, and Birdsall (1961).

II. Contrast

Compared to the literature discussed above, very little has been done to study the effects on RT of stimuli varying in contrast. Of those available, only four provided sufficient detail to attempt a quantitative analysis (Bartlett and MacLeod, 1954; Hovland, 1936; Steinman, 1944; and Steinman and Veniar, 1944). Unfortunately, all of those studies used stimulus durations of about three seconds, thereby preventing an analysis of the possible effects of the interaction between duration and contrast, background luminance and signal luminance. Moreover, the actual results reported showed a very high inter-experimental variation so that while there appeared to be a high degree of consistency within any one study, the absolute RTs reported among the different studies for comparable experimental conditions were too

variable for the kind of analysis described above. More research on this problem is required.

GENERAL DISCUSSION

Is the statement, Response Criterion = RT x L, conceptually meaningful? The answer to that question depends in part upon definition and the meaningfulness of the conceptual framework which incorporates it, and in part upon its usefulness in providing scientific relationships and accounting for data. For the model expressed in Fig. 9, Response Criterion is an index of the cumulated number of impulses. It is as meaningful conceptually and operationally as the relationship between distance and rate x time. That is, distance <u>is</u> rate x time, no more and no less. <u>Additional</u> meaning is gained when this model is related to the physical world. In the same way, additional meaning may be gained for Response Criterion by relating it to the world of neurophysiological events. At present that relationship is postulated rather than demonstrated. But the postulation of a cumulated number of impulses is sufficiently general so that no matter what may actually turn out to be the case, changing its mathematical description may not be too difficult. The difference between the two models, then, is that one already has an additional empirical meaning. They are equally acceptable in terms of operational definition.

Along this line, it is also worth noting that distance is measured as (ft./sec.)sec. = ft. In the same way Response Criterion may be expressed in units of mL-sec. In fact, radiometric units are available with which to provide an exactly analagous dimension. There is probably little gain in

using them, however, since the relationship most desired would be between RT, some function of luminance, and a neurophysiological dimension. Until that dimension is available, response criterion in mL-sec. provides an index of it.

Suppose the neural pulse model is rejected or that one does not wish to employ it. An alternative is the concept of the proximal stimulus. In these terms RT x L in mL-sec. per unit area describes the energy discharge (or absorbance) somewhere in the neurophysiological system, for example, possibly, on the retina, associated with or required for the response. In the same way, Lt is the energy application per unit area or the energy in the distal stimulus. It should be apparent that whether one uses the term, response criterion, as above, or proximal stimulus, as here, the meaning is identical. Both represent the same criterial energy or the same neurophysiological event.

In fact, if the criterion event is to be expressed in energy terms, it should be expressed as a function of change in energy rate or, if in neurophysiological terms, as a change in pulse rate rather than as a cumulated number of pulses. This follows from the finding that there is no difference in RT for response to the onset or to the offset of a flash of light. Even if there were a difference, the cumulated pulse concept would not indicate how a response could be made to an offset without an ad hoc postulation of a second hypothetical process (e.g., "off" receptors). We note then that wherever one searches for the neurophysiological criterion event, what he should seek is a criterion acceleration and deceleration of a process. For the present, however, the cumulated impulses model provides a fruitful behavioral approach.

Attentional concepts are also available which can handle the same phenomena. In particular, the idea of an attentional filter or bandwidth as formulated by Teichner (1968) provides a response-defining criterion which is pre-set by learning, motivational, and other pre-disposing factors. Moreover, that theoretical approach already provides (1) a basis for intensity modification of the criterion with concurrent variations in RT, and (2) a search process related to the criterion bandwidth which allows for an extension of the theory to more complex situations.

No provision was made in the Teichner theory for predicting absolute latencies. It was postulated that the rate of data processing through the filter increases the more narrow the filter, and that the bandwidth is reduced as stimulus intensity is increased. Thus, RT should decrease as stimulus intensity increases. A counting model, e.g., the number of repititions of the same data passing through the filter, will actually fit into the general formulation nicely. Such a model also provides for an understanding of noisy signals. Because the Teichner theory already allows for more complex behavioral phenomena and, as noted, for direct modification of the criterion (bandwidth) by stimulus intensity, we propose this combining of the two formulations.

An important implication of the use of a response criterion concept, regardless of the details of its formulation, is the lack of a need to assume that RT represents a transmission lag. That is, at even the highest luminance some time must be needed for decision. The irreducible minimum is simply the minimal decision time.

It really seems unnecessary to assume a transmission lag in a system as complex and continuously active as the central nervous system. To the

extent that such a lag exists, it may operate at the single cell level, but at the level of information processing where multiple cells are involved, the lag must be too small to be detected. The subject in an RT task always has an expectation (criterion bandwidth) about the stimulus even before the first one occurs. It does not seem relevant to consider RT as the sum of a set of lags-in-series, e.g., a sensory lag, a processing lag, an efferent lag, etc., as proposed by Donders (1889) and as generally assumed. It would seem much more in keeping with the nature of a complex system that the subject is somehow preset for the stimulus. The effector is in a state of readiness on the assumption that a signal will appear. From the onset of the stimulus the system is in a continuous "count-down" during which there is an evaluation and transmission of information. The output system (muscles) become increasingly set. When the decision is made that a signal has in fact occurred, the muscle reacts. If it was not in a state of optimum readiness it would still react, but more slowly. This state of readiness will be determined by such factors as the length of the foreperiod, the luminance of the stimulus, etc. Such an analysis implies parallel processing of the signal by a complex system in which the only significant lag is related to the status of the effector when the signal appears. The fact that a signal has occurred is sensed, processed, and transmitted to the muscle in one complex step. The types of lags associated with single neural events seem more relevant to the analysis of simpler processes.

Engineering Psychological Principles:

Aside from theoretical considerations, this study has provided empirical relationships for the prediction of RT and has indicated where the

greatest lacks of information appear to be. Since the empirical relationships cover the entire range of luminances and signal durations that have been studied and which are likely to be of interest, they may be thought of as having wide general value both as basic information and as a basis for the statement of engineering psychological principles. Stated in these terms, Eq. 10 may be used with Eq. 4 if it is desired to account for the effects of both luminance and time in the design of visual signals. If the small effects of signal size are also of interest, Eqs. 5 and 6 may be used with Eq. 4, instead of Eq. 10. These equations are limited to binocular vision and to the constraints of fit noted earlier. Furthermore, whereas the equations developed predict the mean RT of practiced individuals, the binocular line of Fig. 8 may be used for design problems in which the minimum mean RT is desired. Thus, for estimates for which only a "ball park" value is needed, the binocular line of Fig. 8 provides a generally appropriate value.

REFERENCES

Bartlett, N. R. and MacLeod, S. Effect of flash and field luminance upon human reaction time. Journal of the Optical Society of America, 1954, 44, 306-311.

Berger, G. O. Ueber den Dinfluss der Reizstärke auf die Dauer ein facher psychiser Vorgänge mit besonderer Rücksicht auf Lichtreize. Phil. Stud., 1886, 3, 38-93.

Cattell, J. M. The influence of the intensity of the stimulus on the length of the reaction time. Brain, 1886, 8, 512-515.

Chochelle, R. Variation des temps de réaction auditif en fonction de l'intensité à diverses fréquences. Année Psychologique, 1945, 41-42, 65-124.

Donders, F. C. Over de snelheid van psychische processen. Onderzoekin gedaan in het Physiologisch Laboratorium der Utrechtsche Hoogeschool, 1868-1869. Transl. by Koster, W. G. In Koster, W. G., Attention and Performance II, North-Holland Publ. Co., Amsterdam-London, 1969.

Froeberg, S. The relation between the magnitude of the stimulus and the time of reaction. Archives of Psychology, 1907, 8, 1-38.

Grice, G. R. and Hunter, J. J. Stimulus intensity effects depend upon the type of experimental design. Psychological Review, 1964, 71, 247-256.

Grice, G. R. Stimulus intensity and response evocation. Psychological Review, 1968, 75, 359-373.

Grossberg, M. The latency of response in relation to Bloch's law at threshold. Perception and Psychophysics, 1968, 4, 229-232.

Hovland, C. I. The influence of adaptation illumination upon visual reaction time. Journal of General Psychology, 1936, 14, 346-359.

Hufford, L. E. Reaction time and the retinal area-stimulus intensity relationship. Journal of the Optical Society of America, 1964, 54, 1368-1373.

Hull, C. L. Stimulus intensity dynamism (V) and stimulus generalization. Psychological Review, 1949, 56, 67-76.

John, I. D. Sequential effects of stimulus characteristics in a serial reaction time task. Australian Journal of Psychology, 1967, 19, 35-40.

Kohfeld, D. Stimulus intensity and adaptation level as determinates of simple reaction time. Journal of Experimental Psychology, 1968, 76, 468-473.

Kohfeld, D. L. Effects of ready-signal intensity and intensity of the preceding response-signal on simple reaction time. American Journal of Psychology, 1969, 82, 104-110.

Lewis, M. F. and Mertens, H. W. Reaction time as a function of flash luminance and duration. Office of Aviation Medicine Report AM 67-24, 1967.

Logan, F. A. A note on stimulus intensity dynamism (V). Psychological Review, 1954, 61, 77-80.

McGill, W. J. Stochastic latency mechanisms. In R. D. Luce, R. R. Bush, and E. Galanter (Eds.), Handbook of Mathematical Psychology, Vol. 1, New York: Wiley, 1963.

Mackworth, J. F. The duration of the visual image. Canadian Journal of Psychology, 1963, 17, 62-81.

Swets, J. A. (Ed.) Signal detection and recognition by human observers. New York: Wiley, 1964.

Swets, J. A., Tanner, W. P., and Birdsall, T. G. Decision processes in perception. Psychological Review, 1961, 68, 301-340.

Taylor, D. C. Latency models for reaction time distributions. Psychometrika, 1965, 30, 157-163.

Teichner, W. H. Recent studies of simple reaction time. Psychological Bulletin, 1954, 51, 128-149.

Teichner, W. H. Probability of detection and speed of response in simple monitoring. Human Factors, 1962, 181-186.

Teichner, W. H. and Wagner, M. Visual after-image as a source of information. Human Factors, 1964, 6, 141-156.

Teichner, W. H. Interaction of behavioral and physiological stress reactions. Psychological Review, 1968, 75, 271-291.

Teichner, W. H. and Olson, D. Predicting human performance in space environments. NASA CR-1370, Guggenheim Center for Aerospace Health and Safety, Harvard University, Cambridge, Mass., 1969 (Prepared for the National Aeronautics and Space Administration)

Teichner, W. H. and Krebs, M. J. Predicting human performance I. Estimating the probability of visual detection. Technical Report 1, ONR Contract N00014-70-C-0125, American Institutes for Research, Silver Spring, Md., 1970. (Prepared for the Office of Naval Research)

Vaughan, H. G., Jr., Costa, L. D., and Gilden, L. The functional relation of visual evoked response and reaction time to stimulus intensity. Vision Research, 1966, 6, 645-656.

Welford, A. T. The measurement of sensory-motor performance: Survey and reappraisal of twelve years' progress. Ergonomics, 1960, 3, 189-230.

Wells, G. R. The influence of stimulus duration on reaction time. The Psychological Monographs, 1913, 15, Whole No. 66.

Woodworth, R. S. and Schlosberg, H. Experimental psychology. New York: Holt, 1954.