Visual temporal integration for threshold, signal detectability, and reaction time measures*

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A comparison was made of temporal integration for three different response measures in a visual detection task: (1) response frequency, (2) signal detectability as measured for rating ROC curves, (3) simple reaction times (RTs). These measures were obtained on the same trials, to the same stimuli—orange (581 nm) light pulses of 50 min of visual angle fixated foveally and presented to dark-adapted Os in a monocular Maxwellian view. All three response measures showed a period of luminance-duration reciprocity (Bloch's law), followed by a period of partial integration. The end points of luminance-duration reciprocity (critical duration) and partial integration (utilization time) were shorter for RTs than for the response frequency and signal detectability measures. Neurophysiological implications of differences in time constants of integration for RT and psychophysical measures are discussed.

Numerous studies of temporal integration of luminous energy have demonstrated Bloch's law, which is the reciprocal relation between the luminance and duration of a visual stimulus needed to obtain threshold, e.g., 50% frequency of seeing. The longest duration at which reciprocity is found has been called the critical duration. Psychophysical studies using threshold measures also have demonstrated that for durations longer than critical duration there is a region of partial integration where luminance-duration reciprocity fails and yet where increases in stimulus duration are still effective in modifying the response (Barlow, 1958; Baumgardt & Hillmann, 1961; Sperling & Jolliffe, 1965). The longest duration showing partial integration has been referred to as the utilization time (Kietzman & Gillam, 1972; Piéron, 1952).

Although critical duration frequently has been estimated to be about 100 msec, there is increasing evidence that the specific time constants of integration depend not only upon the obviously important stimulus conditions, but also upon numerous procedural, O, and response factors as well. Thus, procedural differences, such as the use of different stimulus manipulations or data analysis procedures can lead to different estimates of critical duration (Kietzman, 1968) or even to different conclusions about the presence or absence of

temporal integration (Babkoff & Kietzman¹). O differences in temporal integration may reflect actual physiological differences, such as the demonstrated relationship between chronological age and temporal integration (Eriksen, Hamlin, & Breitmeyer, 1970), or simply may be related to the O's use of different response criteria (Levine & Kietzman, 1972). Furthermore, temporal integration may vary with the particular response being measured (Kahneman & Norman, 1964; Raab & Fehrer, 1962). Grossberg (1968, 1970) most recently has even questioned the general validity of Bloch's law for simple reaction times (RTs) to threshold-level stimuli. Grossberg (1968) measured both the frequency and latency of responses in a threshold detection task and concluded that, "Bloch's law failed to hold for latencies of response in a threshold experiment where frequencies of response did, nevertheless, obey the law [p. 229]."

The present study was designed to measure and compare the characteristics of temporal integration for response frequency, signal detectability, and simple RT measures obtained by the same Os in the same task under identical stimulus conditions. The experimental design permitted a precise determination of the durations at which Bloch's law applies and the critical duration beyond which it fails for response frequency, signal detectability, and RT. The design also provided a comparison of temporal integration for these response measures at stimulus durations longer than the critical duration in the region of partial integration.

The first response measured was frequency of seeing, the traditional psychophysical measure, which allowed comparisons with prior threshold studies of temporal integration.

The second response measured was signal detectability, which was used in an attempt to determine what effect the O's response criterion has on threshold and RT measures of temporal integration. The criterion

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Fig. 1. Oscilloscope tracings of some of O.W.C.'s luminance-varied and duration-varied stimuli (E1-E4).

that an O adopts in deciding to respond has been shown to influence the measurement both of thresholds (Barlow, 1956; Swets, Tanner, & Birdsall, 1961) and of RTs (Greenbaum, 1963; Grice, 1968; Murray, 1970). Signal detectability measures (see Green & Swets, 1966), which are believed to be independent of the criterion, may yield different estimates of temporal integration than do threshold and RT measures. In addition to measuring the frequency and latency of detection responses, the present experiment had the Os rate their confidence in the detection responses. These confidence ratings were then used to obtain receiver operating characteristic (ROC) curves and signal detectability measures.

The third response measured was simple RT, which enabled us to investigate further the applicability of Bloch's law for RT. Since a recent study (Kietzman & Gillam, 1972) suggests that partial integration may be an important aspect of temporal integration for RT, the present study compared the periods over which partial integration was demonstrated for RT and psychophysical measures.

METHOD

Stimulus Manipulations

The experimental design used in this study has previously been employed to measure temporal integration for RT (Kaswan & Young, 1965; Kietzman & Gillam, 1972). The stimulus manipulations consisted of varying the luminous energy, i.e., the product of luminance times duration, of a light pulse in two different ways: (1) by varying the luminance with duration fixed at 1 msec, and (2) by varying the duration with luminance fixed. Figure 1 shows oscilloscope tracings of some of the luminance-varied and duration-varied stimuli at four different energy levels (E1-E4). Note that each duration-varied stimulus was paired with a luminance-varied stimulus at the same energy level.

The specific values of the stimulus conditions used for each O were selected on the basis of extensive pilot testing of each O. In the main experiment, there were 5 luminance-varied conditions and 15 duration-varied conditions for a total of 20 stimulus conditions. In the luminance-varied conditions, the luminance of 1-msec light pulses was varied over five energy levels (E1-E5), yielding 20%-95% detection responses. In three separate sets of duration-varied conditions, which sampled different regions of duration, the luminance was fixed and duration varied to obtain the same five energy levels (E1-E5). The actual durations used for each O are shown in the lower portion of Fig. 2.²

Observers

There were two Os. O.W.C., a male undergraduate college student, was paid for his services. He was informed only as to what was necessary to carry out his task and was not aware of the specific stimulus conditions or the purpose of the study. O.G.B., also an E, was of necessity aware of both.

Apparatus

A monocular Maxwellian view optical system presented circular light pulses of 50 min of visual angle to the O's fovea. A glow-modulator light source (Sylvania R1131C), operated at 23 mA and irradiated by an argon ultraviolet lamp, produced light pulses with rise and decay times approximately 20 microsec and 2 microsec, respectively. The light pulses were filtered using Tiffen metallic and Kodak Wratten neutral density filters (to control luminance) and a Schott narrow-band interference filter (max transmission at 581 nm and half-value width of 10 nm). The durations of the light pulses and other events within each trial were controlled using a Logical Instruments Co. multivibrator timer (indeterminacy of 1 part in 10,000). The luminance and duration of light pulses were monitored on an oscilloscopic (Tektronix 532) display of the output of a photomultiplier tube (RCA 1P21). Stimulus luminance was checked daily with a Pritchard photometer (calibrated by means of a Gamma Scientific 220-1 standard). If necessary, the luminance was adjusted (to within approximately 2%) with neutral density filters. The retinal illuminance in trolands was measured using the procedure outlined by Westheimer (1966, p. 672). A second Maxwellian view channel provided the fixation lights (four dim red dots surrounding the light pulses). RTs were measured on an electronic counter that read in 10ths of milliseconds with an accuracy of $.01\% \pm 1$ count.

Procedure

Before each session, the O was positioned at a bite-board and dark adapted for 5 min. During each trial, a warning click was followed by a 2-sec fixed foreperiod, and then, on 75% of the trials, by a light pulse. No light was presented on the other 25% of the trials. The O was aware that the signal would be presented

Fig. 2. Psychometric functions for the 1-msec luminance-varied stimuli (x) and the duration-varied stimuli (□, ○, △). The luminance-varied points were fitted by a straight line, using the method of least squares, and brackets showing the 95% confidence limits surround these points.

on only 75% of the trials. The O's task was to lift his finger from a telegraph key as fast as possible upon seeing the light flash. However, if he did not see the light flash, he was to keep his finger on the key until a second click sounded 4 sec after the warning click. Following the second click, the O rated the confidence in his response by pressing one of three switches, which represented (1) low, (2) moderate, and (3) high confidence. If the O lifted his finger from the telegraph key, he rated his confidence in the judgment that the light did flash. If he did not lift his finger, he rated his confidence in the judgment that the light did not flash. On trials when the light pulse was present, a tone was sounded immediately after the O's confidence rating to give him feedback on the accuracy of his response. The length of each trial was approximately 5 or 6 sec, depending on the time taken to make the confidence rating, and the interval between light pulses was approximately 8-10 sec.

On each day of testing, there were four blocks of 100 trials each—one for the luminance-varied conditions and one for each of the three sets of duration-varied conditions. Within each of these blocks, stimuli at the five energy levels (E1-E5) and blanks were randomized, with the restriction that there be three trials at each energy level and five blanks within each subblock of 20 trials.³ The order of luminance-varied and the three duration-varied blocks on each day was random, with the restriction that each of the 24 possible orders be used once during the course of 24 days of testing. Each O received a total of 9,600 trials—360 trials per stimulus condition and 2,400 blanks.

RESULTS

Response Frequency

The psychometric functions for both Os are shown in Fig. 2. Increasing the luminous energy by varying

duration yielded the same psychometric function as the luminance-varied stimuli, at least up to a duration of 46.5 msec for O.W.C. and 50.8 msec for O.G.B., thus demonstrating luminance-duration reciprocity (Bloch's law). At 65.8 msec for O.W.C. and 68.4 msec for O.G.B., the percent response dropped below the luminance-varied function, suggesting that the critical duration for both Os was in the region of 45-65 msec. However, the data for the longest duration-varied stimuli (triangles) suggest an even longer critical duration. These data, together with those for the other duration-varied stimuli, gave evidence of luminance-duration reciprocity up to a critical duration in the region of 45-95 msec. At longer durations, the duration-varied function continued to increase, but was below and had a shallower slope than the luminance-varied function, which indicates that integration was only partial at these longer durations. There was evidence of partial integration up to the longest durations, i.e., 166 msec for O.W.C. and 211 msec for O.G.B.

Signal Detectability

The Os' confidence ratings were used to obtain ROC curves (see Bruder, 1972, for these data). Since the ROC curves were asymmetrical in form and had slopes of less than unity on double-probability paper, the proportion of area under the ROC, $P(A)$, was used as the measure of signal detectability. $P(A)$, a nonparametric counterpart of the d' measure of signal detectability, is equivalent to

Fig. 3. Adjusted $P(A)$ vs log luminous energy functions for the 1-msec luminance-varied stimuli (x) and the duration-varied stimuli (□, ○, △). The luminance-varied points were fitted by a straight line, using the method of least squares, and brackets showing the 95% confidence limits surround these points.⁵

the proportion of correct responses in two-alternative forced-choice tasks (Green & Swets, 1966).

Figure 3 shows the adjusted $P(A)$ plotted as a function of the log luminous energy of the stimuli for both Os.⁴ The functions obtained by varying duration overlapped the luminance-varied function up to a duration of 46.5 msec for O W.C. and 40.0 msec for O G.B., and thereby demonstrated luminance-duration reciprocity (Bloch's law) for the signal detectability measure. At longer durations, 61-166 msec for O W.C. and 50.8-211 msec for O G.B., the $P(A)$ fell below the luminance-varied function, which suggests that both Os' critical durations for the $P(A)$ measure were in the region of 40-60 msec.

The somewhat longer critical duration evident in the response frequency data for the longest duration-varied stimuli (triangles) was *not* evident in the signal detectability data. The $P(A)$ at these longer durations was in every case below the luminance-varied function and gave evidence of only partial integration. The $P(A)$ continued to increase, showing partial integration for the signal detectability measure, up to the longest duration used for each O.

An explanation of the longer critical duration estimate in the response frequency data is suggested by the false alarm rates shown in Table 1. Both Os gave slightly higher false alarm rates for the blocks containing the longest duration-varied stimuli than the blocks containing the luminance-varied or shorter

duration-varied stimuli. This difference in false alarm rates, and therefore response criteria, could have decreased the difference in response frequency between the luminance-varied stimuli and the longest duration-varied stimuli, and thereby lengthened the critical duration estimate. The signal detectability measure, $P(A)$, which is independent of differences in response criterion, did not show the lengthened critical duration for the longest duration-varied stimuli.

Table 1
False Alarm Rates and Median RTs of False Alarms

Blocks	False Alarm Rate*	False Alarm Median RT (Msec)
O WC		
Luminance Varied	.067	423
Duration Varied		
3.39-9.21 msec	.065	399
24.2-65.8	.072	482
61-166	.096	628
O GB		
Luminance Varied	.058	475
Duration Varied		
8.8-27.7 msec	.078	524
30.0-94.4	.076	482
67-211	.108	502

*Each proportion is based on 600 blank trials.

Fig. 4. Median RT vs log luminous energy functions for the 1-msec luminance-varied stimuli (x) and the duration-varied stimuli (□, ○, △). The luminance-varied points were fitted by a straight line, using the method of least squares, and brackets showing the 95% confidence limits surround these points.

Reaction Time

Figure 4 shows the median RTs plotted as a function of the log luminous energy of the stimuli for both Os. The median RT functions for the luminance-varied stimuli and the duration-varied stimuli were almost identical, up to a duration of 24.2 msec for O W.C. and 27.7 msec for O G.B. Thus, increasing the luminous energy via duration was just as effective in reducing the median RT as equivalent increases in luminance. This is in accord with Bloch's law. At a duration of 30 msec, and all longer durations, the median RT was longer than that for the luminance-varied stimuli. This indicates that the Os' critical durations for the median RT were in the region of 25-30 msec.

Note that the Os' duration-varied stimuli ranging from about 30-50 msec yielded considerably longer median RTs than the equal-energy luminance-varied stimuli, although both the response frequency and signal detectability for these equal-energy pairs were about the same. Thus, the median RTs gave evidence of only partial integration at the same durations where luminance-duration reciprocity was demonstrated for the response frequency and signal detectability data. Increases in duration were partially effective in reducing the median RT, up to a duration of 76-96 msec for O W.C. and 68.4-94.4 msec for O G.B. Further increases in duration did not decrease the median RT, which

indicates that the utilization time for RT was in the region of 65-95 msec.

Table 1 gives the median RTs of false alarms measured from the end of the fixed foreperiod (when the signal would have been presented); less than 1% false alarms occurred prior to this time. The median RTs of false alarms in the blocks containing the luminance-varied and duration-varied stimuli were all long, and the variability of the RTs was extremely high. The semi-interquartile ranges of the false alarm RTs in the blocks were 291-376 msec for O W.C. and 140-192 msec for O G.B. Although there were differences in the median RTs of false alarms across blocks, the differences were small in relation to the high variability of false alarm RTs.

DISCUSSION

The results of this study demonstrated regions of luminance-duration reciprocity (Bloch's law) and partial integration for the response frequency, signal detectability, and RT measures. The RT measure, however, displayed a shorter critical duration and utilization time than did the psychophysical measures. Thus, this study and previous studies (e.g., Kahneman & Norman, 1964; Raab & Fehrer, 1962) support the conclusion that different response measures may yield different time constants of temporal integration.

The response frequency results were in general

agreement with prior threshold studies of temporal integration, even though the experimental design differed from that traditionally used. The response frequency data showed luminance-duration reciprocity up to a critical duration in the region of 45-95 msec, which was followed by a period of partial integration. The end point of partial integration, i.e., the utilization time, was not reached, even at the longest durations used in this experiment—166 and 211 msec. Threshold studies of temporal integration (e.g., Barlow, 1958; Baumgardt & Hillmann, 1961; Sperling & Jolliffe, 1968) have found partial integration out to durations well beyond those used in this experiment.

The signal detectability results suggested that differences in response criterion across blocks influenced the estimate of the critical duration for the response frequency measure. Specifically, the Os' laxer criteria during blocks containing the longest duration-varied stimuli as compared to the blocks containing the luminance-varied stimuli might have produced the longer estimate of critical duration for the response frequency measure than for the criterion-free measure of signal detectability. The critical duration for the signal detectability measure, $P(A)$, was in the region of 40-60 msec. At longer durations, and up to the longest durations used, the signal detectability measure showed only partial integration.

The RT results gave evidence of luminance-duration reciprocity for threshold-level stimuli, up to a critical duration in the region of 25-30 msec. This finding agrees with similar demonstrations of luminance-duration reciprocity for RTs to suprathreshold stimuli (Bernstein, Futch, & Schurman, in press; Kietzman & Gillam, 1972; Lewis, 1964; Pease, 1971). Although Grossberg (1968, 1970) has questioned the validity of Bloch's law for RT, inspection of his RT data for threshold-level stimuli revealed little evidence of deviations from Bloch's law at durations shorter than 20 msec. The semi-interquartile ranges of the RTs in Grossberg's study (1968) and in the present study (see Bruder, 1972, for these data) were also consistent with Bloch's law. Analysis of the cumulative frequency distributions of the RTs (see Bruder, 1972) also supported Bloch's law, in that the RT frequency distributions for equal-energy luminance-varied and duration-varied stimuli up to about 30 msec did not differ significantly ($\alpha = .05$). The critical duration for the RT frequency distributions was about the same as the critical duration for the median RT, and was likewise shorter than the critical duration for response frequency and signal detectability.

The critical duration for RT was followed by a period of partial integration that lasted up to 65-95 msec after stimulus onset. Prior RT studies at threshold (Grossberg, 1968, 1970) and suprathreshold (Kietzman & Gillam, 1972; Raab & Fehrer, 1962) levels have similarly given evidence of partial integration for RT. Our results further indicate that the end point of partial integration, i.e., the utilization time, is considerably shorter for RT

than for response frequency and signal detectability, which continued to show partial integration at longer durations.

Since the response criterion influences RT (Greenbaum, 1963; Grice, 1968; Murray, 1970), the RT measure of temporal integration may be influenced by criterion differences across blocks in a manner similar to the response frequency measure. However, differences in the criterion across blocks for the luminance-varied and duration-varied stimuli were evident only for the longest duration-varied stimuli, for which there was little or no temporal integration for RT. It is doubtful that criterion differences had any influence on RT at shorter durations, for which luminance-duration reciprocity and partial integration were demonstrated for RT.

Previous studies (Kahneman & Norman, 1964; Raab & Fehrer, 1962) have reported differences in time constants for different response measures, but the responses were measured on separate occasions, using different procedures, which makes it difficult to compare time constants. Raab and Fehrer (1962) report that the critical duration they obtained for RT was shorter than the critical durations for psychophysical measures reported in other studies. The stimulus manipulations and other aspects of their procedures were, however, different from those used in the psychophysical studies. Kahneman and Norman (1964) found a shorter critical duration for brightness matches than for an identification task, but these responses were measured on separate trials, using somewhat different procedures. The present study, however, found different time constants for RT and psychophysical measures obtained on the same trials, to the same stimuli presented to the same Os. Furthermore, the time constants were estimated in the same manner by plotting each response measure as a function of the stimulus energy.

There are several neurophysiological implications of the finding of differences in the time constants of temporal integration for RT and psychophysical measures. Hartline (1934) has interpreted critical duration as an index of the time of occurrence of the event in the sensory system that determines the behavioral response. If this were the case, the shorter critical duration for RT than for the psychophysical measures might indicate that RT was determined earlier in the visual system than were the psychophysical measures. A recent electrophysiological study (Shevelev & Hicks, 1971) reports evidence of a systematic difference in the time constants of integration for electrical responses recorded at the different levels of the visual system of cats. However, their data suggest a progressive *shortening* of time constants of integration from the retina to cortex.

Finally, it is possible that the differences in time constants for the RT and psychophysical measures may result from differences in components of the neural response underlying these response measures. Perhaps

RT at the behavioral level reflects neural latency, while psychophysical measures reflect some other component of the neural response, such as response amplitude or frequency. Zacks (1970) presented behavioral data supporting the hypothesis that equally detectable equal-energy flashes do not necessarily evoke identical neural responses. Our finding that equally detectable equal-energy flashes had different RTs supports his hypothesis and further suggests that the neural latency to these equal-energy flashes may have been different. In several electrophysiological studies (Baker, Sanseverino, Lamarre, & Poggio, 1969; Hartline, 1934; Levick & Zacks, 1970; Wicke, Donchin, & Lindsley, 1964), equal-energy stimuli yielded neural responses of equivalent frequency or amplitude but different latencies. The shorter critical duration for RT than for psychophysical measures may be related to the shorter critical duration for neural latency than for frequency or amplitude of the neural responses.

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NOTES

1. Babkoff, H., & Kietzman, M. L. A methodological consideration of suprathreshold studies of temporal integration. Submitted for publication.

2. Measurement of the area in the oscilloscope tracings of the luminance-varied and duration-varied stimuli (such as those shown in Fig. 1) provided a check on the equivalence of the luminous energy of these stimuli. Most stimuli at the same energy level did show oscilloscope tracings of equal area. However, O.W.C.'s duration-varied stimuli, ranging from 3.39 to 9.21 msec. and O.G.B.'s luminance-varied stimuli, at E4 and F5, showed tracings of somewhat greater areas than the other stimuli at the given energy levels. The log luminous energy values in Figs. 2, 3, and 4 reflect the greater energy levels of these stimuli.

3. Stimuli at the five energy levels that were randomized within the same block share a "common" estimate of the false alarm rate obtained within a block. Emmerich (1968) has shown that the rating ROC curves that result when stimuli of different intensities are randomized within a block do not differ from the ROC curves obtained when, as is usually the case in signal detectability studies, different intensities are presented in separate blocks.

4. The $P(A)$ was adjusted, using the same formula for adjusting the percent correct in two-alternative forced-choice tasks for chance success; this adjustment extends the range of

values to 0%-100%, which facilitated comparison of the response frequency and $P(A)$ data.

5. The extremely high value of the adjusted $P(A)$ for O.G.B. at the highest luminous energy level was not included in the least-square fit of the luminance-varied points. The dropping of extreme proportions is recommended when fitting psychometric functions (Guilford, 1954, pp. 130-131).

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