Two-Pulse Measures of Temporal Resolution as a Function of Stimulus Energy*

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Mahneke previously reported that increasing the duration of light pulses reduced the two-flash threshold. He attributed this reduction to the increased "quantity of light" provided by the longer light pulses. Two experiments were conducted to test the hypothesis that increased stimulus energy in the photopic range lowers two-flash measures of temporal resolution. In Experiment I, two-flash thresholds were obtained by increasing either stimulus intensity or stimulus duration over an energy range of 1.4 log units. Comparison of the results obtained from these two manipulations showed that increasing duration reduced two-flash thresholds by 42 msec and 52 msec for two subjects while increasing intensity reduced their thresholds by only 8 and 15 msec. In Experiment II, a change of the stimulus intensity over an even greater range, i.e., 2.4 log units, and use of a more sensitive psychophysical method failed to produce any systematic shift of the two-pulse threshold. It was concluded that for the energy range tested, an increased quantity of light does not modify two-pulse measures of temporal resolution.

INDEX HEADING: Vision.

The two-flash threshold has been measured by determining the interval of time between two successively presented pulses of light that enables a subject to report seeing two flashes a certain proportion of the time. This technique has been interpreted as providing a measure of temporal resolution which has been viewed as a fundamental characteristic of perceptual behavior.1 2

Mahneke3 systematically investigated two-flash resolution and concluded that increases of the "quantity of light," i.e., the total energy, reduced the two-flash threshold. However, in his study, energy increments were obtained by increasing the duration of the pulses, a technique which provides an operational definition of energy increment but presents certain difficulties. Thus, as the duration of the light pulse is increased, the amount of energy being integrated by the nervous system is not necessarily increasing, since the duration of some of the pulses may be longer than the critical duration of Bloch's law.4 Also, the fact that longer stimuli

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4 Mahneke did not refer to Bloch's law or take its implications into consideration. His use of the quantity-of-light explanation for his results suggests that he either considered Bloch's law to be inapplicable (it generally has been tested at absolute-threshold energy levels) or that he considered all of his stimulus durations to be shorter than the critical duration. Recent evidence for supra-threshold stimuli suggests much shorter critical durations than the durations of the pulses used by Mahneke. See T. S. Alba and S. S. Stevens, Vision Res. 4, 391 (1964).
sometimes appear dimmer than shorter stimuli of the same luminance (Broca–Sulzer effect) illustrates the fact that the increase of stimulus duration to increase energy may have complex perceptual results. In the present report, Experiment I was designed to investigate further the effects of energy increments on two-flash discrimination by comparing the effect of increasing energy by increasing pulse duration with the effect of increasing energy by increasing pulse luminance. Stimulus areas, durations, and luminances were approximately within the ranges of those explored by Mahncke.

**EXPERIMENT I**

**Subjects and Stimuli**

Two trained male subjects with normal vision, MK and SW, were tested. The two-pulse stimuli presented to the subjects consisted of different luminance-duration combinations. The combinations (seven for MK and nine for SW) were chosen to allow comparison of the relative effects of manipulating duration and intensity over the same range. The durations and luminances used for both subjects were 4, 27, and 62 msec, and 40, 269, and 612 mL. In addition, SW received a 993-mL stimulus. The total stimulus energy (duration X luminance) of various pairs of stimulus was the same. Thus, a more luminous but briefer pulse had the same energy as a less luminous but longer pulse. In this way, for both subjects two stimuli of different luminance-duration combinations were tested at three of the five energy levels investigated.

**Procedure**

A typical experimental session consisted of 150 judgments or trials, 75 for each of the two luminance-duration stimulus combinations tested in that session. The particular combinations to be used and the order in which they were tested for a session were determined randomly. The 75 trials for each stimulus were divided into three consecutive blocks of 25 trials with a rest period following each block. Within each block, six to eight interpulse interval values were varied randomly from trial to trial. The exact interpulse intervals employed were different for the two subjects, and for the particular stimulus being tested, but for both subjects the values were changed in 5-msec steps. The range of intervals was from 6 to 86 msec for MK and from 16 to 91 msec for SW.

The frequency of the subject’s report of “two flashes” was taken as a function of the interpulse interval. Sixteen curves showing the frequency of seeing two flashes, one for each duration–luminance combination, were obtained. Each curve was based upon at least 20 stimulus presentations per point and 180 presentations per curve. The slopes of the psychometric curves for the different stimulus combinations were similar, and therefore the two-flash threshold was specified as the interpulse interval that produced a report of “two flashes” 50% of the time. The specific threshold values (see Table I) were obtained by determining a line of best fit for the empirical points by the method of least squares.

At the beginning of a session the subject was dark-adapted for at least 5 min in a light-tight booth. Then he was given an auditory signal that the experiment was to begin and that he could trigger the stimuli at any time. To prepare for the stimuli he fixated on four dim, red fixation lines through a 3-mm artificial pupil. His head position was fixed by use of a bite board and chin and forehead rest. Intertrial time was approximately 5–8 sec, depending upon how quickly the subject triggered the stimuli following the preparatory signal.

All stimulus combinations were tested from three to seven times during the four weeks that it took to complete the experiment. To estimate the reliability of the measurements across sessions, separate curves showing the frequency of seeing two flashes were obtained for alternate “odd” and “even” numbered sessions. Spearman rank-correlation coefficients were obtained by comparing frequencies from the “odd” sessions and the “even” sessions. The results from the different sessions were reliable, as is shown by the fact that the rank correlations obtained ranged from 0.75 to 1.0. A test of the significance of these correlations demonstrated that the magnitude of all but three of the correlations were greater than chance at the 0.01 level of significance (two-tailed test). Two of the remaining three correlations were significant at the 0.05 level while one correlation was at the 0.10 probability level.

**Apparatus**

A one-channel optical system provided a monocular Maxwellian view of an image of the crater of a glow-modulator gas-discharge tube (Sylvania R 1131C). The white-appearing target was determined by a circular field stop. It subtended a visual angle of 20 min and was focally fixated. The duration, slope, and luminance of the light pulse were continuously monitored by
use of two photomultiplier tubes (RCA 1P21) whose spectral sensitivities were corrected by filters (Kodak Wratten filter 106) to approximate the CIE photopic luminous efficiency curve. Luminances were controlled by neutral density filters (Kodak Wratten filter 96) calibrated in our laboratory to an accuracy of 5%. The glow-modulator tubes were electronically gated. The duration of the pulses and of the dark intervals were controlled by a transistorized, nine-channel multivibrator timer with an indeterminacy of 1 part in 10,000. Temporal characteristics of the waveform of the light pulses showed that, at the current level used (23 mA), risetime was approximately 20 μsec and decay time was approximately 2 μsec.

**Results**

Table I shows the two-flash thresholds of both subjects for the different stimulus luminance-duration combinations. The columns correspond to the different log luminances and the rows to the different log relative luminances. The two-flash threshold values (in msec) appear in the cells with the log of the relative energy (luminance×time) expressed in arbitrary units shown in parentheses below each threshold value. The same energy value may appear more than once because it was obtained with different luminance–duration combinations. For both subjects, as the duration of the stimulus increased for a fixed luminance (reading horizontally) the threshold dropped rapidly. On the other hand, as the luminance of the stimulus increased for a fixed duration (reading vertically) the thresholds decreased only slightly. Even an additional increase of luminance for SW (log 2.0 relative luminance) failed to produce threshold shifts comparable to those obtained by changes in duration. A comparison of threshold values for the six equal-energy pairs (three for each subject) shows them to be quite different; the lower threshold of each pair always was obtained with the longer duration stimulus. These six differences were tested with a t test and all were found to be significant at the 0.01 level of confidence.

A comparison of the difference between duration and luminance effects for both subjects is shown in Fig. 1 (based on the rows and columns of Table I for which there is an entry in all cells). Note that energy is plotted on the upper abscissa. The dashed lines show that when the stimulus duration increased, while the luminance remained constant, there was a marked reduction of the two-flash threshold: 42.2 msec for SW and 51.6 msec for MK; this reduction was approximately linear as a function of the log of the stimulus duration. On the other hand, the continuous lines show that if the luminance was increased over the same range (or even a greater range for SW) while duration remained constant, there was only a slight reduction of the two-flash threshold: 8.5 msec for SW and 14.9 msec for MK. We can conclude that two-flash thresholds are lowered considerably when energy is increased by lengthening the duration of the two pulses but that they are reduced only slightly when energy is increased by increasing the luminance of the two pulses of light. The fact that the two operations to increase stimulus energy failed to produce the same results brings into question the exact role of energy in two-flash thresholds.

**EXPERIMENT II**

In Experiment I, increasing the luminance, and therefore the energy, of the stimulus by a little over one log unit only slightly reduced the two-flash threshold. In the present experiment, the effect of increasing luminance over a wider range was investigated. In addition, a more sensitive psychophysical method was employed. In other research done concurrently with these experiments, we had found that a temporal forced-choice psychophysical method yielded thresholds which were one half to one third of those obtained with the method employed in Experiment I. We, therefore, shifted to a temporal forced-choice method for this experiment with the thought that the different and more sensitive method might increase the probability of detecting luminance effects upon threshold measures, if they exist.

In the temporal forced-choice method, the instructions to the subject were to report which one of several sequentially presented stimuli was the different stimulus. This was in contrast to the instructions used for the method of the first experiment for which the subject was instructed to base his judgment on a predetermined perceptual characteristic—stimulus "twoness." The difference of the subject's task in these two experiments leads us to suggest that the two different methods may actually be investigations of two different types of thresholds, requiring different terminologies. In Experiment I we measured the two-flash threshold, and in the present experiment we measured the two-pulse threshold, a term which takes into account the fact that the

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1 Similar terminology was proposed by S. H. Bartley, in his *Principles of Perception* (Harper & Brothers, New York, 1958), p. 99, where he suggests that a distinction he made between the terms "pulse" and "flash" with the former referring to the stimulus and the latter to the response.
method does not instruct a subject on what to base his discriminations. He need not, in fact, see two flashes.

**Procedure**

With the forced-choice method, the stimuli were presented in four successive observation periods that followed one another at one and one-half sec intervals. One of the four stimuli, the test stimulus, consisted of two pulses of light separated by a variable dark interval. Three of the four stimuli, the comparison stimuli, were identical double-pulse stimuli with a zero dark interval, so that they were actually single pulses of light. Each pulse of light was 5 msec, so the duration of each comparison stimulus was 10 msec. From trial to trial, the two-pulse test stimulus appeared in a different observation period except for the limitation that, as the subject was informed, the test stimulus never was permitted to appear in the first observation period. For each trial, the subject's task was to report the temporal position of the test stimulus. He was not informed about the accuracy of his responses. His accuracy in discriminating the test stimulus, adjusted for chance, was the dependent variable. The independent variable of the experiment was the interpulse interval; values were chosen to ensure that the subject's performance would vary over a wide range of discrimination accuracy. Four trained subjects with normal vision, three men and a woman (subject PA), were tested. The range and absolute values of the interpulse intervals differed for the various subjects. For MK and PA, they ranged from 0 to 50 msec in 10-msec steps while for JG and TN, they ranged from 5 to 55 msec in 5-msec steps. The experimental parameter was the luminance of the two-pulse stimulus, and each subject was tested at three different luminances. For three of the subjects, the luminances were 2.5, 40, and 612 mL. The same luminances were used for MK except that a 62 mL stimulus was substituted for the 40 mL stimulus. These luminance values overlap those used in Experiment I; the additional range of Experiment II was obtained by using a stimulus of lower luminance than in Experiment I.

In a daily experimental session, two blocks of 20 trials each were randomly assigned to each luminance. Within each block, the interpulse intervals were varied randomly. Data were collected for at least five experimental sessions. The data were plotted to show the relationship between interpulse interval and the accuracy of discrimination; luminance was the parameter. Lines of best fit for the data were determined by the method of least squares. The two-pulse threshold was specified as the interpulse interval that produced 50% correct judgments after correction for chance. The visual angle subtended by the circular target was 30 min. All other apparatus were the same as in Experiment I.

**Results**

Figure 2 shows the two-pulse threshold of all luminances for all subjects. No systematic change of the thresholds is evident as a function of increased luminance, even when it is varied over a range of 2.4 log units. The average threshold for the four subjects is shown by the curve with the dashed line. These thresholds all fall within a 5-msec range. An additional and expected result of Experiment II was that the thresholds obtained by the forced-choice method were less than half of those obtained in Experiment I. This is demonstrated particularly by the data for MK, who participated in both experiments.

**DISCUSSION**

Taken together, the results of these two experiments strongly suggest that energy increments, per se, do not change the two-flash or two-pulse thresholds. This conclusion is based partly on the result found in Experiment I that equal-energy stimuli failed to give the same two-flash thresholds, apparently because the effect on the threshold of changing stimulus duration is greater than the effect of changing luminance. Furthermore, in Experiment II, little, if any, systematic change was noted when energy was increased by increasing luminance as much as 2.4 log units.

The present results do not substantiate Mahneke's "quantity of light" hypothesis, despite the fact that they do constitute a confirmation of Mahneke's observation that a marked relationship exists between stimulus duration and the two-flash threshold. Previous two-flash investigations also fail to lend support to the "quantity of light" hypothesis, although those studies
were not designed specifically to measure the effect of luminance increments. Thus, Dunlap concluded that the effects of "brightness" are variable. Venables reported that changes of stimulus intensity over a 1.6 log unit range failed to produce shifts of the two-flash threshold, although for an intense stimulus (5380 nL) he obtained higher thresholds. Obert-Thorn found no significant difference between two-flash thresholds for two luminance that differed by 3 log units. Unfortunately, Ireland's comprehensive investigation of the effects of luminance upon the two-flash threshold has only one condition comparable to those used in the present experiments. In that investigation, monocular two-flash thresholds were obtained for five subjects under two luminance conditions, one log unit apart. The group average for the subjects showed a lower two-flash threshold by 10 msec for the higher luminance. This result corresponds quite closely to the result of Experiment I for a luminance change over approximately the same range. Of the five subjects tested by Ireland, two were unaffected by change of luminance.

It should be noted that the results of the present experiments, and of earlier two-pulse experiments, are not comparable to those studies using multiple pulses to obtain critical-flicker-frequency (CFF) thresholds. Ireland summarized a major difference when he concluded on the basis of his luminance comparisons for both foveal and peripheral retinal regions that: "Certain properties of the critical two pulse interval (two-flash threshold) were found to differ from those of the critical flicker frequency. For example, neither monocular nor binocular critical two-pulse intervals seemed to follow the familiar \( f = \log I \) (Ferry-Porter law) relationship approximated by CFF." Other differences between two-pulse and CFF studies previously have been reported. A type of experiment which shares with the two-pulse experiment the manipulation of a single dark interval is one in which a light stimulus having a total duration of 1 sec, or even longer, is interrupted by a single dark interval. As in the two-flash case, the dependent variable is the shortest perceptible dark interval. Under these conditions, the higher the luminance of the interrupted light the shorter the perceptible dark interval. In fact, it has been suggested that the "quantity of absent light" is a constant. This would parallel the reciprocity for single light pulses, i.e., Bloch's law. It should be noted that experiments using such long-duration light pulses, and also CFF experiments, investigate a light-adapted visual system functioning under nearly steady-state conditions. Such experiments are quite distinct from studies that use only two brief pulses of light, in which cases the visual system is undergoing rapid and marked changes. This distinction is clearly illustrated by the results from CFF studies that vary the total number of pulses presented. Here, as the number of pulses is increased, the CFF increases very rapidly at first, then less rapidly, until an asymptotic CFF value is reached.

The problem of explaining why increasing pulse duration produces lower resolution thresholds still remains. It is tempting to attribute this shift to the increasing time separation of either the "on" or "off" neural processes. Such an explanation would be consistent with the lack of a luminance effect, since altering the luminance of both pulses presumably would not alter to any great extent the time between either the "on" or "off" processes. Studies of the neural processes underlying two-pulse stimulation, especially when luminance and duration are varied so as to yield equal energy, might help to explain the stimulus duration effect on the two-flash threshold and might also help to clarify two-pulse interactions in general.

Note added in proof. M. F. Lewis, in this issue [J. Opt. Soc. Am. 57, 814 (1967)], presents data which show an inverse relationship between two-pulse threshold and stimulus luminance, with a 15-20 mscc reduction in threshold over a luminance increment of 3.5 log units. In his study, which involved a different forced-choice technique, most of the threshold reduction is obtained for the lowest luminance levels, all of which are lower than any tested in the present report.

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1 W. S. Battersby and R. Jaffe, J. Exp. Psychol. 46, 154 (1953).