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Temporal and Spatial Visual Masking. I. Masking by Impulse Flashes

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Masking is defined as the change in threshold energy $e_T^*(\tau)$ of a test stimulus **T** induced by a masking stimulus **M** of energy e_M as a function of the relative time τ of occurrence. Masking is maximum when **T** and **M** occur simultaneously. A slight decrease in threshold for tests preceding the masking impulse by about 0.1 sec was explained as an alteration in appearance of the subsequent masking flash by a "subthreshold" test flash. Impulse-contrast threshold e_T^*/e_M was investigated for masking impulses **M** of seven different energies superimposed on five backgrounds **B**. The increases in test threshold caused by **M** and by **B** were found to be independent and a modified Weber's law (adjusted contrast threshold $C_\delta^* \approx 0.1$) held approximately. This conclusion was supported in a supplementary investigation of C_δ^* using a category-rating-scale method.

Impulse masking results were applied to predicting the masking peak at the onset of a long flash by treating the first 60 msec as an impulse. The lowering of thresholds of tests delayed in a long masking flash implied other detection mechanisms (e.g., temporal resolution). Theoretical predictions accounted for 94% and 97% of the variance in two relevant experiments, correctly predicting the effect of masking-flash duration and of background intensity.

In both steady and intermittent light, masking is attributed primarily to fast processes (time constant $\ll 1$ sec) which presumably have a neural rather than a photochemical basis.

THE action of one visual stimulus on the visibility of another is called "masking." All visual stimuli may be studied as masking stimuli; the observed complexities of masking indicate that it involves much or all of the visual system. Therefore, an understanding of visual masking may generate a profound understanding of vision.

The highly nonlinear nature of visual masking makes it necessary to study a great variety of masking situations. Many of the experiments to be described are basically of the same form as earlier ones.[1–19] They investigate new situations and introduce systematizations. The present article is limited to studies of masking by impulses and a hypothesis concerning its relation to masking by long flashes. It is prefaced by

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general introductory remarks and by a complete method section intended also to serve subsequent reports.

Definitions

It is well known that the minimum energy an observer needs to detect a visual stimulus depends upon what else has been, is, and will be present in his visual field. The stimulus he is trying to detect may be called the test **T** (or test field, test patch, etc.). We may denote a visual stimulus other than the test either as a masking field **M** (if it varies in time), or as a background **B** (if it is steady). The word masking is used because light other than the test in the visual field usually causes an increase in threshold for the test; that is, it masks it. Thus visual masking refers to a phenomenon observed in experiments involving two visual stimuli. The visual masking experiment is designed to determine just what changes in test visibility are induced by a particular masking stimulus.

Masking Stimulus

A monocular masking stimulus **M** is described by giving its luminance $l_\mathbf{M}$ as a function of four variables: time t, wavelength λ, and spatial location (x,y) or (r,θ). To emphasize the dependence of $l_\mathbf{M}$ on these variables we may write $l_\mathbf{M}(x,y,t,\lambda)$.

Test

The test **T** similarly may be denoted $l_\mathbf{T}(x,y,t-\tau,\lambda)$. Here τ is the time delay of the test with respect to the masking stimulus.

Background

A background **B** usually is an unvarying field of steady luminance $l_\mathbf{B}(x,y,\lambda)$. It is useful to designate **B** separately from **M** because it enters into computations differently.

Pre-adaptation "backgrounds" are time-varying backgrounds. In all of the work to be reported, pre-adaptation "backgrounds" are turned off $\frac{1}{4}$ sec or longer before the onset of **M** but are assumed to be equivalent to continuous backgrounds[14,20–22] during the interval of interest, thus the appellation "background."

Test Energy

In masking experiments, interest usually is directed at how the areal density of luminous energy of the test

$$e_\mathbf{T}=\int_0^\infty\int_{-\infty}^\infty l_\mathbf{T}dtd\lambda$$

varies as a function of other variables. With very brief stimuli whose energy is spread uniformly over a spatial area, it is more convenient to consider the areal density of luminous energy e at each point than it is to consider total energy. The units of areal density of luminous energy used here are ft-L×msec and the quantity is abbreviated to "energy" when no confusion arises.

Test Threshold

An asterisk superscript is used to denote a threshold quantity. Experimentally determined values of test threshold energy are designated as $e_\mathbf{T}^*$. The value of $e_\mathbf{T}^*$ depends mainly on the masking stimulus **M** (all x, y, t, and λ), on **T**, on who the observer O is, and on the criterion k (i.e., "just barely visible," "equal in detectability to a reference standard," etc.). Other factors (e.g., motivation, sequential-response dependencies, etc.) will not be specifically denoted. Thus we may write $e_\mathbf{T}(\mathbf{M};\mathbf{T};O;k)$.

Threshold Masking Response

In the usual temporal-masking experiment, only test energy $e_\mathbf{T}$ and the time delay τ between occurrence of the test and masking stimulus are varied. The variation of threshold $e_\mathbf{T}$ with τ [abbreviated $e_\mathbf{T}^*(\tau)$] is determined. In the temporal- and spatial-masking experiment the spatial location of **T** relative to **M** also is varied and $e_\mathbf{T}^*(\tau,x,y)$ is determined. The entire function $e_\mathbf{T}^*$ may be called a threshold masking response (to the masking stimulus **M**).

Designation of Impulse Masking Flashes

The present article deals with a variety of impulse masking flashes superimposed on various backgrounds. These have luminances representable by $l_\mathbf{M}(x,y)\delta(t)$ and $l_\mathbf{B}(x,y)$, where $\delta(t)$ is the unit impulse. An impulse **M** is most conveniently described by its areal density of luminous energy ("energy")

$$e_\mathbf{M}(x,y)=\int_{-\infty}^\infty l_\mathbf{M}(x,y)\delta(t)dt.$$

In all the experiments to follow, the masking and test stimuli are periodic in time. In each case, the period (usually 1 sec) is explicitly stated in the text but is omitted from the notation in order to keep it simple.

Three Principles of the Masking Procedure

The first complete temporal-masking experiment was conducted by Crawford.[5] He presented a circular pattern of light (masking stimulus **M**) to foveal view for 524 msec. The threshold luminance for a smaller, spatially superimposed 10-msec flash of light (test **T**) was determined for each of various times of occurrence before, during, or after **M**. In this way, threshold luminance—thereby energy—of the test was obtained

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as a function of time [threshold masking response $e_T{}^*(\tau)$].

Crawford found that the peak of the threshold masking response occurred when the onsets of the test and masking stimuli coincided approximately. He also noticed that the masking stimulus masked tests which preceded it by as much as 100 msec. Subsequent to Crawford, a number of investigators have used more or less similar procedures to determine complete[1–7] or partial[8–19] masking responses. Three methodological implications of these procedures are discussed below.

Sampling

The method of threshold determination is a sampling method. This is not obvious in Crawford's experiment, because one test flash occurs with each masking flash. As long as masking flashes are widely separated in time, this one-to-one relation is not a drawback. However, when masking flashes occur at a rapid rate (e.g., 20 flashes/sec) it may no longer be desirable to have one test flash paired with each masking flash. In this case, the time between successive test flashes could be chosen to meet a different criterion, namely that successive test flashes do not appreciably interact with each other. Each test flash occurs at the same phase τ relative to the masking flash with which it is paired (for example, exactly at the onset), but this pairing need occur only once in every n masking flashes.[3,23] A sampling procedure permits us to determine the response to any kind of masking stimulus that can be repeatedly presented to the eye. In particular, it is desirable to use "infrequent" sampling in order to measure responses to rapidly flickering masking stimuli.

Impulse in Time

The test flash should be "instantaneous." In visual masking, "instantaneous" may mean several msec or shorter in duration. A very brief flash is called an impulse. The purpose of using an impulse test flash is primarily for simplicity. If **T** is of long duration, then the threshold energy $e_T{}^*$ for this flash is closely related to an averaged sensitivity for impulse tests during the whole time spanned by the longer test flash.[24] It is easier to interpret thresholds obtained with impulses, particularly when the relation between long and short test flashes is not known exactly.

The masking stimulus of course also may be an impulse. In masking experiments to be reported here, the response to impulse masking stimuli is determined with impulse tests.

Point in Space

The third consideration is the effect of area of the test stimulus. Just as temporal effects are sampled by an impulse in time, spatial effects may be determined by an "impulse" in space; i.e., a point. The threshold for a spatially extended source should be predictable from the threshold at each point of the extended area.

By using a test stimulus of very small area to approximate a point source, it is possible to find the response to any spatial pattern of masking stimulus at each retinal location. For example, **T** may be located inside, at a boundary, or outside the area stimulated by **M**. At each spatial location, the response to the masking stimulus $e_T{}^*(x,y,t)$ is determined as a function of time, using infrequent sampling if necessary. Formally, there is a close analogy between the spatial- and the temporal-masking experiment.

These three considerations show that it is possible to measure a threshold masking response to any spatial or temporal distribution of light on the retina (masking stimulus). In general, this requires the use of a sampling method with an impulse point source. In the experiments to be reported, the three principles are used to measure responses to a variety of impulse masking stimuli. All the experiments are limited to short-term effects, less than about 1 sec in duration.

So far, we have assumed that the observer's task was to detect a patch of light, masked by flashes of light. For every such experiment there is a complimentary experiment in which the observer's task is to detect a patch of "darkness."[25] This variation will be explicitly considered. Certain other relevant variables, such as the effect of peripheral stimulation and variations in wavelength are not considered in great detail, although the procedure easily can be generalized to cover these cases.

METHOD

Apparatus

Tachistoscopes

The experiments were conducted over a period of 5 years. Three different sets of apparatus, each having certain advantages over its predecessor, were used to present stimuli to subjects. These devices (tachistoscopes)[26] all used a similar principle to permit normal monocular or binocular viewing of the visual stimuli. By means of partially reflecting mirrors, two or three separate stimulus fields were optically made to appear superimposed[27]: a masking stimulus, a test, and, when present, a background field which was intended primarily to regulate the average light flux reaching the eye. Except in one instance, viewing was monocular. Viewing distance was varied from 16 to 42 in. Field sizes are given in terms of visual angle.

Two different kinds of light sources were used: argon flash lamps and fluorescent bulbs. The argon gas

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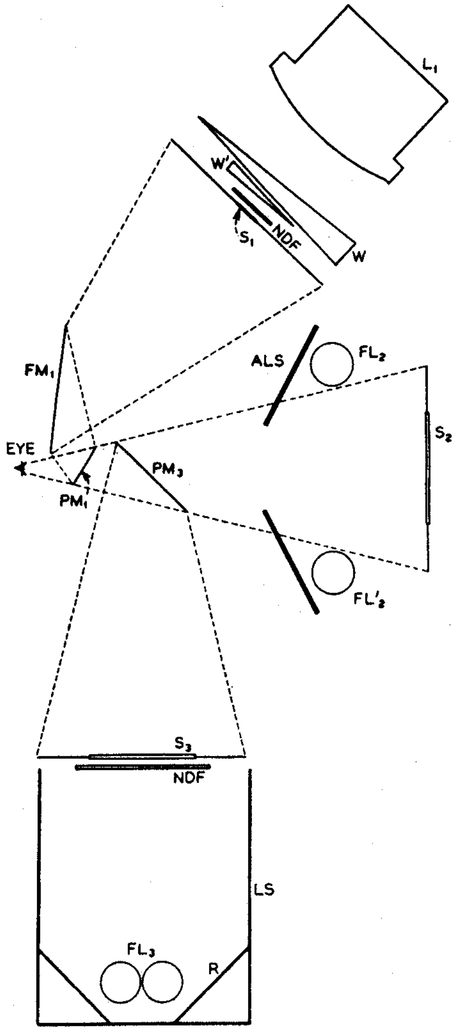

FIG. 1. Schematic diagram of a three-field tachistoscope. Subscripts refer to the individual stimulus fields. ALS, adjustable light shield; FL, fluorescent lamp (end view); FM, front-surface mirror; L, gas-discharge flash lamp; LS, light shield; NDF, neutral density filter; R, reflecting surface; S, stimulus field; W, adjustable neutral density logarithmic wedge; W′, balancing wedge.

discharge lamps generated flashes of light less than $\frac{1}{10}$ msec in duration. Fluorescent lamps generated square waves of light of 1-msec duration and longer, as well as steady light.

Figure 1 illustrates schematically the location of the various elements in a three-field tachistoscope. The partially reflecting mirrors (PM_1, PM_3) optically superimpose the three fields. The reflections are vertical rather than horizontal so that the optical path for each eye will be more nearly equivalent.

Fields may be viewed either by transmitted or by reflected light. The test field S_1 normally is viewed by transmitted light from a gas discharge lamp. Field S_2 illustrates the arrangement of fluorescent lamps for viewing stimuli by reflected light; field S_3, the arrangement for transmitted light. Any light source may be used with any field. When only two fields are used, the partially reflecting mirror PM_1 is removed. Intensity of the test field usually is under continuous control of the observer by means of a hand switch, which operates the optical wedge.

Fluorescent Lamps

A large number of fluorescent lamps were tested for their ability to produce rectangular pulses of white light. The Sylvania Super Deluxe Cool White (SDCW) lamp was selected. Figure 2 shows the circuit used to obtain simultaneous square waves from two of these lamps. The circuit supplies regulated dc to the lamps while the timing relay is closed. The current is controlled by the 300-V source and by the variable resistance *R*. The duration is controlled by a timing circuit which opens and closes the relay. With WE 291 mercury-wetted relays, operating times of one msec and longer are possible.

Figure 3 shows oscilloscope traces of the light output of these lamps as measured by an RCA type 934 vacuum photocell through a Corning #3486 yellow filter, which combination has maximum sensitivity at about 545 nm. Figure 3 shows that the SDCW lamps produce constant pulses of light with a duration of 5 msec as well as pulses of 50 msec. Comparable results

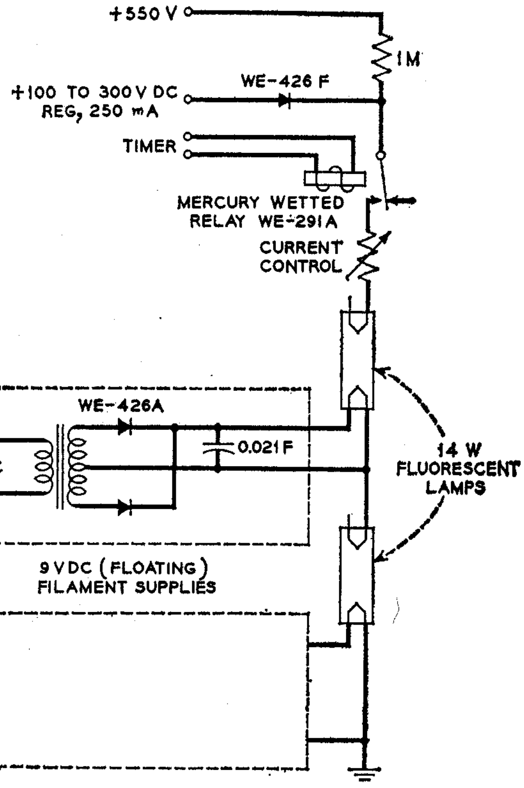

FIG. 2. Electrical circuit for operating fluorescent lamps to produce rectangular pulses of light.

are obtained for shorter and longer times and at all other regions of the visible spectrum.

Over a range exceeding 10 to 1, the light output is nearly proportional to the current with little color change. The linear range of variable intensity was supplemented with neutral density filters.

Gas-Discharge Lamps

Two similar flash lamps are used, GR Strobulux 648A and GR Strobolume 1532C. Each of these lamps, when set to give flashes of maximum intensity, produces bluish-white light of which 90% is confined to a duration less than about 0.04 msec. Less intense flashes are even shorter. Usually, Kodak color-balancing filters were used to minimize color differences due to different light sources or light paths.

Photometric Calibration of Impulse Flashes

Impulse energy is determined by a split-field match of a surface illuminated by the gas-discharge lamp (impulse) and a surface illuminated to a known luminance by a fluorescent-lamp flash of 5.00 msec duration. The impulse flash is adjusted to occur during the middle of the 5-msec flash (see Fig. 4). In this way, the area illuminated by a brief flash of unspecified waveform is matched to a known luminance and duration, the equivalent energy *e* being computed in ft-L×msec.

The calibration match does not depend upon the particular duration of the fluorescent lamp. Longer and shorter flashes give the same *e* if the impulse is centered in the longer flash. The calibration match is independent of background luminance, the level at which the match is made (at moderate energies), and slight color differences between fields that sometimes prevent the disappearance of the boundary. However, a constant error which depends on geometry may occur if the split-field match is used with small test fields. The day-to-day repeatability of the match is about 5%. The split-field method of calibrating stimuli illuminated by gas discharges was not used during some of the earlier experiments.

Timer

Electronic, phantostron-type[28] timers are used to control all time intervals, e.g., the duration of light flashes and the times between various flashes. For example, the duration of a 5-msec light flash can be set to an accuracy on the order of microseconds. Generally, short time intervals are set to an accuracy of 0.05 msec; it is not considered necessary to set long intervals more accurately than 0.1%.

Monitoring and Calibration

By means of photocells, every stimulus presentation is displayed on a calibrated cathode-ray oscilloscope. Critical time intervals are continuously monitored with an electric counter.

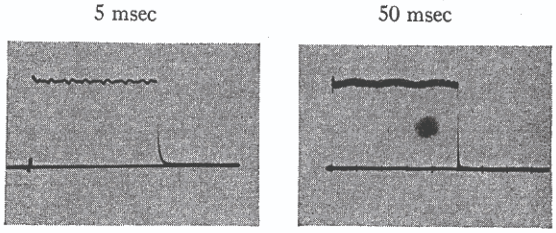

Fig. 3. Oscilloscope traces of light pulses produced by Sylvania SDCW, 14W fluorescent lamps. Ordinate is the same for each trace; the time base has been reduced by 10× for right figure. The slight 60-cps ripple in right figure is an artifact.

Neutral density filters and the wedge unit are calibrated for density with the fluorescent light being used. Transmittance of the neutral filters as a function of wavelength is obtained with a Beckmann spectrophotometer. Mathematical and experimental checks show that the filters are sufficiently neutral so that for practical purposes they have the same density for all of the white light sources used.

Because of the construction of the tachistoscopes, absolute luminance levels for the various stimulus fields are measured with a Spectra brightness meter.[29] The meter was originally calibrated against a Macbeth standard and a Spectra standard, subsequently against a standard lamp obtained from the National Bureau of Standards. Absolute light levels are to be regarded as approximate, but probably within 25%.

Observers

Six employees of the laboratories served regularly as observers for periods ranging from several months to three years. Data obtained in the first ten sessions or so usually were not used. Occasionally, inexperienced observers were recruited from among laboratory personnel to check specific points.

Psychophysical Method

Method of Adjustment

Preliminary experiments indicated that data obtained by the method of limits were considerably more variable but not otherwise different from data obtained by the method of adjustment. The method of constant stimuli

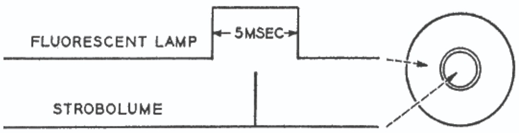

Fig. 4. Photometric calibration of gas-discharge lamps. The gas-discharge lamp illuminates the disk (illustrated at right) while the fluorescent lamp illuminates the concentric annulus. The time relation between the two flashes is illustrated at left.

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[28] D. Sayre, *M. I. T. Radiation Laboratory Series, 19* (McGraw-Hill Book Co., Inc., New York, 1949), p. 195.

[29] Photo Research Corporation, 837 North Cahuenga Blvd., Hollywood, California.

is too time-consuming for gathering the necessary amount of data. The method used in most experiments, therefore, is the method of adjustment. In this method, the observer is given continuous control of one parameter in the stimulus presentation (usually the energy of the test) and asked to set this parameter so that the test spot is "just barely visible." With experience, observers develop a stable criterion of "just barely visible" and learn to make consistent settings within a reasonable time. Bracketing (varying the parameter both above and below its final setting) makes the process of adjustment very similar in practice to an efficient method of limits.

Sequential Procedures

Two procedures are used to determine the amount of data to be obtained. (a) In any given condition, the observer makes two consecutive settings. If these differ by less than a prescribed amount (usually 23%, i.e., 0.1 log units), he progresses to the next condition. If not, he is required to make a third setting. If the third does not fall between the first two, he is required to make two more settings. (b) The condition is then repeated in subsequent sessions until the experimenter is satisfied that a reliable mean (for all sessions) has been reached.

In determining the mean, only the average threshold obtained in each session is used, whether it is the mean of two, three, or five settings.

For practiced observers, two sessions (four or five settings) usually are sufficient. However, when the difference method is used to obtain small differences between large quantities, as many as ten sessions occasionally are necessary. The sequential methods create an incentive for careful settings because the expected number of repetitions increases rapidly as a function of the average error.

Pupil Size

No direct attempt is made to compensate for variations in pupil diameter. There are a number of reasons for believing that pupillary variations do not influence the main results. (1) Most experiments are conducted with only slight variations in the average amount of light reaching the eye during successive seconds. This is accomplished by means of large continuous (or frequently repeated) background fields. (2) The observer is required to look at the stimulus until a "steady-state" level of light adaptation has been reached before he makes a setting. The average pupil aperture compensates for only a fraction of a change in average luminance. (3) Within a particular experiment, the time intervals between flashes are short (several tenths of a second) compared to the response time for the pupil. (4) In masking experiments, pupil fluctuation is a second-order effect because changes in steady-state pupil size affect both the masking and test stimulus. Thresholds are reproducible from day to day and from month to month. The disadvantages of uncontrolled pupil size are offset by the naturalness and convenience of ordinary viewing and by the reproducibility of the results.

MASKING BY IMPULSE FLASHES

In physical systems the impulse response of the system is defined as the output of the system when the input is an impulse. The impulse response has special significance for the analysis of the system, particularly if the system is a linear one. In a linear system it is possible, from measurement of the response to a single impulse, to calculate the response of the system to any other input whatsoever.

By analogy, in these experiments, the fovea is stimulated by a very brief masking flash. The masking flash may be considered as an impulse "input" to the eye. The threshold for a brief test flash is then measured when it occurs at various times before and after the impulse masking flash. The data which describe the change in test threshold as a function of the time of occurrence of the test (threshold masking response) may be considered the "output" of the eye in response to a stimulating impulse; i.e., an impulse response.

If the relation between masking stimulus (input, $l_{\mathbf{M}}$) and threshold masking response (output, e_{T}^*) were linear, then the one experiment described above would suffice to predict all other temporal-masking experiments using an identical spatial arrangement of the stimuli. But, the original data of Crawford[5] are sufficient to reject the linear hypothesis. They show a large relative peak in threshold at the onset of a masking light but not the required symmetrical dip in threshold at light termination (see, for example, Fig. 5).

To analyze a nonlinear system, it is necessary to know the impulse response. Knowledge of impulse response is particularly useful when parameters of the system vary with time (e.g., adaptation) because these variations are minimal during impulse stimuli. Masking by impulses also provides a link between temporal-masking experiments and measurements of contrast thresholds. The zero point of the impulse response (simultaneity of masking and test impulses) corresponds to the contrast threshold in a brief flash. Its relationship to contrast will be considered in Exp. 5.

1. Response to the Pre-Adaptation Field

A 250-msec flash was used in some experiments as a pre-adaptation background. Repeated at 1 cps, this flash supplies more light to the eye than the other stimuli and thereby it—and not the masking stimuli—determines the average light flux. Since the response to the 250-msec flash itself is of only secondary interest, it is desirable to determine in advance what changes in threshold may be expected because of exposure to the pre-adaptation background.

Procedure

A circular masking field of 1.38° alternately was illuminated to 50 ft-L for 250 msec and extinguished for 750 msec. The exposure was repeated once per sec.

The test field was a disk, 0.36°, concentric with the masking field.[30] It was illuminated for about 0.04 msec—at a time fixed relative to the masking flash—once per sec. By the method of adjustment, the subject determined the intensity of the test flash for which it was just visible, for each fixed time τ relative to the masking field. The physical arrangement of the stimuli is indicated at the bottom of Fig. 5. Viewing was binocular.

Results

Typical results obtained by a practiced observer are shown in Fig. 5. Each point $e_T^*(\tau)$ is the average of four (or more) settings made by the sequential method in two sessions. The data show four phases: (1) in the dark period of the cycle the threshold is low and nearly constant, (2) in the first few msec after onset of the masking flash, the test threshold is at a peak, (3) during the remainder of the light period it drops to a lower value, (4) in a few hundred msec after the light is turned off, test threshold falls to the dark value. The shape of the curve is similar to that which Crawford[5] obtained with a 524-msec masking flash and a 10-sec test.

Rapid changes in threshold are confined to an interval from about 50 msec prior to onset of the masking field to about 200 msec after its termination. For the remaining 500 msec of the cycle, the threshold changes only slowly. In subsequent experiments, the impulse masking flash is delivered to the eye during the 500-msec "quiescent" period.

2. Masking by Impulse Flashes of Three Different Energies

Procedure

A pre-adaptation background **B** subtending 9.31°, luminance of 41 ft-L was exposed for 250 msec, once per sec.[31] This field stabilized the total amount of light reaching the eye per second. **B** provided 10 250 ft-L×msec, much more than any other stimulus used in the experiment except the most intense masking flash. The pre-adaptation background therefore is responsible for most of the long-term light adaptation in this experiment.

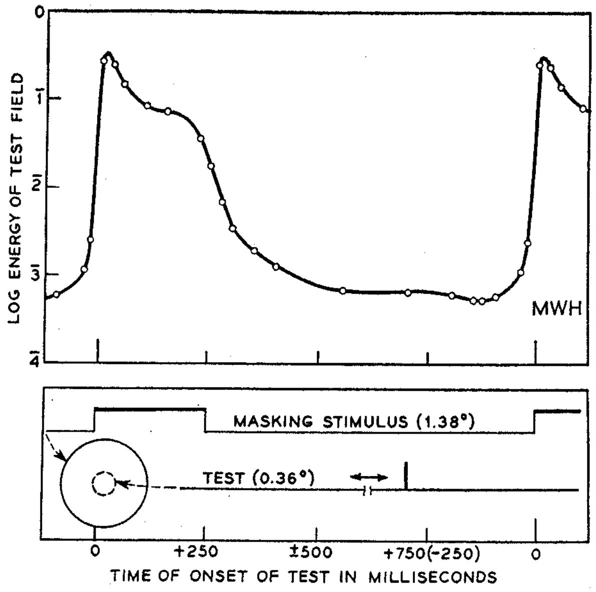

FIG. 5. Masking response $e_T^*(\tau)$ to a 250-msec flash. Lower figure illustrates procedure. First traces indicate time sequence of masking stimulus $l_M(t)$, lowest trace indicates test $l_T(t-\tau)$. The arrow and broken baseline indicate a variable time τ of occurrence of test. Spatial arrangement of stimuli is illustrated at far left; dashed outline of test indicates it is superimposed on masking disk. Upper figure illustrates results. Ordinate gives test threshold energy e_T^* in log units of attenuation relative to arbitrary reference. Abscissa gives time base τ relative to masking-stimulus onset (refer to lower figure). Positive times indicate test occurrences after masking-stimulus onset. The last seven data points at far right are the same as those at far left.

Three hundred msec after the termination of **B**, the masking impulse **M** occurred. It subtended 1.80° and 90% of the light was emitted within 0.04 msec. Three different e_M were used (56, 567, and 15 700 ft-L×msec). More intense flashes were not used because of subjects' complaints of headaches after the experimental sessions.

"Experimental" thresholds [masking impulse present, designated as $e_T^*(\mathbf{M}+\mathbf{B},\tau)$] were determined for an 0.04-msec test by the sequential method. "Control" thresholds [masking impulse omitted, $e_T^*(\mathbf{B},\tau)$] were alternated with experimental thresholds in an ABABA... order (BABAB... order in alternate sessions). The test **T** subtended 0.24°. Viewing was monocular.

Results

The abscissa of Fig. 6 represents the delay τ between **M** and **T**. The ordinate indicates the induced change in test threshold. Each point is the difference between the logarithms of the experimental- and control-test thresholds. The experimental-test threshold was obtained with a masking flash, and the control-test threshold was obtained without a masking flash.

In Fig. 6, data are shown for two observers and for the three different e_M. Each point is the average of four (or more) judgments obtained by the sequential method in two sessions. Points between −50 and −200

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[30] The test stimulus in this and subsequent experiments, though small, definitely is not a point source. As spatial position is not varied and as there are no boundaries near the test, it is probable that the observed test-threshold changes are quite similar (though not exactly equivalent) to those that would have been observed with a point test. Preliminary observations support this assumption.

[31] The pre-adaptation field used in Exp. 2 is larger than the one used in Exp. 1, but as both are substantially larger than the test, their masking effect is similar (see for example, Battersby *et al.*[2]).

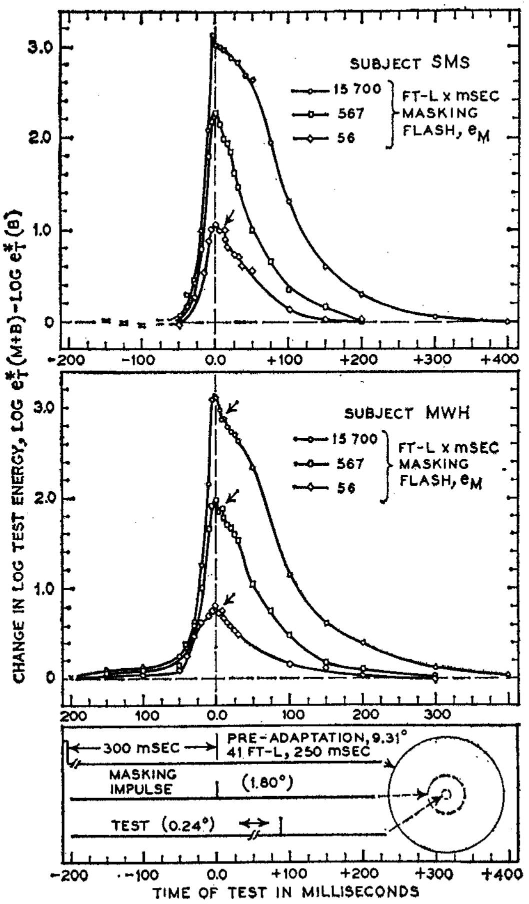

FIG. 6. Masking responses $e_T{}^*(\tau)$ to three impulse flashes of different energies. Lowest figure illustrates procedure (see Fig. 5). Pre-adaptation field **B** terminated at -300 msec; masking impulse **M** occurs at time 0.0; time of test **T** is variable. Spatial arrangement of stimuli illustrated at far right, not to scale. Upper figures illustrate results. The dashed vertical line at time 0.0 indicates the masking flash. An increase in test threshold [$e_T{}^*(\mathbf{M}+\mathbf{B}) > e_T{}^*(\mathbf{B})$] is indicated by ordinate values greater than zero, a decrease [sensitization, $e_T{}^*(\mathbf{M}+\mathbf{B}) < e_T{}^*(\mathbf{B})$] is indicated by negative ordinate values. The short horizontal parallel lines (-75, -100, -125, -150 msec, observer SMS; -200 msec, observer MWH) indicate the range within which all three curves lie.

msec are the average of 8 (or more) judgments in four or more sessions.

The data clearly show that even a virtually instantaneous masking flash causes a very considerable change in threshold for tests which precede it by 40 msec and which follow it by as much as several hundred msec. Generally, $e_T{}^*$ is proportional to e_M. The maximum threshold change occurs when the **T** and **M** are simultaneous ($\tau=0$) except for the most intense **M**, when for observer SMS a **T** occurring 5 msec before the **M** is masked most. In addition to the main masking effect, two details are suggested in these curves: (1) a slight second peak indicated by an arrow in Fig. 6, and (2) a slight dip (sensitization) about 100 msec before the onset of **M**.

3. Chromatic Threshold Effects

A slight secondary peak was observed in all masking responses for observer MWH but only at low intensities for observer SMS. The first peak occurred about at $\tau=0$ (simultaneous onset of **M** and **T**) and the second peak about 10 msec later ($\tau=10$ msec). The second peak did not exceed a 10% increase in threshold. Preliminary observations had indicated it to be more pronounced with certain combinations of colors of **M** and **T**. A supplementary experiment was conducted with four possible combinations of red and green masking and test flashes.

Procedure

The red flashes were produced by inserting a Kodak Wratten filter 70 (dominant wavelength 676 nm) and the green flashes by inserting Wratten filter 74 (dominant wavelength 539 nm) between the source and the observer. In order to minimize the variance between successive masked thresholds, control-threshold determinations (background only) were omitted. In other respects the procedure was the same as in the previous experiment with broad-spectrum white flashes.

Results

The procedure and results are illustrated in Fig. 7. The data are not threshold differences but simply thresholds. There is a slight difference in scale for the two observers. The over-all shape of the masking-impulse response curves depends on the color of the test and masking flashes. The occurrence of a second peak or the lack of it, show less obvious color dependencies. Observer MWH shows a maximum secondary peak at $\tau=+12.5$ msec when **M** is green and **T** flash is red. This peak corresponds to about a 10% change in threshold. There are even less spectacular secondary peaks with other color combinations. These smaller secondary peaks all occur at $\tau=10$ msec. For MWH the perturbations in the masking response, though small, occur reliably and to about the same extent in each session, as well as in averaged data.

The one possible example of a second peak for observer SMS (red masking, green test) also occurs at $+10$ msec. The time of 10 msec corresponds approximately to the minimum interval at which the temporal disparity between **M** and **T** begins to be evident.[32]

4. Sensitization by a Masking Flash

A provocative detail in the impulse masking response curves is the sensitization that occurs about $\frac{1}{10}$th sec before the onset of **M**. That is, subject SMS sets **T** to a lower threshold when **M** follows **T** than when no

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[32] In an earlier investigation of chromatic interactions in masking, Bush[17] failed to note a similar second peak. However, his masking stimulus (560 msec) and test (40 msec) were orders of magnitude longer than those used here.

M occurs. To indicate the results more fully, in Fig. 6 the limits of the data have been represented by two short lines rather than by average points. All three curves fit between the short horizontal lines indicated in Fig. 6. The figure shows that the maximum sensitization (equivalent to a 6% decrease in e_T^*) occurs 75 to 100 msec before **M**.

Sensitization occurs repeatedly in spite of precautions, such as counterbalancing of trials and an increased number of judgments. A similar kind of sensitization was observed in the first experiment (Fig. 5, subject MWH) 125 msec prior to a 250 msec **M**. Subject MWH also shows a similar effect prior to a 500 msec **M**. It is curious, but typical of these small effects, that subject MWH did not show sensitization prior to an impulse **M**.

"Backward sensitization" has not been previously reported. Therefore, a survey experiment was conducted in order to see how frequently it occurred in a population of five observers.

Procedure

The masking stimulus **M** was a 1.38° field illuminated to a luminance of 44 ft-L for 10 msec. A 250-msec (1.38°, 42-ft-L) field served as a pre-adaptation background **B**. Termination of **B** was followed by **M** after 300 msec. The test field **T** subtended 0.138° and was illuminated for 2.3 msec. The subjects adjusted the intensity of **T** to be "just visible." Two or more different settings were made at each point. The sequence of settings was conducted in a pseudo-random, balanced order.

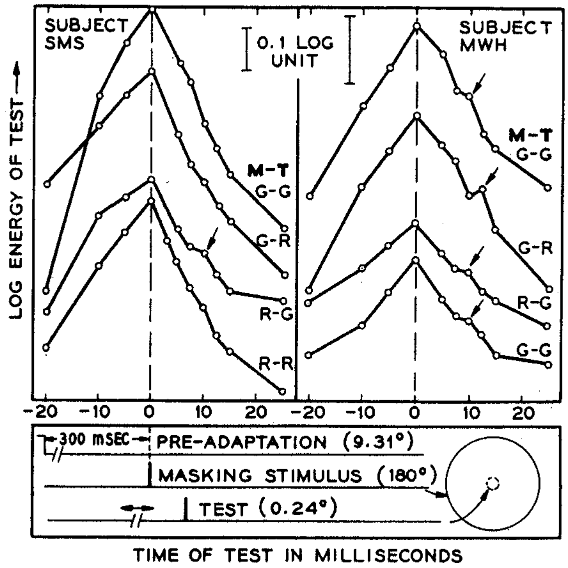

FIG. 7. Masking by red and green impulse flashes. Lowest figure illustrates procedure and spatial geometry. (Pre-adaptation field **B** is not indicated.) Upper figures indicate thresholds. Bar markers indicate the scale. Each curve has been moved up or down an arbitrary amount. Spectral composition of the various masking–test-field combinations is indicated at right by color names (R = red, G = green).

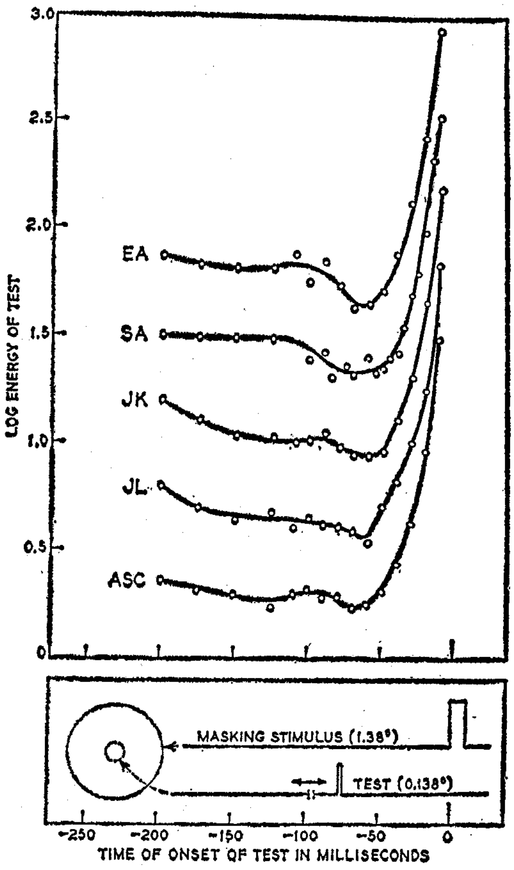

FIG. 8. Masking prior to a 10-msec flash. Lower figure illustrates procedure and spatial arrangement of stimuli. Pre-adaptation stimulus terminated at −300 msec is not indicated. Upper figure illustrates absolute thresholds $e_T^*(\tau)$ of five observers. Each curve has been displaced up or down an arbitrary amount for ease of comparison.

There are several differences in procedure between Exp. 4 and Exp. 2. These differences in part are attributable to the fact that Exp. 4 was conducted about a year earlier. (1) Viewing is binocular, not monocular as in Exp. 2. (2) The test illumination is produced by a fluorescent lamp rather than by a gas-discharge lamp. One significance of this is that the discharge lamp produced an audible click simultaneously with the light flash; the operation of the fluorescent lamps was silent. (3) The spatial geometry of the stimuli is slightly different.

Results

The threshold masking response $e_T^*(\tau)$ for each observer is shown in Fig. 8. Each observer's data has been moved up or down in the figure to permit easy comparison of the curves. Data are presented for the 200 msec preceding onset of **M**. These data are not threshold differences (as in Fig. 6) but simply thresholds. The termination of **B** at $\tau = -300$ msec therefore causes a slow change in base line.

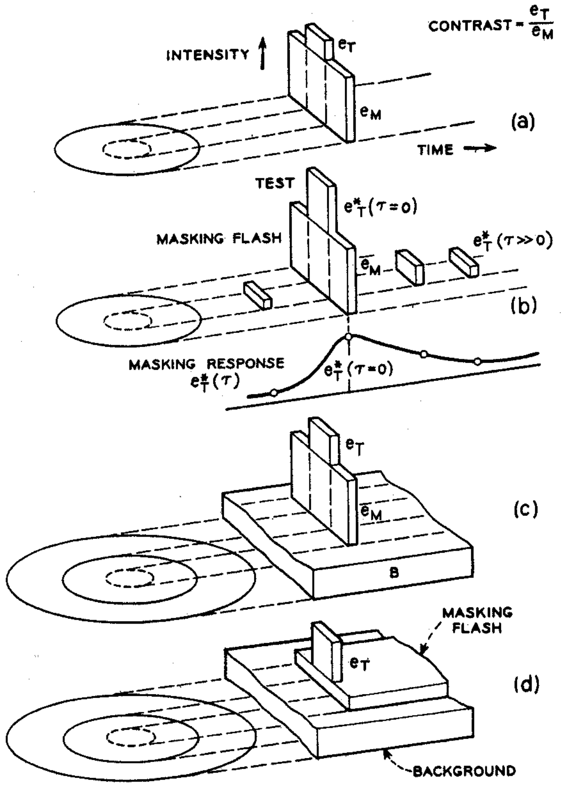

FIG. 9. Comparison of four masking procedures. Spatial geometry of the stimulus is illustrated schematically at left. The temporal sequence is illustrated on the right. The left-to-right dimension represents time, the depth dimension represents spatial position along a diameter of the stimulus, and the vertical dimension represents luminance. The height of the test indicates its energy e_T at threshold. (a) Defining conditions for impulse contrast, C_δ. (b) Defining conditions for threshold masking response to an impulse **M**("impulse response"). Four possible temporal positions are indicated for the test flash, but only one test occurs on a particular trial. Heights of the test increments are drawn proportional to their thresholds. Below, a graph of these test heights plotted against their time of occurrence defines the threshold-masking response $e_T^*(\tau)$ (see Fig. 6 for data). (c) Conditions for measuring contrast threshold against a variable background (see Fig. 10). (d) Conditions investigated by Boynton and Kandel. The effect of varying background luminance on e_T^* was determined (see Table I).

Four, perhaps all five observers show sensitization (a dip in the curve) at about 75 to 100 msec before the onset of **M**. In fact, there is a suggestion that the detailed shape of the curve may be even more complicated for some observers.

Discussion

Backward sensitization does not represent a change in e_T^* of more than 25% for any observer. Nevertheless, it is an ubiquitous effect which may be observed under a variety of conditions of visual stimulation. It will be seen again in several of the following experiments.

The nature of backward sensitization surprisingly was suggested in an experiment on brightness matching. In this experiment observer SMS viewed various temporal sequences of **T** and **M** flashes as above. SMS was asked to adjust the test flash energy e_T so that brightness observed at the center of the masking disk **M** was just barely unchanged by **T**. When **T** and **M** coincided, this brightness judgment was identical to a threshold determination for e_T^*. When **T** and **M** were widely separated in time, **T** had little influence on the appearance of **M**. However, when **T** preceded **M** by 100 msec, **T** apparently caused the subsequent **M** to appear different in its center (the area corresponding to **T**). In order to maintain a uniform appearance of **M** disk, the e_T had to be 25% less than its previously determined "threshold" value.

This result demonstrates that a **T**—even one below its own threshold—can alter the appearance of a subsequent **M** occurring about 100 msec later. The change in the nature of what is being detected accounts for the puzzling aspects of backward sensitization. First, there is the haphazard presence or absence of the phenomenon in the same observer under very similar viewing conditions. Presumably, the observer sometimes examines **M** and sometimes not. When an audible click occurs simultaneously with **T** (as with the gas-discharge lamps), the time interval within which **T** occurs is clearly defined for the observer. An induced change occurring within a subsequent interval may be overlooked. When the audible time marker is removed (as in Exp. 4 by using fluorescent lamps) an observer must search the whole stimulus presentation for any kind of change in appearance. Under these conditions four or five observers clearly showed backward sensitization.

In summary, backward sensitization can occur when a test flash of an energy slightly below its own threshold alters the appearance of a subsequent masking flash, and when the subject by instruction or by chance observes this change.

5. Contrast Thresholds in Impulse Flashes[33]

Consider two adjacent surfaces, one of luminance l_M, the other of luminance l_M+l_T. Stimulus contrast C_∞ may be defined as the ratio l_T/l_M. The subscript indicates the duration of the stimuli. For stimuli brief enough to be considered impulses, contrast may be $C_\delta=e_T/e_M$. Impulse contrast so defined does not depend on the particular time waveforms $l_T(t)$ and $l_M(t)$.

Impulse-contrast threshold may be defined as e_T^*/e_M. However, in order to analyze the separate effects of **B** and **M** upon e_T^* it will be more useful to define an adjusted impulse-contrast threshold

$$C_\delta^*=[e_T^*(\mathbf{M}+\mathbf{B})-e_T^*(\mathbf{B})]/e_M.$$

Here **M** is an impulse flash of energy e_M, **T** is a flash of energy e_T added to a portion of **M**, $e_T^*(\mathbf{M}+\mathbf{B})$ is the threshold value of e_T when **T** is added to **M** plus a

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[33] For a preliminary account of this experiment see G. Sperling, Am. Psychol. 17, 354 (1962).

background **B**, and $e_T^*(\mathbf{B})$ is the threshold value of the test on **B** alone. When **B** induces small threshold changes as compared to **M**, C_δ^* reduces to e_T^*/e_M.

The definition of stimulus impulse-contrast C_δ is illustrated in Fig. 9(a). An incremental disk of energy e_T is superimposed upon a background of energy e_M. Figure 9(b) illustrates the similarity of the presentation which defines C_δ to that which defines an impulse masking response. C_δ is defined for the particular case in which **M** and **T** occur simultaneously. In the masking experiment, **M** and **T** occur in all time relations.

In Exp. 2 it was noted (see, for example, Fig. 5) that $\max e_T^*(\tau)$ occurs when **T** and **M** coincide ($\tau=0$). Thus to a good approximation the impulse-contrast threshold times the energy of the masking flash equals the peak of the impulse-response curve,

$$C_\delta^* \cdot e_M = \max e_T^*(\tau).$$

Since the shape of the various impulse responses was qualitatively similar, knowledge of the peak of the curve would be sufficient to describe an impulse response in considerable detail.

Brindley[34] studied e_T^*/e_M as a function of flash intensity. He found it to vary from about 0.1 to 0.2 from dim to very intense flashes. In extremely intense flashes, however, the threshold increased sharply, presumably because of exhaustion of all the available photochemical pigment.

Brindley also noted that in flashes with energy greater than about 100 cd-sec/m² (3×10^4 ft-L×msec), contrast threshold is higher because contrast must be discriminated in the after-image rather than in the primary image. This suggests that the background upon which the flashes appear is important for the discrimination of contrast. A flash which looks blindingly bright in darkness can seem quite innocuous when added to a steady bright background. For this reason impulse contrast threshold C_δ^* was studied both as a function of masking-impulse energy e_M and of background luminance l_B.

Procedure

Three concentric, circular-disk fields were optically superimposed: background **B** (9.31°), masking stimulus **M** (2.33°), and test **T** (0.23°). **M** and **T** were illuminated simultaneously for about 0.04 msec, at 1-sec intervals. Masking-flash energy e_M was varied from 0.139 to 159 000 ft-L×msec. **B** was illuminated to one of four steady luminances (0, 0.37, 3.7, 41 ft-L) or it was illuminated for 250 msec to 41 ft-L and dark for 750 msec. In the latter case (41-ft-L pre-adaptation), **M** and **T** occurred 300 msec after termination of the 250-msec **B**. This presentation is comparable to the one used in the preceding experiments.

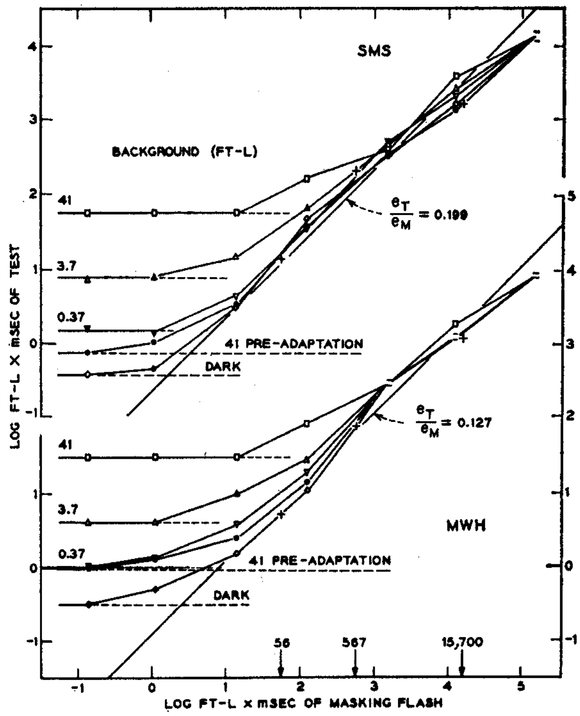

FIG. 10. Test threshold as a function of masking-impulse energy and background luminance, data for two observers. Points with same background luminance are connected. The 41 pre-adaptation refers to a 0.25-sec field of 41 ft-L terminated 0.3 sec before masking flash. When points fall too close together to be graphed individually, the range is indicated by parallel horizontal dashes. Control-threshold levels (masking flash omitted) are indicated by the horizontal lines. The energies e_M of the three masking impulses of Exp. 2 are indicated on the abscissa and the obtained test thresholds at simultaneity $e_T^*(\tau=0)$ are indicated by crosses (see Fig. 6). The values of e_T/e_M corresponding to the average adjusted contrast threshold C_δ^* of the data are indicated (for method of calculation see text and Fig. 11.)

By the method of adjustment, test threshold e_T^* was determined. In each session, only **B** was varied, **M** being held constant. The order in which various **B**'s were presented within a session was the same in sessions 1–7 and reversed in sessions 8–14. The observer adapted for 5 min to each **B**. For each condition, the observer made two adjustments. Before each threshold determination (sessions 8–14) or after each determination (sessions 1–7) the observer's threshold was determined with the background alone (no masking flash). These two test thresholds are designated respectively as $e_T^*(\mathbf{M}+\mathbf{B})$, $e_T^*(\mathbf{B})$.

Viewing was with the right eye only. As in previous experiments, fixation was central. The visual presentation (steady **B**) is illustrated schematically in Fig. 9(c).

Results and Discussion

Test energy $e_T(\mathbf{M}+\mathbf{B})$ is graphed against e_M in Fig. 10. Each point is the average threshold, based on four or more judgments in two sessions. The results are similar at each level of **B**. Increasing the intensity of either **B** or **M** increases $e_T^*(\mathbf{M}+\mathbf{B})$. For the **M** of lowest energy, $e_T^*(\mathbf{M}+\mathbf{B})$ is determined almost entirely by the

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[34] G. S. Brindley, J. Physiol. **147**, 194 (1959).

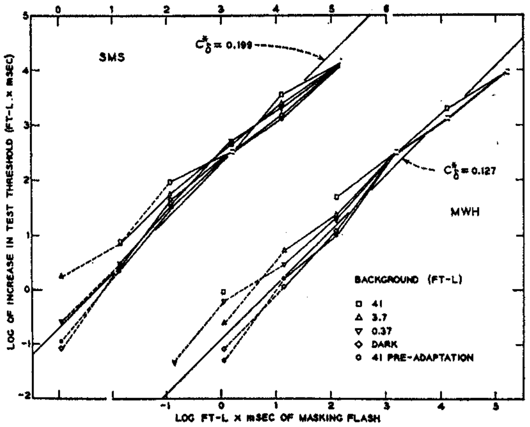

FIG. 11. Threshold changes induced by impulse masking flashes added to five different backgrounds. The ordinate is the logarithm of the increase in test thresholds in ft-L×msec $\{\log[e_{\mathrm{T}}^*(\mathbf{M}+\mathbf{B})-e_{\mathrm{T}}^*(\mathbf{B})]\}$; top scale refers to observer SMS; bottom to MWH. Points with same backgrounds are connected. Points for which the difference in thresholds is less than 40% (0.15 log units) are connected by dotted lines. Best-fitting line of unity slope is indicated.

B; at high masking energies, $\log e_{\mathrm{T}}^*(\mathbf{M}+\mathbf{B})$ increases linearly with $\log e_{\mathbf{M}}$. The slope is slightly less than unity, indicating that $e_{\mathrm{T}}^*/e_{\mathbf{M}}$ decreases at high energies. At the highest energy, $e_{\mathrm{T}}^*/e_{\mathbf{M}}$ is about 0.06 for observer MWH and about 0.08 for SMS. The interspersed thresholds with the background alone, $e_{\mathrm{T}}^*(\mathbf{B})$, do not vary with masking-stimulus energy; their levels are indicated by the horizontal dashed lines.

Thresholds in a 250-msec pre-adaptation background obtained earlier from complete impulse responses $e_{\mathrm{T}}^*(\mathbf{M}+\mathbf{B},\tau=0)$ (Fig. 5) are indicated by crosses in Fig. 10. The agreement between experiments is good; the maximum discrepancy is about 40% (0.15 log units) for one point. Observer SMS's threshold in background alone diminished by 25% to 50% between experiments. While this change affects the ratio of thresholds, it does not appreciably affect the difference between thresholds (see below).

Does the same **M** cause the same increase in threshold, independent of the **B** upon which it is superimposed? To answer this question it is necessary to consider the change in threshold energy produced by a masking flash of $e_{\mathbf{M}}$ ft-L×msec, that is, $e_{\mathrm{T}}(\mathbf{M}+\mathbf{B})-e_{\mathrm{T}}(\mathbf{B})$. Figure 11 displays $\log[e_{\mathrm{T}}^*(\mathbf{M}+\mathbf{B})-e_{\mathrm{T}}^*(\mathbf{B})]$ vs $\log e_{\mathbf{M}}$. The coordinates are logarithmic because of the great range of the data.

When the expected value of a difference is small the logarithm of the difference fluctuates wildly, owing to the statistics of differences. For example, when $e_{\mathrm{T}}^*(\mathbf{B})$ slightly exceeds $e_{\mathrm{T}}^*(\mathbf{M}+\mathbf{B})$ (as should happen half the time with infinitesimal $e_{\mathbf{M}}$) the logarithm of the difference is not defined.

All points for which the logarithm is defined are graphed in Fig. 11. Data points based on threshold changes of less than 40% (0.15 log units) are connected by broken lines. These points are statistically unreliable, biased overestimates of the true threshold difference. Although they indicate trends in the data, little importance should be attached to them, or to variation among them, and they are omitted from subsequent statistical analyses.

The most striking fact about Fig. 11 is that the five separate curves of Fig. 10 are collapsed almost to one, and that the slope over four or five decades is nearly unity. To a good first approximation, the data imply that **B** has no effect on the threshold increase in ft-L×msec produced by **M** and that a modified Weber's law is valid when the effects of **B** and **M** are considered separately.

The observed relation between

$$\log e_{\mathbf{M}} \quad \text{and} \quad \log[e_{\mathrm{T}}^*(\mathbf{M}+\mathbf{B})-e_{\mathrm{T}}^*(\mathbf{B})]$$

may be examined statistically. For the SMS data, the slope of the regression line is 0.861 and the corresponding product-moment correlation is 0.989. For MWH the slope is 0.891 and the correlation is 0.988. A regression line with slope less than unity indicates that C_δ^* is greater in dim flashes than in intense ones. The proportions of variance accounted for by the best-fit lines of slope 1.0 ($C_\delta^*=$constant, a modified Weber's law) are 0.962 and 0.952, numbers whose square roots correspond to "correlations" only slightly lower than those of the regression lines.

Inspection of Fig. 11 shows that masking flashes which produce small percentage changes in threshold (i.e., small changes in log threshold) are somewhat more effective than flashes which produce large percentage changes. Thus a dim masking flash added to a bright background barely alters the log threshold, but this small perturbation may correspond to an increase in e_{T}^* several times greater than the same masking flash produces in darkness. Logarithmic (ratio) plots such as Fig. 10 produce the false impression that flashes viewed in darkness produce the biggest threshold changes.

In summary, Fig. 10 shows that masking flashes which produce substantial threshold changes do so independently of the background. Consideration of linear threshold differences (Fig. 11) suggests that even masking flashes which produce only small precentage changes in threshold do so almost independently of background. Statistical analysis indicates that a modified Weber's law (slope of regression line assumed $=1$) accounts for over 0.95 of the variance in the data. As there is no discontinuity in the curves of Fig. 11, these conclusions appear to apply even to masking flashes which themselves are below "threshold."

6. A Methodological Check

Introduction

The presentation rate of one flash per sec in the previous experiment means that at high flash energies much light adaptation is due to the masking flash itself, especially when the background is dim. The failure to observe any influence of **B** on $e_T{}^*(\mathbf{M}+\mathbf{B})$ with large e_M might be due to a cumulative adaptation caused by the repeated **M**, an adaptation which overwhelms the effect of the **B**. An obvious way to test this hypothesis is to change the **M** flash presentation rate. The following experiment uses a presentation rate of one **M** flash per minute.

The change in presentation rate necessitates certain changes in procedure. The method of adjustment no longer is feasible. The 1-min time between presentations is too long for the memory or patience of an observer using the method of adjustment. A "yes–no" procedure also is quite slow. Moreover, it yields thresholds readily influenced by factors extraneous to the visual presentation, such as changes in the observer's criterion.[35] As the experiment seeks to measure small differences between conditions, it would be desirable to minimize the possibility of criterion changes or to be able to detect them when they occur.

The usual alternative to "yes–no" detection requires a multiple-stimulus presentation followed by a single "forced choice" judgment. Its application would require either two or more simultaneous masking flashes (both could not be central) or two or more successive flashes, separated by an interval of 1 min. The simultaneous, noncentral presentation would be a great change from the presentation used so far. In the successive judgment, the subject estimates the probability of **T** in each **M** flash, then chooses the highest. The problem is that successive flashes must be separated by 1 min. Since the subject presumably recodes his information about the flash into one dimension (subjective probability), he could be asked for this recoded response directly. Therefore, by analogy to the temporal forced-choice experiment, subjects were asked to estimate the probability of **T** having occurred in each **M** presentation. This procedure is an elaboration of a rating scale method which has been used successfully in threshold determinations.[36–39]

Procedure

The stimuli were of the same geometry and duration as in the previous experiment; viewing was monocular as before. Only three of the five background conditions ($l_B=41$ ft-L, 0.37 ft-L, dark) and one intense masking flash ($e_M=72\,600$ ft-L×msec) were used. Fixation marks adjacent to **M** were continuously present: dark marks in the light backgrounds, 4 dim light spots in the dark background. Ten different test stimuli were produced, varying from $e_T=0.022e_M$ to $e_T=0.55e_M$ in approximately equal ratio steps. The simultaneous occurrence of **T** and **M** constituted a stimulus presentation [refer to Fig. 9(c)].

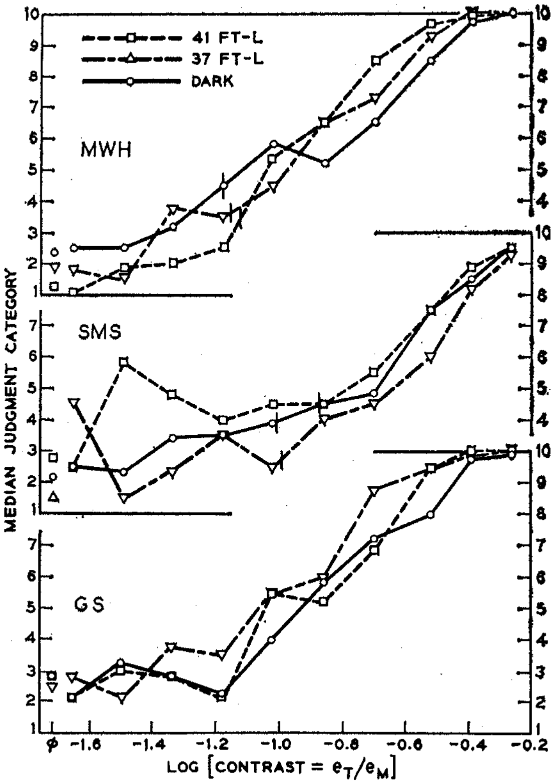

FIG. 12. Confidence of detection in three different backgrounds as a function of test energy e_T. Masking flash energy e_M was 72 600 ft-L×msec. Vertical bars (observers SMS,MWH) represent thresholds measured in Exp. 5 (see Fig. 10 and text for details.) The results of "catch" trials are plotted above Φ which has been displaced slightly to the left on the abscissa. Its true contrast is the same as for the adjacent set of connected data points. The ordinate values above Φ are based on 50 trials each, other points 10 trials each.

Sessions began with 5 min adaptation to darkness $l_B=0$ (or $l_B=41$ ft-L on alternate days), followed at 1-min intervals by a warning buzzer. As soon after the warning as he was sure of his fixation and accommodation, the observer pressed a button which initiated a visual presentation 0.5 sec later. Two sample trials ($e_T=0.022e_M$ and $e_T=0.55e_M$) were followed by 10 different tests and five "catch" trials in random order. This viewing condition was followed by an analogous adaptation and presentation sequence in the next background until all three backgrounds had been viewed.

After each stimulus presentation, the observer was asked to rate on a 10-point scale his confidence that **T** had occurred. The scale was defined as follows: (1) certain—no, (2) very sure—no, (3) pretty sure—no, (4) probably—no, (5) unsure—probably no, (6) un-

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[35] J. A. Swets, editor, *Signal Detection and Recognition by Human Observers: Contemporary Readings* (John Wiley & Sons, Inc., New York, 1964).

[36] J. P. Egan, A. I. Schulman, and G. Z. Greenberg, J. Acoust. Soc. Am. **31**, 768 (1959).

[37] J. A. Swets, W. P. Tanner, and T. G. Birdsall, Psychol. Rev. **68**, 301 (1961).

[38] D. J. Weintraub and H. W. Hake, J. Opt. Soc. Am. **52**, 1179 (1962).

[39] J. Nachmias and R. Steinman, J. Opt. Soc. Am. **53**, 1206 (1963).

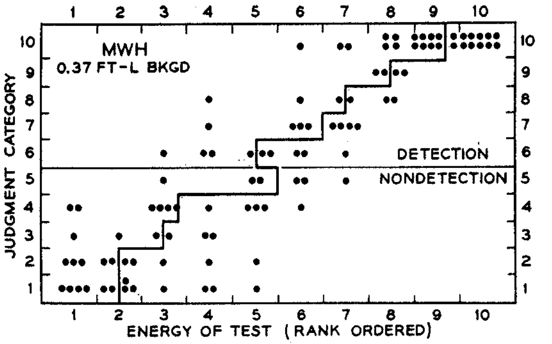

FIG. 13. A sample of data obtained by category rating of near "threshold" stimuli. Background luminance is 0.37 ft-L. On the average, the energy difference between adjacent test ranks is 38%. Each point represents one judgment by observer MWH. The horizontal line separates "yes" (detection) from "no" (nondetection) judgments. The connected vertical lines represent the median test energy which elicited each judgment category of response.

sure—probably yes, (7) probably—yes, (8) pretty sure—yes, (9) very sure—yes, (10) certain—yes. On the five catch trials in each condition, immediately after his response, the observer was told that T had been omitted on that trial.[40] No other information about the stimuli or sequence was given the observer.

The two observers of the previous experiment and the author served as observers. After several practice sessions, the experiment continued for 10 sessions, for a total of 10 judgments for each e_T in each of the three backgrounds.

Results

Figure 12 illustrates the median-judgment category as a function of test-stimulus energy. Data for each observer and each background are shown. The greater the test-stimulus energy, the more certain the observer is that he sees it, as indicated by judgment category. Observers are absolutely certain they see the brighter tests. The same degree of certainty is never reached for dim tests. No matter how dim the test is, observers usually are unsure of its nonoccurrence.

In Fig. 12, test-stimulus energy is plotted on a logarithmic scale $[\log C_\delta = \log(e_T/e_M)]$ to facilitate comparison of the various curves. Visibility differences between conditions would manifest themselves as lateral displacements of the curves. The data indicate that the various backgrounds do not affect visiblity by more than about 25% ($\Delta \log C_\delta \cong 0.1$) and furthermore, that the direction of these slight shifts varies from observer to observer. The conclusion of the previous experiment is confirmed: background does not appreciably affect $e_T{}^*/e_M$ in an intense flash.

The logarithmic plot of the data in Fig. 12 fails to indicate one aspect of the data. On a linear plot, the points on the left of Fig. 12 are compressed and the ogival shape of the curve is lost. On such a linear graph, the left part of the curve becomes nearly a straight line. The slope indicates that over a range of from five to seven categories, confidence increases at a rate of about one category unit per increase in e_T of $0.05e_M$ for observer MWH and at a smaller but constant rate for observers GS and SMS.

Results: Methodological Issues

The apparent continuity of detection categories and nondetection categories is one of the most interesting aspects of the data; subjects provide significant information about the test stimulus even when they say they cannot detect it. The best way to illustrate this is to consider the conditional distribution of test stimuli to which a particular response was made.

Figure 13 indicates all the responses made by observer MWH with a background of 0.37 ft-L. For each response category $(1, \ldots, n)$, Fig 13 also represents the rank of the median stimulus e_T to which this response occurred. The fairly regular progression of the median indicates that observer MWH is able to maintain differentiated criteria, not only for levels of detection but also for levels of nondetection. For example, Fig 13 illustrates that of the 23 occurrences of judgments of 1 or 2 (certain no, very sure no) in only 7 cases were the test stimuli of rank 3 or higher ($e_T \geq 0.046e_M$), whereas of the 17 occurrences of judgments of 4 or 5 (probably no, unsure probably no) in 15 cases the tests ranked 3 or higher.

Figure 14 illustrates the extent to which each of the observers is able to maintain differentiated criteria for levels of detection and nondetection. The abscissa represents judgment category; the ordinate, the rank of the median stimulus eliciting that judgment. For each observer, the data have been averaged across backgrounds.

Figure 14 shows that observers differ in the extent to which they are able to maintain clearly differentiated, monotonically related criteria; MWH's criteria were perfectly monotonic; GS and SMS each showed two inversions. Observers MWH and GS maintain several different criteria of nondetection; SMS discriminates only slightly among nondetected tests.

Discussion: Methodological Issues

One third of the presentations were catch trials, to repress "false positive" responses It is noteworthy that observers were unable to avoid reporting detection occasionally and high-category nondetection frequently for the "catch" test stimuli. These uncertain categories of response probably result from the blotchy appearance of a brief masking flash. The appearance varies from

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[40] Actually, $e_T = 0.022e_M$ was presented on catch trials as it was inconvenient to produce $e_T = 0$ without informing the subject. This test stimulus contained about $\frac{1}{5}$ the energy of the previously determined threshold. The identity of the observers' distribution of responses to the "blank" and to the next-more-intense stimulus ultimately justified its use.

flash to flash and it is not surprising that occasionally a subjectively brighter area in the center of the objectively uniform masking stimulus should be mistaken for the test spot. This illusory signal-in-noise appearance of **M** is a characteristic of the visual system, not of the stimulus. That is, for constant signal-to-noise ratio at threshold, e_T^* should increase as the square root of e_M[41–44] whereas it actually increases almost in direct proportion to e_M.

No "threshold" theory of detection is adequate to account for the data. As has already been noted, particularly by Nachmias and Steinman,[39] there is a continuity of process above and below detection. The ability of observers to discriminate among stimuli below "threshold" may account in part for the ability of experienced observers to make such extremely precise judgments by the method of adjustment.

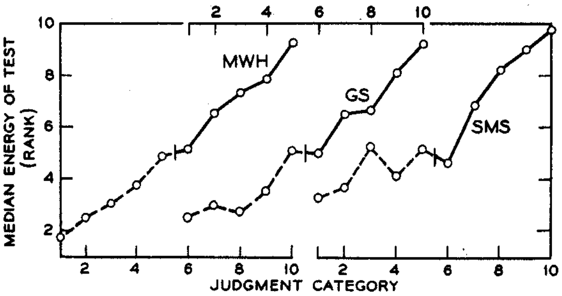

FIG. 14. Consistency of judgmental criteria. Data are shown for three observers. Each point represents the median energy of the tests (average of the three background conditions) which elicited each judgment category. Vertical bars divide "yes" (detection) and "no" (nondetection) judgments.

GENERAL DISCUSSION

Relations of Masking by Impulses to Masking by Steps

Several attractive approximations emerge from the data obtained: (1) the height of an impulse response is proportional to the impulse energy (Weber's law for the impulse-contrast threshold) and (2) it is independent of the background upon which the impulse is superimposed. Although neither of these approximations is strictly true, the intent of this discussion is to relate these results of masking by impulses to other masking experiments, particularly those in which masking responses were obtained for long pulses (steps).

The results of Crawford and others have shown that masking is a nonlinear process.[45] Therefore, superposition cannot be assumed and convolution calculations are not appropriate. The hypothesis is proposed that nonlinearity results when one process of detection supersedes another, depending on the time between test and masking flashes. An attempt will be made to relate the peak of the masking response of longer pulses to the peak of the impulse response.

Hypothesis[33]

The luminance energy occurring during the first 50 to 60 msec of a longer flash is considered as though it all occurred in an impulse. The peak threshold is C_δ^* times this energy.[46]

$$\max e_T^*(\tau) = \bar{C}_\delta^* \int_0^{60} l_M(t)dt. \qquad (1)$$

Here $\bar{C}_\delta^*$ represents an average value of C_δ^*, and $l_M(t)$ is assumed to be a step function at $t=0$.

There is a good rationale for this hypothesis. The first part of the long masking flash together with the impulse test flash physically constitutes a contrast target. Subsequent light from the masking stimulus may be regarded as a background which appears after the target. But as background has been shown to have little effect on impulse-contrast thresholds, it may be neglected.

At the core of the hypothesis is the assumption that detection of a test in an impulse flash is based purely on a contrast judgment, i.e., a comparison of light in adjacent retinal areas. The peak of masking response to a step (so called on-response) is assumed to be caused by the observer's reliance on spatial contrast for detection; the subsequent lowering of threshold after the peak is due to the observer's ability to discriminate the temporal pattern of illumination at the test location from the (steady) background.

Detection is defined as a function having two or several discrete values (e.g., 0="no, I do not see it," 1="yes, I see it"; etc.).

Contrast detection is defined as a function whose argument is contrast $[l_M(x_1,t)/l_M(x_2,t)]$ or some similar concatenation of $l_M(x_1,t)$ and $l_M(x_2,t)$ in which the luminances of adjacent areas x_1, x_2, enter only in combination and never individually.

Pure temporal detection is a function whose argument depends only on the time variation of luminance values at one location [e.g., $l_M(x,t)-l_M(x,t-\tau)$].

The definition of a detection function can be readily generalized to a function whose instantaneous value depends on all past luminances or to a function whose argument is not simply luminance, but some transformation of the visual stimulus, presumably carried out by the visual system. For some reasons for choosing a particular definition of detection see Sperling.[47]

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[41] A. Rose, J. Opt. Soc. Am. **38**, 196 (1948).

[42] A. Rose, Proc. I.R.E. **30**, 295 (1942).

[43] Hl. de Vries, Physica **19**, 553 (1943).

[44] M. H. Pirenne and F. H. C. Marriott, in *Psychology: A Study of a Science*, edited by S. Koch (McGraw-Hill Book Co., Inc., New York, 1959), Vol. I, pp. 288–361.

[45] See above section, *Masking by Impulse Flashes*, p. 546.

[46] No assumption is made about the time τ at which $\max e_T^*(\tau)$ occurs.

[47] G. Sperling, Doc. Ophthalmol. **18**, 3 (1964).

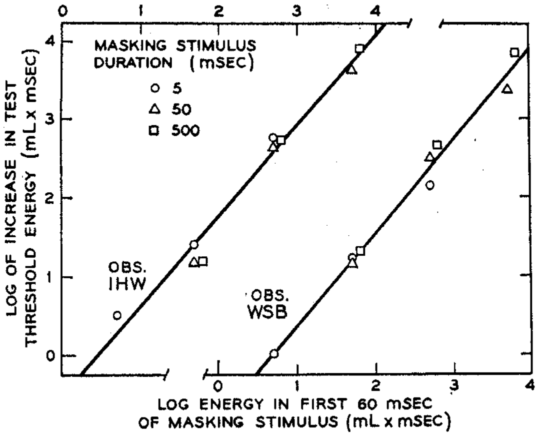

FIG. 15. Effect of masking-stimulus luminance and duration on peak test threshold, max $e_T^*(\tau)$. Ordinate is logarithm of increase in test-threshold energy (mL×5 msec) induced by masking stimulus: $\log[\max e_T^*(\tau) - \min e_T^*(\tau)]$. Abscissa is logarithm of masking-flash duration in msec×flash-luminance in mL, using effective duration of 60 msec for flashes of 60 msec or longer, it is $\int_0^{60} l_M(t)dt$. Upper scale refers to observer IHW, lower scale to observer WSB. Equations of regression lines: IHW, $\log C_\delta^* = -0.551 + 0.152 \log e_M$, $(r=0.985)$; WSB, $\log C_\delta^* = -0.830 + 0.190 \times \log e_M$, $(r=0.993)$. Best-fitting lines of slope one (not shown): $C_\delta^* = 0.65$ (IHW); $C_\delta^* = 0.43$ (WSB). Data from Battersby and Wagman (see Ref. 10, Fig. 4, p. 756).

Duration of Masking Flash

Battersby and Wagman[1] studied masking threshold responses to rectangular pulses of 5, 50, and 500 msec duration. The stimuli were somewhat larger than those shown in Fig. 6 and viewing was peripheral.

In Battersby and Wagman's data, the shape of the masking response to a 5-msec masking flash (which may be considered an impulse response) is quite similar to the shape of the response to a 50-msec flash of $\frac{1}{10}$th the intensity, and to the initial response to a 500-msec flash. For quantitative comparison, however, only the peaks of the masking responses will be considered.

Figure 15 illustrates Battersby and Wagman's observed peak of the threshold response as a function of the luminous energy contained in the first 60 msec of these masking flashes. The points were estimated from an enlargement of their published graph[1] as more precise data were no longer available.[48] The change in threshold is estimated by $\max e_T^*(\tau) - \min e_T^*(\tau)$.

The regression lines through the calculated points have slopes and correlation coefficients respectively of 1.15 $(r=0.985)$ and 1.21 $(r=0.994)$. These slopes are significantly greater than one. The best-fitting lines of slope 1.00 (modified Weber's law) represent adjusted contrast thresholds C_δ^* of 0.65 and 0.48 for IHW and WSB, and account for 0.96 and 0.92 of the threshold variance. The C_δ^*'s are substantially higher than the typical values shown in Fig. 11. This is accounted for mainly by the 7° peripheral viewing. Before venturing an explanation of the large slopes and C_δ^* it is instructive to examine certain aspects of the data.

For subject WSB a 50-msec flash of 10 mL produces more masking than an equal energy flash of 100 mL for 5 msec. The shapes of the two masking responses are quire similar, however. Because the peak of the masking response is greater for the longer flash, it follows that it is more efficient to distribute masking-stimulus energy in time after the instant of maximum masking rather than to cluster all the energy at the single, most effective instant of time. Obviously, this type of masking implies a more complex process than a simple integration of masking energy.

The peak of the masking response for the most intense 500-msec flash is about double the peak response to a 50-msec flash, for subject IHW, and triple for subject WSB. This means that masking light occurring more than 50 msec after the test can still double or triple the threshold energy requirement. The author has noted effects on test threshold occurring up to 150 msec later. This effect occurs only at high masking luminances. At low luminances, peak masking for 500- and 50-msec flashes is very similar. As threshold integration time is shorter at high intensities than at low,[49–54] the great masking effectiveness of intense long flashes must arise not from longer integration but from a masking process which benefits from the spreading-out of light in time.

In intense masking flashes, the subject does not always detect the test stimulus directly.[6,34] Particularly with test presentations corresponding to the peak of the masking response, the subject detects a negative after-image of the test. The apparent "superintegration" of masking energy for intense, long flashes seems to be the result of detection of an after-image, which occurs 50 msec or more after the test and which may therefore be influenced by light occurring 50 msec or more after the test.

Equation (1) predicts thresholds well in presentations which minimize the observer's dependence on after-images for detection. When conditions favor after-image production, observed thresholds tend to be higher (e.g., double or more) than those predicted by Eq. (1). The after-image process therefore would account for the slope being greater than one in Battersby and Wagman's data, because after-images are more important at high intensities. Admittedly, this is but a partial and imprecise account of the divergence of test threshold measured in intense long flashes from those measured in comparably energetic impulse flashes. Intense long flashes viewed after darkness pose problems not only for the observer but also for the theoretician. The final account will not be a simple one.

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[48] W. S. Battersby (private communication).

[49] C. H. Graham and E. H. Kemp, J. Gen. Physiol. **21**, 634 (1938).

[50] M. Keller, J. Exptl. Psychol. **28**, 407 (1941).

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[53] H. B. Barlow, J. Physiol. **141**, 337 (1958).

[54] H. R. Blackwell, J. Opt. Soc. Am. **53**, 129 (1963).

TABLE I. Comparison of test threshold luminances (mL) with the masking stimulus "on" $l_T^*(\mathbf{M}+\mathbf{B})$ and without the masking stimulus $l_T^*(\mathbf{B})$. $B_m = \log[l_T^*(\mathbf{M}+\mathbf{B})/l_T^*(\mathbf{B})]-2.15$ is Boynton and Kandel's estimate of neural masking response. Masking response as calculated in text is given in the last column, $\log[l_T^*(\mathbf{M}+\mathbf{B})-l_T^*(\mathbf{B})]$. Masking stimulus = 38 mL, duration = 560 msec; pre-adaptation background **B** extinguished 280 msec before onset of **M**. Data from Boynton and Kandel (Ref. 14, p. 278), average of three subjects.

$\log l_B$	$\log l_T^*(\mathbf{M}+\mathbf{B})$	$\log l_T^*(\mathbf{B})$	$\log[l_T^*(\mathbf{M}+\mathbf{B})/l_T^*(\mathbf{B})]-2.15$	$\log[l_T^*(\mathbf{M}+\mathbf{B})-l_T^*(\mathbf{B})]$
−4.20	0.98	−2.11	0.95	0.98
−1.50	0.98	−2.12	0.95	0.98
−0.50	0.83	−1.85	0.54	0.83
0.50	0.68	−1.49	0.02	0.68
1.50	0.52	−1.10	−0.53	0.51
2.50	0.53	−0.36	−1.26	0.47
3.00	0.73	0.35	−1.77	0.50
3.50	1.25	1.23	−2.13	[−0.10][a]

[a] Insufficient data.

Effect of Background

A second prediction from impulse responses is that the peak of the masking response to a long flash should be independent of the background upon which it is superimposed. In a thorough study, Boynton and Kandel[14] measured the thresholds during the onset of a long pulse of light as a function of the background illumination. Their procedure is illustrated schematically in Fig. 9(d), and may be compared with Fig. 9(c) which illustrates the procedure used with impulses in Exp. 5. In their main experiment, however, the background was terminated 280 msec before the masking flash.

Boynton and Kandel used a 40-msec test flash, which definitely is not an impulse test, being in fact near the limit of integration. Their long test flash makes comparison difficult because the long test tends to give lower values for the sharp peak than does an impulse. Furthermore, the threshold to a long flash is very sensitive to changes in the shape of a peak, and possibly is subject to other less systematic differences. The best comparison with Boynton and Kandel's data is for simultaneous onset of test and masking stimulus because this presentation is most nearly comparable to the conditions for producing C_δ. The procedure can be considered as a production of C_{40} followed by continuation of the background.

Table I gives average thresholds obtained with masking stimulus, with the background alone, the difference of the log thresholds minus 2.15, and the log of the difference of the two thresholds. As the pre-adapting background varies from dark to 3.2 mL, the log of test threshold change varies from 0.98 to 0.68 (log mL); for backgrounds between 32 and 1000 mL the variation is only between 0.51 and 0.47 (log mL). This latter change (0.04) should be contrasted with Boynton and Kandel's estimate of the change in effectiveness of the masking stimulus: 2.72 over the full range being considered and 1.24 over the range of backgrounds from 32 to 1000 mL.

We can work backwards to estimate a contrast threshold. From Table I, the logarithm of the typical observed threshold change is 0.5 (3.2 mL). Test energy $e_T^* = 3.2\ \text{mL}\times 40\ \text{msec} = 128\ \text{mL}\times\text{msec}$. Masking energy $e_M = 38\ \text{mL}\times 60\ \text{msec} = 2280\ \text{mL}\times\text{msec}$. Thus $e_T^*/e_M = 128/2280 = 0.06$. This figure may be an underestimate due to the long masking flash, but it lies within the range of observed foveal values.

In Boynton and Kandel's data, the logarithm of the threshold is about 0.5 higher for flashes which may be expected to induce after-images, i.e., intense flashes following a dark background. The elimination of subsequent after-images by pre-adaptation to high luminances may account in part for the authors' apparently contradictory finding that increasing the background luminance can reduce test thresholds.

The most complete study of the effect of background upon masking was made by Onley and Boynton.[19] They studied masking of a 40 msec test by 300-msec flashes of different intensities following pre-adaptation to various backgrounds. The apparent brightness of the

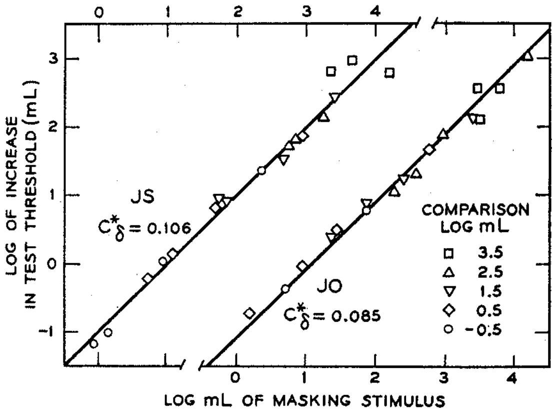

FIG. 16. Effect of masking-stimulus luminance on test threshold (test occurs at nominal +12.5 msec after onset of masking stimulus, see text.) Masking stimuli of apparent brightness equal to a comparison standard are coded with points of same shape, as indicated. Background pre-adaptation was varied from 1 to 1000 mL (Obs. JS) and from 1 to 8900 mL (Obs. JO). Points of equal brightness are arranged from left to right in order of increasing pre-adaptation luminance. Equations of regression lines (not indicated): JS, $\log C_\delta^* = -1.0.20 + 0.011 \log e_M$ ($r=0.987$); JO, $\log C_\delta^* = -1.207 + 0.033 \log e_M$ ($r=0.985$). Data from J. Onley and R. M. Boynton (see Ref. 19, p. 938).

masking stimuli also was determined. Complete data were generously made available by Onley.

As with the data of Boynton and Kandel, the most relevant data for comparison with the present work is from the case in which the onsets of the test and masking stimuli coincide. However, there is some internal evidence of a slight time shift in the data.[55] Therefore, the data actually used here as an estimate of the 0.0-coincidence values were obtained by extrapolating between nominal 0.0 msec and +25 msec, and represent a nominal time $\tau=+12.5$ msec.

In Fig. 16 the induced threshold change $[l_T^*(\mathbf{M}+\mathbf{B})-l_T^*(\mathbf{B})]$ is graphed as a function of the masking-stimulus luminance. Points corresponding to masking stimuli of equal apparent brightness are coded by the same shape; the relative pre-adaptation intensity can be deduced from their relative placement.

The slopes of the best-fitting lines and the product-moment correlation coefficients between masking luminance and adjusted test threshold are, respectively, 1.01 ($r=0.987$) and 1.03 ($r=0.985$) for the two sets of data. These slopes are not significantly different from 1.00. The best-fitting lines of slope 1.00 (modified Weber's law) correspond to an adjusted contrast threshold $C_{40}^*=0.106$ and 0.085, for JS and JO, respectively.

These values are based on an assumed integration time equal to the test duration of 40 msec. An assumed time of 60 msec would reduce them by 33%. The best-fitting Weber's-law lines account for 0.966 and 0.976 of the variance in the data.

Masking flashes of equal luminance may differ enormously in apparent brightness, depending on the luminance of the pre-adaptation background. However, masking flashes of equal luminance produce equal changes in test threshold $[l_T^*(\mathbf{M}+\mathbf{B})-l_T^*(\mathbf{B})]$ regardless of their appearance. In this treatment of these data, pre-adaptation background and apparent brightness are ignored as determining factors in the masking produced at the onset of a long flash; threshold change is directly proportional to masking luminance.

Fast Versus Slow Masking Process

In order to avoid physiological inference, the terms fast and slow are used where previous authors have used neural and photochemical. Fast and slow are used relative to 1 sec. The discussion will attempt to demonstrate that threshold phenomena seen in the above experiments are attributable primarily to fast processes.

(1) The threshold response to a masking impulse is fast. The data show that even after an intense impulse, threshold changes are negligible several tenths of a second later.

(2) The data obtained with the 250-msec masking flash here and for longer flashes elsewhere show that initial recovery from these flashes is equally fast.

(3) The question is whether in steady light the threshold is high due to the cumulative action of light for several seconds (as would be required by a slow photochemical process with a time constant of several seconds), or whether the threshold is influenced primarily by the light preceding the test by a few tenths of a second.

The answer is implicit in (2) above but can be demonstrated by direct comparison of the action of two backgrounds: the 0.25-sec pre-adapting flash repeated at 1 sec intervals and an "equivalent" steady background. A pre-adapting field of 100 ft-L for 0.25 sec produces about the same level of adaptation 0.3 sec after its termination as does a steady light of 0.37 ft-L. All contrast thresholds measured in the two different backgrounds are comparable.

In viewing the steady background, only 1/28 as much light impinges on the cornea each second as in viewing the repeated 0.25-sec pre-adapting field, yet the adaptation level is the same or slightly higher. From the great effectiveness of a steady light relative to an intermittent one, it follows that the steady light's effect is dependent on fast processes. Had it been terminated 0.3 sec before the test, it would have had to contain at least 28 times more flux in each second in order to produce the same adaptation level.

Occasionally, during steady fixation, the 0.37 ft-L background subjectively fades out completely. The fading does not seem to perturb thresholds. That fading does not influence thresholds is not surprising, since the boundaries which determine visibility of the pre-adaptation field are more than 4° away from the test. Thus, a steady light's main influence on thresholds depends not on a slow cumulative adaptation, nor on whether it is visible or faded out, but simply on its instantaneous presence.

It is important not to misconstrue the above statements to mean that there are no slow masking processes, such as, for example, dark adaptation. What is asserted is that in masking by a steady light, the role of slow processes is dwarfed by that of fast masking processes. This point is worth emphasizing because the opposite statement appears often in the masking literature.[56,57]

A useful observation from the comparison of different pre-adaptation fields is that similar thresholds are obtained with a bright pre-adaptation field which is terminated before the test and with a continuous background field. Boynton and Kandel[14] observed this similarity in their experiment and their result is extended here to impulse-contrast thresholds. The author

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[55] Onley and Boynton's[19] data show instances where increasing masking luminance does not produce increases in thresholds of tests which nominally occurred at 0.0 msec (coincidence of onsets). This result is more likely to have occurred at negative times (test flash preceding) than at 0.0.

[56] H. D. Baker, J. Opt. Soc. Am. 45, 839 (1955), p. 843.

[57] See Ref. 14, p. 284; also Ref. 1, p. 758.

also has observed the shape of the whole masking impulse response (not only the peak) to be independent of how the state of adaptation was achieved. This means that in many masking experiments we may substitute a steady background for a pre-adaptation field.

CONCLUSIONS

Visual masking depends upon several qualitatively different detection processes; it is a highly nonlinear phenomenon. Masking by impulses was studied, particularly presentations in which test and masking impulse flashes occur simultaneously. In this case, no purely temporal information is available—detection must be of the contrast between test and surround—therefore, threshold is at a maximum. As time information also becomes available, threshold drops, which defines the impulse masking response.

The adjusted impulse-contrast threshold C_δ^* was found to be fairly independent of background when effects of background and of the masking flash were considered separately. Also, a modified Weber's law ($C_\delta^* \approx 0.1$) held approximately. These two properties make C_δ^* a useful quantity.

Generally good predictions of masking by long flashes can be made by considering that portion of the masking response where detection depends on a spatial-contrast judgment. The principle is to consider the first 60 msec of the long flash as an impulse. Presentations which generate negative after-images tend to cause threshold increases greater than those predicted by theory. Apparent brightness was irrelevant to masking because only masking energy mattered for the type of detection process studied here.

ACKNOWLEDGMENTS

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APPENDIX: GLOSSARY

Note: Boldface capitals refer to visual stimuli, lowercase italics refer to physical units, and an asterisk indicates a threshold value. The physical units in which a quantity is described are given in parentheses.

T, **M**, **B** are the test, masking, and background stimuli.
Φ is the null stimulus.
t is time (msec).
τ is the delay of **T** relative to **M** (msec). [Negative values of τ imply **T** precedes **M**.]
l_T, l_M, l_B are the luminance of test, masking, and background stimulus, respectively (ft-L).
e_T, e_M are the areal density of luminous energy in test, and masking stimuli, respectively, abbreviated to "energy" where no confusion arises (ft-L×msec).
$e_\mathrm{T}^*(\mathbf{M}+\mathbf{B})$ is the test threshold energy measured when both **M** and **B** are present (ft-L×msec).
$e_\mathrm{T}^*(\mathbf{B})$ is the test threshold measured when only **B** is present (ft-L×msec).
$e_\mathrm{T}^*(\tau)$ is the threshold masking response [the threshold energy of **T** as a function of its delay τ relative to **M** (ft-L×msec)].
max $e_\mathrm{T}^*(\tau)$ is the peak of threshold response, maximum is with respect to τ (ft-L×msec).
$\delta(t)$ is the unit impulse: $\delta(t)=0$, $t\neq 0$ and

$$\int_{-\infty}^{\infty} \delta(t)dt=1.$$

C_t is $l_\mathrm{T}/l_\mathrm{M}$, the contrast in a stimulus of duration t (subscript δ indicates impulse stimuli).
$C_\delta^* = [e_\mathrm{T}^*(\mathbf{M}+\mathbf{B}) - e_\mathrm{T}^*(\mathbf{B})]/e_\mathrm{M}$, adjusted impulse-contrast threshold.