Transient adaptation refers to the rapid fluctuations in the sensitivity of the eye that result from sudden changes in luminance level. The research reported here examines the effects of transient adaptation and resultant losses in visibility by using luminance levels comparable to nighttime highway lighting conditions. At low luminance levels, sudden increases produce losses in visibility equivalent to those previously found at higher levels. However, at low luminance levels, decreases produce smaller losses than those observed at higher luminance levels. The results also suggest that there is a preadapting level or range of levels below which there is little or no difference between visibility losses for 10- and 100-fold decreases and above which there is a difference. The transition appears to be a gradual one and is complete at about 8 ft-L. The findings of these investigations suggest that visibility loss depends more on the ratio of steady-state thresholds, particularly at low luminance levels, than on the ratio of luminance change as previously supposed. Research has been initiated on the problem of nonuniformities in roadway luminances in the motorist's visual environment. Results indicate that the size of a nonuniformity may have little effect on transient adaptation. However, experiments to examine multiple nonuniformities and the effect of nonuniformities at various distances from the line of sight on transient adaptation are planned.

VISIBILITY LOSSES CAUSED BY TRANSIENT ADAPTATION AT LOW LUMINANCE LEVELS

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Visual adaptation is the process wherein the sensitivity of the eye adjusts to variations in luminance level over time. Some of these changes in sensivity are accomplished in a few hundred milliseconds, but others take several minutes to an hour. The research on transient adaptation is concerned with the faster changes, which are thought to be primarily neural in nature. Adaptation that takes place over a longer period of time, which appears to be more closely related to the concentration of photopigment in the receptors of the eye (1), is not covered here.

When the eye is presented with a sudden increase or decrease in the prevailing level of illumination, a transient burst of neural activity occurs in the retina that is relayed along visual pathways, signaling the change (2, 3). If the individual is asked to perform a visual task at this time, such as the recognition of a test letter, he or she will need greater contrast between the letter and the background if recognition is to take place. This is because the visual system is busy handling information related to the change in luminance level. Thus, the activity produced by the change masks the letter, i.e., makes it less visible. The greater the change in luminance level is, the greater is the additional contrast necessary to recognize the test letter. Eventually, the activity due to the sudden change subsides and reaches a steady state of complete adaptation.

The momentary loss in visibility associated with transient adaptation occurs whenever an individual changes his or her point of regard to surfaces having different luminances, when he or she views a variegated surface, or when natural illumination changes occur in the visual environment. Because variation in the visual field is necessary for vision to exist, the research on transient adaptation has addressed the question of how much variation in luminance should be permitted in the field of view and still allow adequate visibility to be maintained.

A number of experiments have been conducted by Boynton and associates at the University of Rochester (3, 4, 5, 6, 7). These have dealt with luminance levels similar to those encountered in interior lighting conditions. The research presented here was undertaken to provide a similar description of transient adaptational effects at lower luminance levels comparable to those found in nighttime highway lighting conditions.

Transient adaptational phenomena have obvious relevance to the visual problems of driving and highway illumination. Virtually all of the information available to the motorist is in the form of visual signals from the roadway or instrument panel. Anything that impairs his visibility can be detrimental to his overall performance. At night especially, the driver is often confronted with situations in which there are pronounced differences in luminance from one point of fixation to another, for example, when he looks from oncoming headlights or fixed luminaires back to the dark shoulder of the road. Brilliant signs and brightly lighted intersections and rest stops on high-speed throughways pose problems in transient adaptation. Less obvious, but still capable of impairing vision, are the effects of looking from a dark window to a lighted instrument panel or vice versa. Indeed, transient adaptational phenomena may play a disproportionately large role in the visual problems of night driving.

Several laboratory procedures have been used to investigate transient adaptation (3, 4, 5, 6, 7, 8). In one of these, a target to be identified such as a flash-illuminated letter was presented in a fixed location at a particular time relative to the change in the prevailing luminance level. The observer saw the letter superimposed on the changing background. The interval between the beginning of the transition from one background (B_1) to another (B_2) and the onset of the test letter flash is designated by τ. This procedure is shown schematically in Figure 1. An increase in luminance is shown in Figure 1a and a decrease is shown in Figure 1b. The four experiments reported here follow this experimental paradigm.

The results of previous investigations have typically been interpreted in terms of the ratio of the contrast threshold of the target in the transient state of adaptation to the contrast threshold after complete adaptation to the new luminance level. Contrast threshold in the transient state is defined as the luminance required for a test letter target to be just recognizable (B_t) divided by the luminance of the background against which it is presented. In most cases the letter is presented after the change so that the background luminance is B_2. If the contrast threshold for a letter presented against the changing background is divided by the contrast threshold for a letter presented against a steady background, the resulting ratio φ provides an index of visibility loss.

$$\varphi = \frac{B_t/B_2}{B_s/B_2}$$

where

B_t/B_2 = contrast threshold of letter presented at a particular time (τ) following the change from B_1 to B_2 and

B_s/B_2 = contrast threshold of the letter presented against the steady background B_2.

This quantity reduces to the dimensionless ratio

$$\varphi = \frac{B_t}{B_s}$$

where

B_t = increment threshold of letter presented at a particular value of τ during the transient state of adaptation and

B_s = increment threshold of letter presented against the unchanging background B_2 or during the steady state of adaptation.

At $\varphi = 10$, for example, to recognize a test letter requires 10 times as much light in the transient condition as in the steady-state condition. Log φ, the value usually determined, equals 1.0 in this example. Generally speaking, φ can be viewed as a measure of contrast.

METHOD

The first two experiments described are concerned with transient adaptation at luminance levels that approximate moonlight and outdoor lighting conditions. The third experiment is the logical outgrowth of the first two. Whereas the first two experiments have been reported previously (8), the third experiment represents a recently completed extension of the research. The fourth experiment is the first in a series of experiments examining the effects of luminance nonuniformities on transient adaptation and is an effort to simulate a roadway problem.

Apparatus

The apparatus used in this research was essentially a free-viewing system. The subject looked through a pellicle beam splitter at a 14 × 18-deg background field of flashed opal glass. His head was positioned by a chin and forehead rest. The background field was illuminated by two slide projectors. Luminance was increased by adding the luminance of one projector to that of the other; a decrease was effected by occluding one projector. Light from the projectors was presented and cut off by shutter vanes mounted on rotary solenoids placed in front of them. The luminance from each projector was controlled by neutral density filters, and fine regulation was achieved by small variations in lamp voltage. The subject binocularly viewed the transilluminated opal screen and saw by reflection from the pellicle beam splitter a test letter centered within four fixation points as shown in Figure 2. The fixation points defined the location at which the letter would appear and allowed the subject to accommodate his eyes to the proper distance. A slide changer combined with the associated optics projected the test letter in focus in the plane of the subject's pupils.

The test letters were slides of eight equally discriminable Sloan-Snellen letters that were randomly reordered for every experimental session (9). The letters were transilluminated by a microilluminator bulb. The luminance was regulated by neutral density filters, and fine adjustment was achieved by means of a circular neutral density optical wedge that was positioned by a bidirectional digital stepping motor. The axial shaft of the wedge was connected to a linear potentiometer, which allowed the experimenter to read the wedge position on a remote voltmeter. Another rotary-solenoid shutter controlled the presentation of the test flashes, which were 50 msec in duration. The luminance of all light sources was continuously monitored by means of selenium sun batteries and microammeter output.

Procedure

Procedures used in these experiments were similar to those of Boynton, Rinalducci, and Sternheim (7). From a prevailing luminance level, B_1, the background was either increased or decreased by 1 or 2 log units or 10- or 100-fold to a second luminance, B_2, that was maintained for a short period after which the luminance was returned to the B_1 level. For each ratio of change, the threshold was determined for each of 12 values of τ ranging from -100 to +400 msec. Negative τ-values indicate that the test letter was presented before the luminance change, whereas positive τ-values indicate that the letter was presented after the change. Thresholds were also determined against unchanging backgrounds of B_1 and B_2 luminances or steady-state conditions to provide reference points for the computation of φ.

In each experimental session the subject was allowed to adapt to B_1 for 5 to 7 min.

Figure 1. Schematic of sequence of events in stimulus presentation: (a) transition from background luminance B_1 to a higher luminance B_2 and (b) transition from B_1 to a lower B_2 luminance.

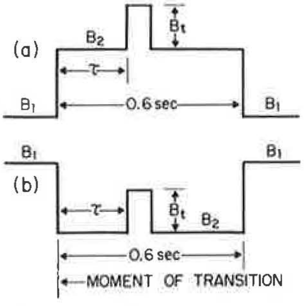


Figure 2. Stimulus configuration as seen by the subject (6).

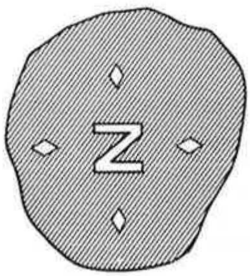


Figure 3. Schematic of the four transient and five steady-state conditions investigated in experiment 1.

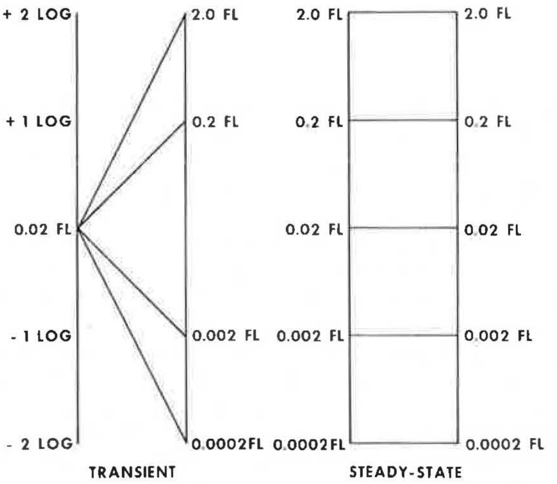
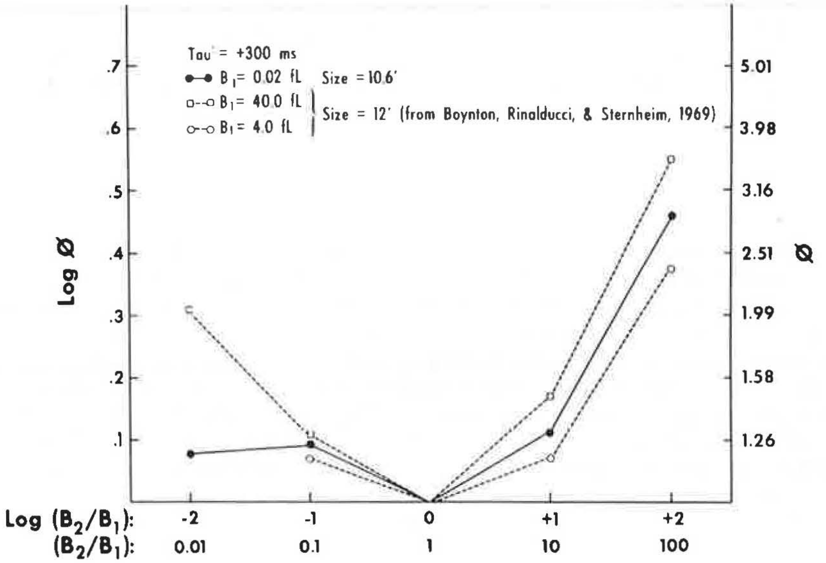


Figure 4. Visibility loss as a function of the ratio of luminance change for experiment 1.



Then began a 15-sec cycle in which the background changed from the B_1 luminance to B_2 for 600 msec and back to B_1 for 14.4 sec. The long recycle times, combined with the brief duration at which the background luminance remained at B_2, ensured that the observer was fully adapted to B_1 at the moment of transition to B_2. Two seconds before the moment of transition from B_1 to B_2 or 2 sec before the presentation of the test letter in the steady-state condition, a warning buzzer sounded. The subject's task was to depress a key corresponding to the letter he believed had been presented. If the subject depressed the correct key, a bell rang and the stepping motor moved the wedge about 0.1 log unit in the direction of increasing density, thus causing the flash on the succeeding trial to be dimmer. If incorrect, the bell did not ring, the wedge was turned in the direction of decreasing density, and the next flash was brighter. Thus, a forced-choice technique giving knowledge of results was combined with the up-and-down psychophysical method (10, 11).

Thirty trials were performed for each threshold determination. Threshold was defined as that luminance at which the letters were correctly identified 50 percent of the time. An Iconix electronic timing system controlled stimulus presentation.

EXPERIMENT 1

Design

Figure 3 shows the transient and steady-state conditions investigated in experiment 1. B_1 was always 0.02 ft-L, which is roughly equivalent to the ambient light provided by the full moon (12). B_2 luminance levels were 0.0002, 0.002, 0.02, and 2.0 ft-L. These provided for a 1- or 2-log-unit decrease or increase. Changes of these magnitudes have been shown to produce significant losses in visibility, at least where higher levels of B_1 have been used (7). In all, there were four transient and five steady-state conditions.

In this experiment, the test letter subtended an angle of 10.6 min at the eye and had a critical detail of 2.12 min. This target size is similar to that used by Boynton et al. (7), who subtended an angle of 12 min with a critical detail of 2.4 min.

Ten subjects, ranging in age from 18 to 32, participated in this experiment. All had a visual acuity of 20/20, either corrected or uncorrected.

Results and Discussion

The results of experiment 1 are shown in Figure 4. In Figure 4, visibility loss in terms of φ for τ = +300 msec (where the test letter flash is presented 300 msec after the moment of transition from B_1 to B_2) is plotted as a function of B_2/B_1 or the ratio of luminance change. In the same slide log φ is also plotted in terms of log (B_2/B_1). τ = +300 msec was chosen for several reasons.

1. It provides a basis for a direct comparison of the data obtained by Boynton and his associates (3, 4, 5, 6, 7), who used τ = +300 msec in much of their work.
2. The +300 msec appears to be a reasonable estimate of the length of a single fixation by a person in an ordinary search or reading task.
3. The threshold at +300 msec is no longer changing rapidly, so that this value is probably more stable and reliable than values obtained at shorter intervals.
4. At +300 msec φ assumes a smaller value than it would at a shorter interval and is therefore a reasonably conservative estimate of the visibility loss under conditions of scanning a nonuniform field.

Although other values of τ were used, the data reported here are restricted to τ = +300 msec.

Figure 4 shows that the largest impairment of visibility was obtained for the 2 log-unit increase in luminance. Selected data from Boynton et al. (7) are also plotted for comparison. Visibility losses resulting from 1- and 2-log-unit increases and the 1-log-unit decrease appear to be comparable in both experiments, even though the preadapting luminance was much lower in the present experiment. However, visibility losses from a 2-log-unit decrease were found to be no greater than those due to a 1-log-unit decrease at the low luminance levels used. That these results at low luminances deviate from previously obtained data at higher luminances is the major finding of experiment 1.

EXPERIMENT 2

Design

In experiment 2 the B_1 luminance level was 0.2 ft-L. This is approximately equivalent to the luminance provided by automobile headlights on asphalt pavement (12). Figure 5 shows the four transient and five steady-state conditions examined. The B_2 levels in this experiment were 0.002, 0.02, 2.0, and 20.0 ft-L, which again provide for 1- and 2-log-unit decreases and increases. As in experiment 1, the test letter subtended an angle of 10.6 min. Ten subjects also participated in this experiment, and their ages ranged from 18 to 33.

Results and Discussion

The results of experiment 2 are shown in Figure 6. The data are plotted as in experiment 1 for values of φ at τ = +300 msec. For ease of comparison this figure also includes the results obtained in experiment 1, which are quite similar. Again, the 2-log-unit decrease fails to produce a greater visibility loss than the 1-log-unit decrease. It should be noted, however, that large decreases in luminance from such low levels (0.02 ft-L, in particular) to even lower levels (such as 0.002 and 0.0002 ft-L) will not usually be experienced in the highway environment. Even so, these visibility losses are on the order of 26 percent.

Previous studies (3, 4, 5, 6, 7) suggested that, to a first approximation, visibility loss was a function of the ratio of the background luminances B_1 and B_2 and that the absolute values of the luminance levels involved played a relatively minor role. Figure 7 (6) shows the value of φ (at τ = +300 msec) as a function of the factor by which the prevailing luminance level is changed. This generalization, however, was inadequate for many conditions where B_1 and B_2 were much greater than 400 ft-L. Boynton has suggested (3) that, just as there is an upper limit to the applicability of this generalization, there is also likely to be a lower limit.

The existence of a lower limit might be attributed to the fact that we are dealing mainly with luminance levels in the mesopic range, near the absolute threshold of the photopic or cone visual system. The cone photoreceptors are primarily involved in the task used to examine visibility loss in these experiments. Within a portion of the photopic range, the eye's sensitivity may be approximated by Weber's law, which states that the smallest difference in luminance that can be detected is roughly proportional to the background luminance. At higher luminances it has been found to be a good approximation under some conditions and a poor one under others. However, it is well known that, at luminances approaching the absolute threshold of cones, Weber's law breaks down. Therefore, varying magnitudes of adapting-field change should not be expected to produce threshold increments different in proportion to the background luminance on which they are superimposed (13).

One explanation for the exaggerated heightening of thresholds observed in transient adaptation is that the luminance change gives rise to a burst of activity in the visual system, and this activity essentially overwhelms or masks activity from a signal superimposed on this change. However, because of a breakdown in Weber's law at low luminance levels the differences in neural activity for a 1- or 2-log-unit decrement

Figure 5. Schematic of the four transient and five steady-state conditions investigated in experiment 2.

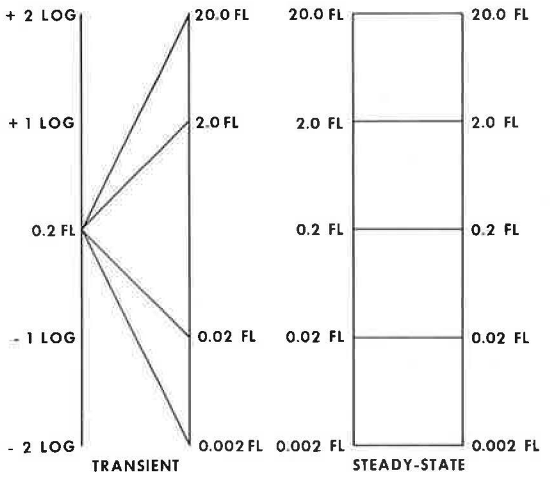


Figure 6. Visibility loss as a function of the ratio of luminance change for experiment 2.

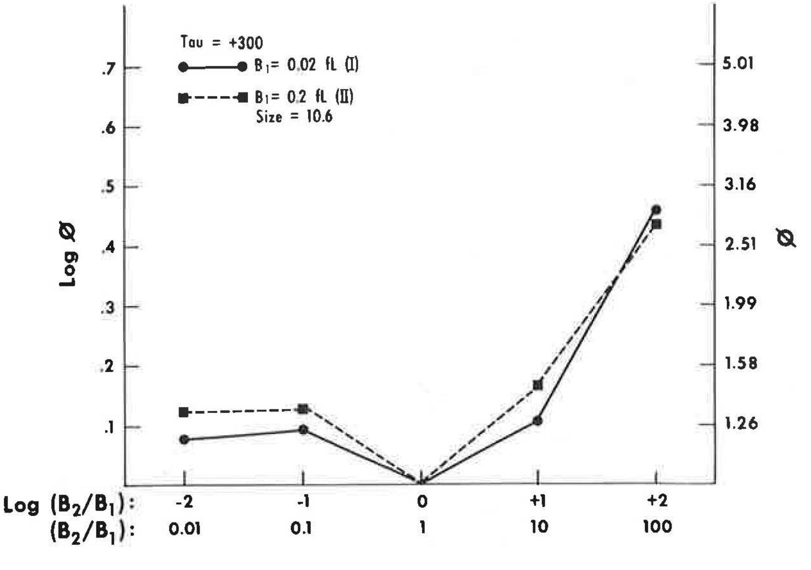


Figure 7. Phi as a function of the factor of change from one luminance to another.

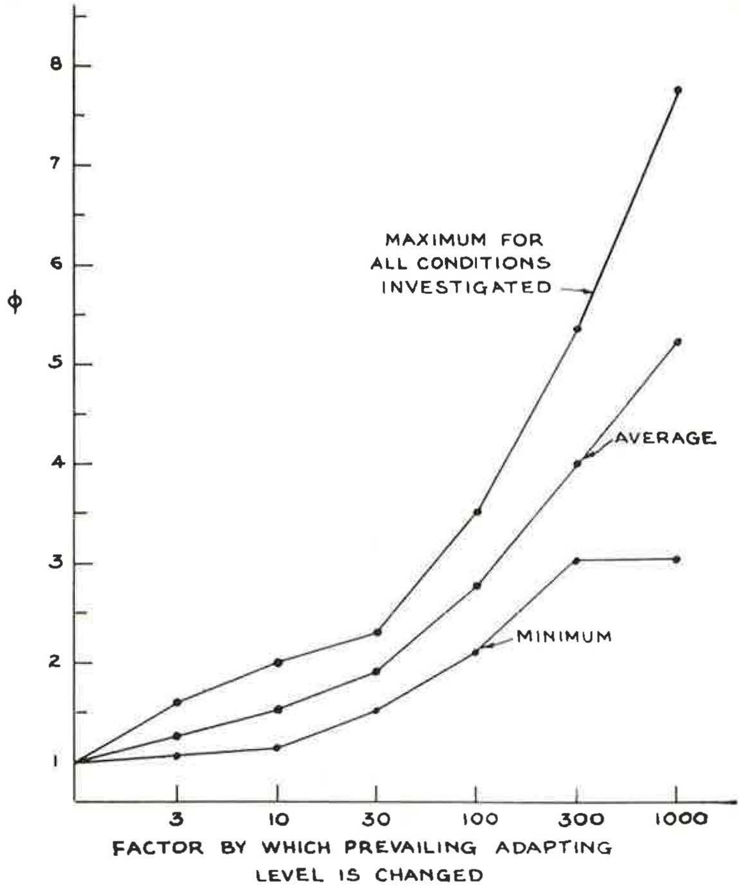
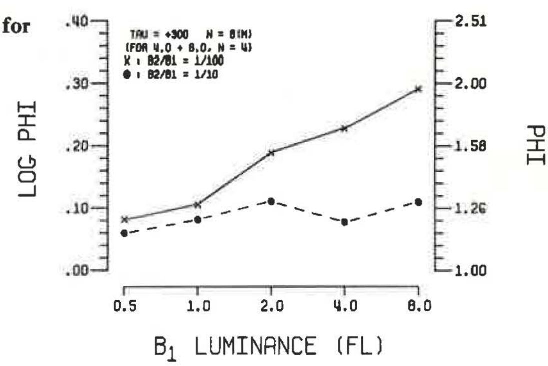


Figure 8. Phi as a function of B_1 luminance level for 10- and 100-fold decreases in luminance.



may not be significant. Both magnitudes of change might be equivalent in their ability to produce visibility loss.

EXPERIMENT 3

Design

The results of experiments 1 and 2 suggest that there is a preadapting level or range of levels below which there is little or no difference between visibility losses for 10- and 100-fold downward changes and above which there is a difference. Experiment 3 was directed at determining where the break-off point is. Visibility losses for 10- and 100-fold decreases were examined for B_1 levels of 0.5, 1.0, 2.0, 4.0, and 8.0 ft-L. Eight subjects were tested at B_1 levels of 0.5 to 2.0 ft-L and four subjects each for 4 and 8 ft-L. The procedures for experiment 3 were basically the same as for experiments 1 and 2 with only minor modifications.

Results and Discussion

Figure 8 shows the combined data for all subjects with φ (and log φ) plotted as a function of B_1 luminance for 10- and 100-fold decreases. The data suggest that the transition from where there is no difference in visibility losses to where there is a difference is a gradual one. Based on previous investigations using much higher B_1 luminance levels (3, 4, 5, 6, 7), the transition appears to be complete at about 8 ft-L (values of φ at +300 msec are approximately the same). Figure 9 shows the data for two subjects who participated in all phases of experiment 3.

Boynton (3) has suggested that visibility loss depends on the ratio of adaptational change (or ratio of background luminances). However, research on transient adaptation at low luminances shows that this relationship breaks down (8, 14). A previous report (8) demonstrated by using data obtained in experiments 1 and 2 that the ratio of the higher steady-state threshold to the lower one shows a high degree of relationship with visibility loss (φ for τ = +300 msec) at low luminances and is equivalent to the ratio of backgrounds at higher luminances. For experiments 1 and 2 the correlation (Pearson product-moment correlation coefficient) between the ratio of steady-state thresholds and φ was found to be high ($r = +0.865$) and statistically significant. For experiment 3 the correlation was also high ($r = +0.792$) and statistically significant. Therefore, we propose that the ratio of steady-state thresholds provides a more adequate basis for predicting and assessing visibility loss in transient adaptation over a wider range of luminance levels.

EXPERIMENT 4

Experiment 4 was the first of a series of experiments to examine the effects of luminance nonuniformities on transient adaptation. Again this is an attempt to simulate a roadway problem. At night a driver's visual field often includes a roadway that is cluttered with variations in luminance and nonuniformities in brightnesses. The first experiments deal with unrestricted or full-area background fields. Later research will examine nonuniformities within a restricted portion of the field by simulating, for example, a ribbon of highway pavement. Initial experimentation on luminance nonuniformities involves examining simple situations before proceeding to the more complex ones.

Design

In this experiment the area of a square patch of light was varied and was seen against

Figure 9. Phi as a function of B_1 luminance level for 10- and 100-fold decreases for experiment 3.

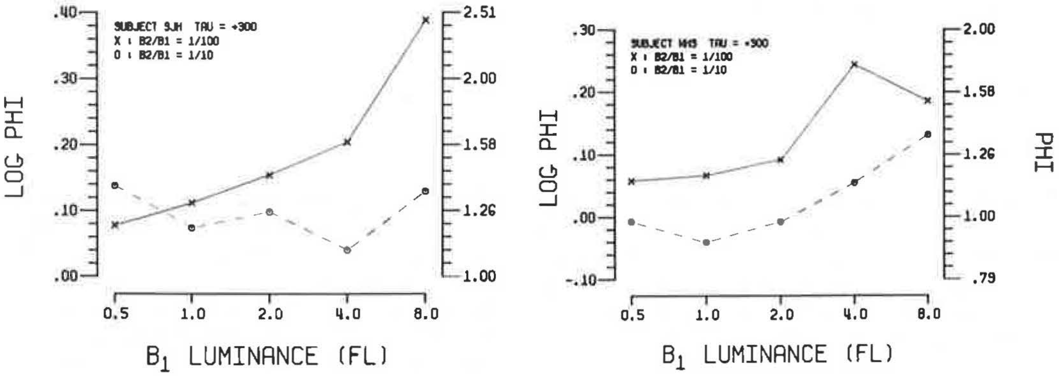


Figure 10. Stimulus configuration for experiment 4.

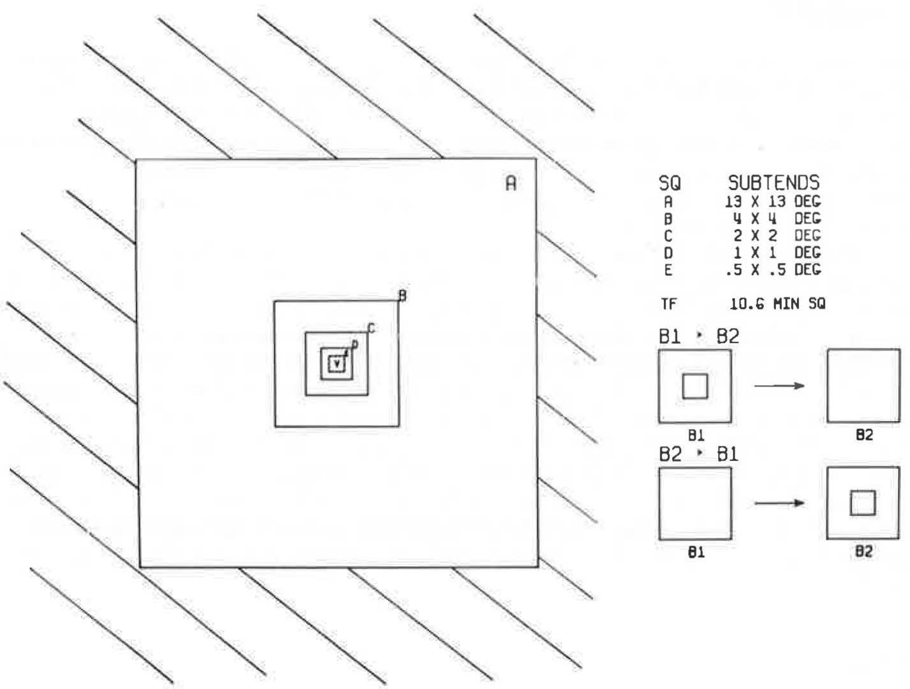
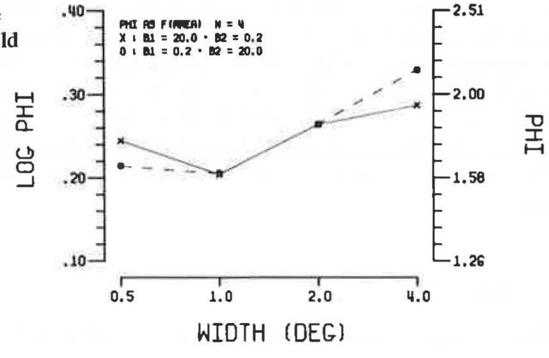


Figure 11. Phi as a function of the area of the square patch superimposed on a background field for 100-fold increases and decreases for experiment 4.



a uniform luminous background field. The luminance of the patch was suddenly increased or decreased by a factor of 100. The width or diameter of the square was varied from 0.5 to 4 deg. Figure 10 shows the stimulus configuration and the relationship between the square patch (nonuniformity) and the background. Figure 10 shows a background square measuring 13 by 13 deg on which one of the square patches or nonuniformities is superimposed (B, C, D, or E). Only one square patch was used at a given time. The test-letter flash, V, which measured 10.6 min, is shown centered within a square patch. In the lower right-hand corner of the figure a schematic representation of the luminance change is shown. In the first case (B_1 to B_2), the bright patch is superimposed on the dim background and the bright patch is then terminated, providing a decrease in luminance. In the second case (B_2 to B_1), the dim background is presented and a bright square patch is then superimposed momentarily on it, providing an increase in luminance.

Thus the observer was confronted with a change from a uniform field to a nonuniform field or vice versa created by square patches of light of a luminance 100-fold higher than their background. The square patches were projected on a uniform background provided by a back-projection screen. For the increase, $B_1 = 0.2$ ft-L and $B_2 = 20$ ft-L and for the decrease, $B_1 = 20$ ft-L and $B_2 = 0.2$ ft-L. Four subjects were used in this study.

Results and Discussion

The results of experiment 4 are shown in Figure 11 where φ and log φ for $\tau = +300$ msec are plotted as a function of the size of the bright patch. Although the effect of area is small there is a general upward trend or loss in visibility with an increase in the size of the bright patch. This is probably the result of an increase in light flux or stray light with an increase in the size of the square patch.

Two subsequent experiments are planned in this series. They will examine the effects of the number of luminance nonuniformities (or number of square patches) and their distance from the line of sight on visibility loss during transient adaptation.

CONCLUSIONS

Several points might be reiterated from the experiments that have been reported here. First, at luminance levels comparable to those found in night driving, sudden increases in luminance produce losses in visibility equivalent to those previously found at higher initial luminance levels. However, for decreases from a low luminance level to an even lower one, smaller losses were observed than those found at higher luminances. Second, the results also suggest that there is a preadapting level or range of levels below which there is little or no difference between visibility losses for 10- and 100-fold decreases and above which there is a difference. The data show that the transition is a gradual one and appears to be complete at about 8 ft-L. Third, the results of the present investigation indicate that at low luminance levels the value of φ depends more directly on the ratio of steady-state thresholds than on the ratio of luminance change. Finally, initial research on luminance nonuniformities indicates that, when the size of a luminance nonuniformity is varied, there is little marked effect on transient adaptation. Subsequent experiments will examine multiple nonuniformities and the effect of nonuniformities at various distances from the line of sight on transient adaptation and visibility losses.

ACKNOWLEDGMENT

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