DISCOMFORT GLARE AND DURATION OF GLARE SOURCE

by

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INTRODUCTION

Light, if sufficiently bright, can produce discomfort. This is commonly referred to as discomfort glare.

Empirical methods to quantify discomfort glare have been used to study the effects of different environmental conditions on discomfort glare. Research on discomfort glare exemplifies the empirical approach. In a typical study (Putnam and Gillmore, 1957) the observer, under a certain set of conditions, is required to adjust the luminance of a source of light so that he is at the threshold of discomfort glare. An important aspect of empirical research on discomfort glare is that the observer is asked to make a subjective judgement. If one was studying disability glare it would be possible to get an objective evaluation of the subject's capacity to perform a visual task at a certain illumination level by asking him to actually perform the task and observing how well he does it. A similar study of observing a person's performance at a visual task to determine his level of comfort (or discomfort) in a particular environment cannot be carried out because discomfort glare is a subjective reaction rather than an aspect of performance of a visual task, at least in the short run.

Some studies have been carried out in an attempt to relate discomfort glare to physiological changes produced by the glare source. Although Fugate and Fry (1965) have shown that at least under certain conditions discomfort glare is linked to the activity of the muscles which control the diameter of the pupil, no quantitative relationship has been established between discomfort glare and any physiological attribute.

Various investigations are in agreement as to how some factors influence discomfort glare. Over a limited range of conditions these findings can be expressed (Hopkinson and Collins, 1970) by the formula:

$$\text{Glare constant} = \frac{B_s^{1.6}\, w^{0.8}}{B_a\, A^2}$$

where B_s is luminance of source

w is solid angle subtended by source

B_a is general background luminance

A is angle between direction of viewing and direction of source.

The glare constant does not account for all the factors that affect discomfort glare. For instance, it does not show how discomfort glare changes with a change in the duration for which the light source is "on".

Bloch's Law

When the duration of a flash of light is small, a high level of luminance is needed in order to detect the stimulus. As the duration of the flash increases, the necessary level of luminance decreases.

A mathematical statement of this phenomenon is provided by Bloch's Law:

Lt = a constant

where L is threshold luminance

t is threshold duration.

Figure 1 (Marks, 1974) shows that Bloch's Law holds at the absolute threshold of vision for durations up to about 0.1 second. It also indicates that at relatively long durations (greater than 0.1 second), the luminance required for a threshold response becomes independent of duration.

<u>Magnitude Estimation</u>

Raab (1962) investigated the effect that the duration of a flash of light has on estimated brightness. Figure 2 (Marks, 1974) shows how the brightness of a flash of light varies with duration for each of several levels of luminance. It can be seen that for brief flash durations, in order to produce any constant level of brightness, a reciprocity exists between luminance and duration. Put mathematically,

Lt = a constant

where L is luminance

t is duration

This is the same relationship that was found to exist at the threshold level (Bloch's Law).

An interesting feature of Figure 2 is that the curves for different luminances reach maximum values of "estimated brightness" at different values of duration. As the luminance

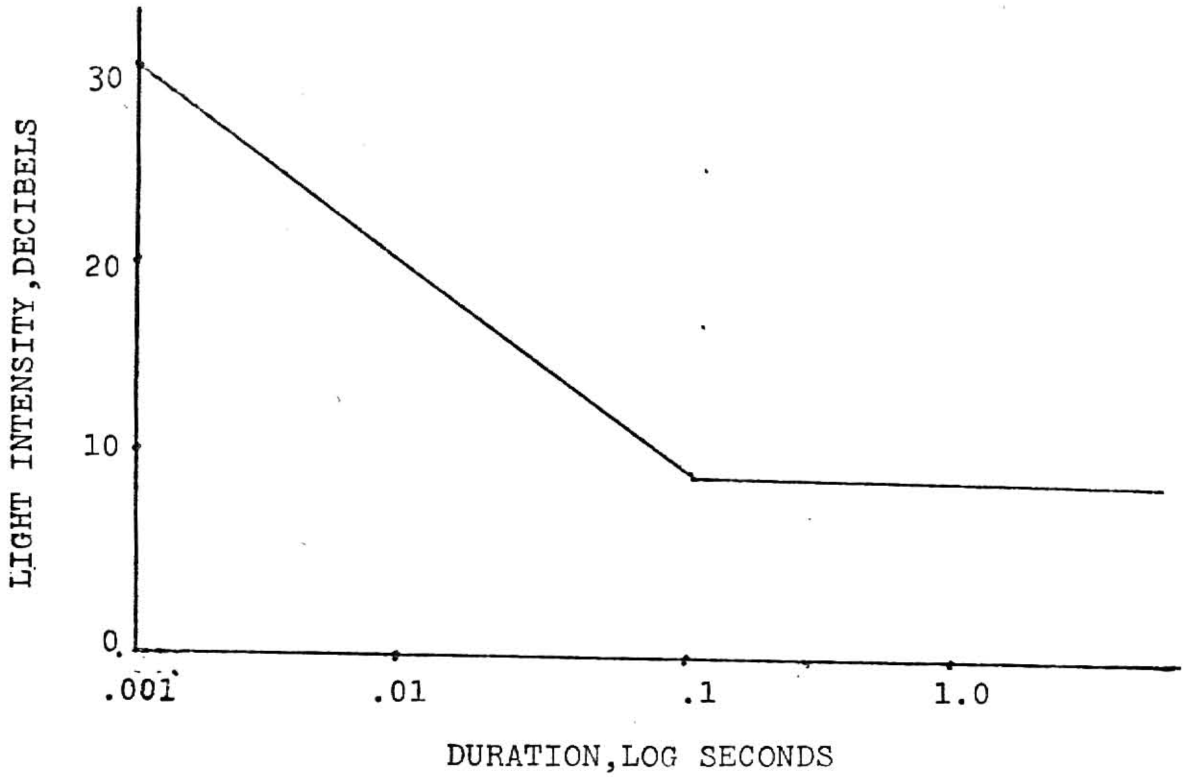

Figure 1. Relationship between duration of a flash of light and the level of luminance required to detect it.

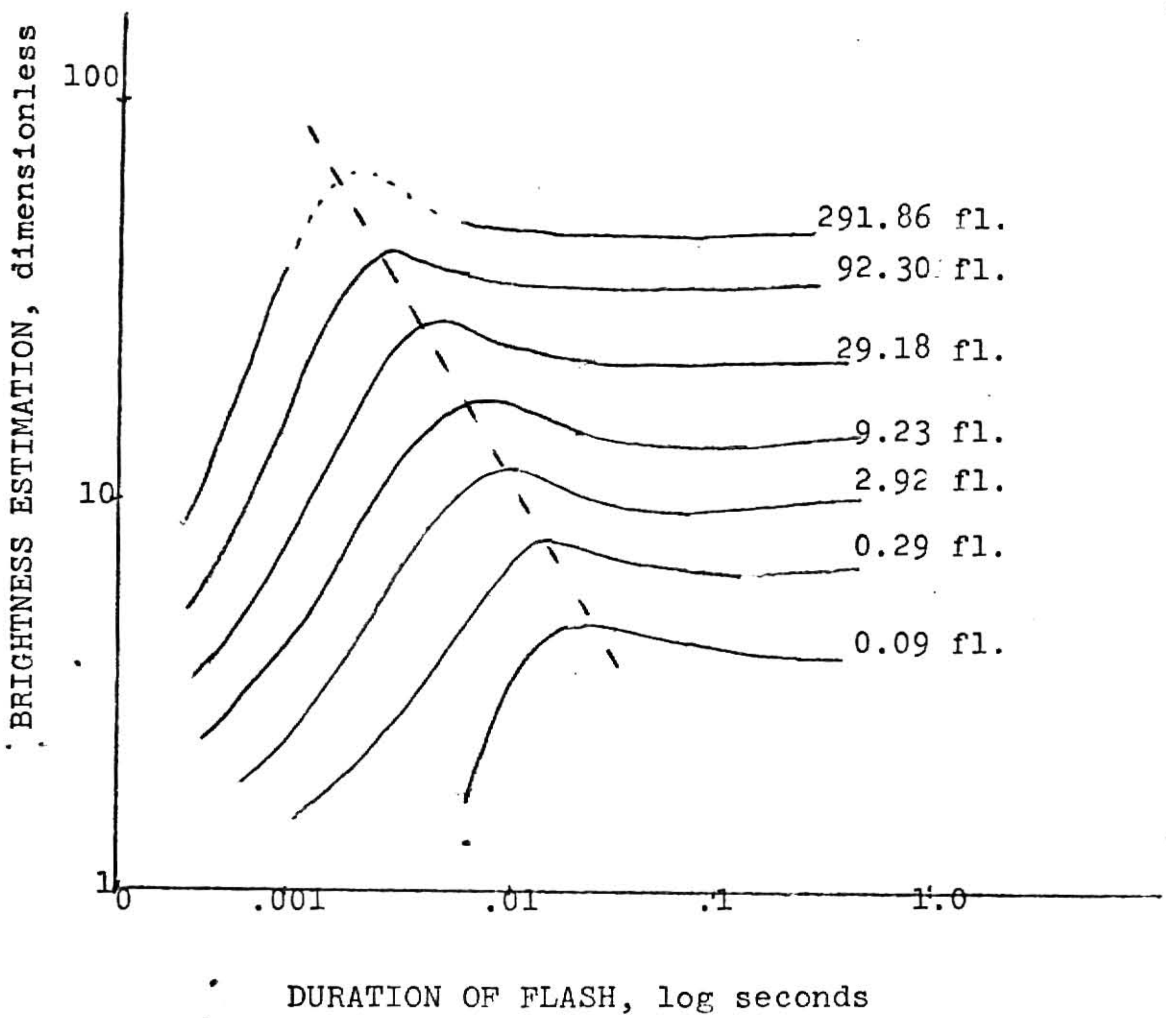

Figure 2. Magnitude estimates of the brightness of flashes of light as functions of flash duration.

The dashed line shows how the temporal locus of the Broca-Sulzer enhancement decreases as luminance (in foot-lamberts) increases.

decreases, the duration at which the maximum is reached increases. This is indicated by the dashed line in Figure 2.

Figure 2 also shows that at longer durations, brightness is independent of duration. A curious phenomenon occurs in the region of the critical duration (where the function attains a maximum). This phenomenon consists of a hump in the function and is referred to as the "Broca-Sulzer Effect".

Variation of Discomfort Glare with Flash Duration

According to Woodworth and Schlosberg (1971) the statement

$$Lt = \text{a constant}$$

where L is a visual function

t is duration

is true for a wide variety of visual functions, for durations less than a critical duration. It has been seen that it applies to threshold luminance and supra-threshold estimated brightness. The present question is whether this relationship will hold good for discomfort glare.

Pilot Study

A pilot study was undertaken by Gupta and Ahmed (1975) with the light source placed at 15^{o} above the horizontal line of sight. The size of the source was 3.14×10^{-5} steradian and a background luminance of 0.1 foot-lambert was used.

Figure 3 shows the results. A concept called "borderline between comfort and discomfort" or "BCD" was used as a measure of discomfort glare. BCD is defined as "that point when the light is not annoying or uncomfortable, but if it were made any brighter, it would be uncomfortable". Figure 3 shows that there appears to exist a critical duration, t_c, and for durations less than t_c, a plot of BCD (linear scale) vs. duration (log scale) gives an almost straight line. This indicates that BCD decreases as a logarithmic function of duration rather than as a power function which Bloch's Law implies.

It is interesting to note that because of the relatively short range over which temporal summation can usually be carried out, there has been some difficulty in deciding whether estimated brightness grows as a logarithmic function or as a power function of duration. As Marks (1974) points out, there does seem to be a strong reason for preferring the power relation.

Figure 3 also indicates that BCD reaches a minimum at an "on" time of approximately about one second. This curve may be compared with the curve relating "brightness estimation" to duration (Figure 2). A comparison indicates that the phenomenon which produces the sensation of brightness might be related to the phenomenon which produces discomfort glare.

At smaller durations, increasing the duration results in a decrease in BCD i.e. it results in greater discomfort. At

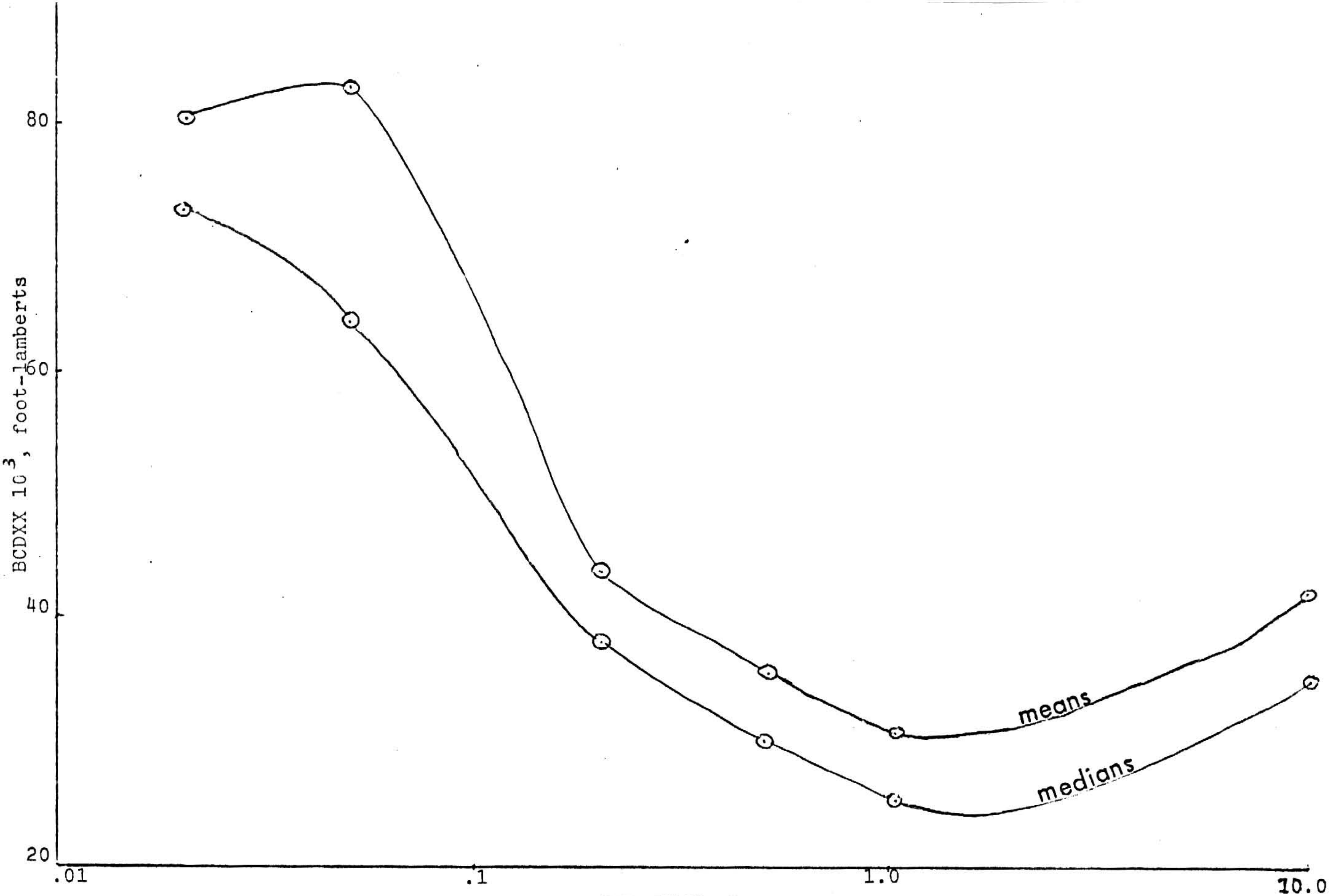

Figure 3. Variation of BCD with duration.

smaller durations, increasing the duration also increases the brightness estimated. At greater durations, BCD rises i.e. there is less discomfort. At higher durations, the brightness estimated also decreases before the curve flattens out. In this sense there is a correspondence between the effect of increasing duration on BCD and "estimated brightness", both of which call upon the observer to make a subjective judgement. The difficulty is that the critical durations are different-0.001 to 0.1 second for "estimated brightness" versus approximately one second for glare.

Collection of data over a wide range of "on" time values will consequently not only give us knowledge as to how BCD varies with duration but may give insight into the phenomenon of discomfort glare - if it can be related to Bloch's Law over a certain range of flash durations and if it can be related to other phenomena like brightness estimation; if there is a certain value of duration at which BCD is a minimum (maximum discomfort) and if so the magnitude of this critical duration.

The variation of BCD with duration at durations greater than the critical duration is also of interest. The pilot study (Figure 3) seems to indicate that at a critical duration, the curve stops falling and starts rising. If measurement of BCD at relatively long durations yields the same result, it can be concluded that discomfort glare is unlike "threshold luminance" (Figure 1) in that at durations greater than the critical duration, the BCD-duration curve starts rising, unlike the "threshold luminance" versus duration curve which flattens out.

Pupillary Constriction as an Index of Discomfort Glare

Various studies have been done to investigate the changes that take place in the human eye when it is exposed to a glare source.

Fry and Allen (1952) demonstrated in two subjects that a 1 - 12° patch of constant luminance placed at 0°, 3°, 6°, 12°, and 20° from the fovea in the dark adapted retina will evoke the same magnitude of pupillary constriction. This shows that there is no decrease in pupillo-motor sensitivity out at least 20° from the fovea.

It is generally known that there is a considerable difference in BCD values if the glare source is placed along the line of sight rather than 15° away from the line of sight. Another pilot study carried out by Ahmed with three subjects arrived at the same conclusion.

There has been speculation (Fugate and Fry, 1956) as to the usefulness of pupillary constriction as an index of discomfort glare. The two studies mentioned above, one by Fry and Allen (1952) and the pilot, seem to indicate that discomfort is not related to just magnitude of pupillary constriction. If so, this concurs with Fugate and Fry's (1956) statement that pupillary constriction per se cannot be used as index of discomfort glare. It also indicates there may be truth in the belief of King and Fry (1970) that it is the oscillation of the pupil that produces the discomfort and not the size to which the pupil is constricted.

Since data exist on just three subjects, it is premature to draw any conclusions. Measuring BCD for different durations when the glare source is on the line of sight and when it is 15° from the line of sight will not only help evaluate the effect a change in viewing angle has on BCD, but will also shed light on the usefulness of pupillary constriction as an index of discomfort glare.

PROBLEM

This thesis is undertaken to study the variation of discomfort glare with different durations of the glare source. The concept of "borderline between comfort and discomfort" or BCD is used as a measure of discomfort glare. The glare source is presented along the horozontal line of sight as well as 15° above the horizontal line of sight to study the effect that this change has on BCD.

Hypotheses

BCD decreases with increasing duration of glare source. There will come a point where BCD reaches a minimum, then starts increasing.

BCD readings when the light source is placed at 15° above the line of sight will be higher than when it is along the line of sight.

METHOD

Task, Informed Consent and Instructions

For each of the twenty experimental conditions (corresponding to ten durations for each of two angles at which the glare source was placed) which were presented in random order, the observer made two adjustments with the voltage reset to a low value each time. These two voltage readings were each transformed to foot-lamberts and then averaged. This mean luminance was the basic datum of the experiment.

When the observer reported to the laboratory, he was asked to read a description of the experiment entitled "Informed Consent for Discomfort Glare" (Figure 4) and to indicate his willingness to participate. He was then seated in the observer's chair in the experimental booth and the instructions were read to him:

> "There is a concept called "borderline between comfort and discomfort" or (BCD). First, take the control and increase the intensity of the light to the maximum level. Look at the light! Most people would say that this level of light is uncomfortably glaring. Now take the control and drive the light down until it is at the minimum level. Look at the light! Most people would say that this level is comfortable; that is, not glaring. Now, somewhere between these two extremes should be a point of change, a threshold, where the light is at the borderline between comfort and discomfort. This is what we call BCD. This point should be such that the light is not annoying or uncomfortable for you, but if it were any brighter it would be uncomfortable. Take your time to find the BCD point. It may take a little time at first to decide whether the light is comfortable or not. Adjust

Informed Consent for Discomfort Glare

This is an experiment on discomfort glare. You will be shown a small light source. You may look directly at this or it may be above your line-of-sight. It will vary in size. The background brightness will vary. The light source will switch on and off. For each of the experimental conditions you will be asked to adjust the source from a low brightness upwards to a level which is not quite uncomfortable. At no time do we want you to adjust the light to a level which is uncomfortable. There should be no discomfort nor risk from this procedure; however, you are free to stop your participation at any time. Naturally, we would prefer that you would continue to the end of the time period so that we can get all of our data.

If you have any questions, now or later, feel free to ask.

Figure 4. Informed Concent for Discomfort Glare

the brightness up and down until you find your BCD. Do not set the brightness at the borderline between tolerable and intolerable -- that is a higher level. Similarly do not use the pleasantness-comfortable criterion -- this is a lower level. BCD is between these two criteria.

Now I want you to make your first adjustment to BCD. Take your time, turn the control back and forth as much as you need. Make sure the light isn't annoying or uncomfortably high. It is possible that with a certain filter (notice that there are 4 filters here), you cannot make the light as bright or as dim as you wish to. If so, tell me and I'll change the filter. Regardless of where the light is, look straight ahead at this point at all times. When you have completed your adjustment, signal me."

An eight-by-eight by ten foot observer's booth was used, (Figure 5). The observer sat with his face in a facerest looking horizontally at the pole of a two-foot radius hemisphere sitting on edge. This hemisphere was constructed of posterboard painted flat white. Apertures were placed at the pole and at 15° above the horizontal line of sight.

The background luminance was produced by masking an incandescent lamp (15 watts) placed directly above the observer in such a manner that it illuminated the hemisphere uniformly and was at the same time outside the observer's range of vision.

The glare source itself was a CTT, 125 volt, 1000 watt projector bulb. By means of an electonically controlled, tachistoscopic shutter, the time for which the source was presented was varied. It was presented for a certain time and occluded for three seconds.

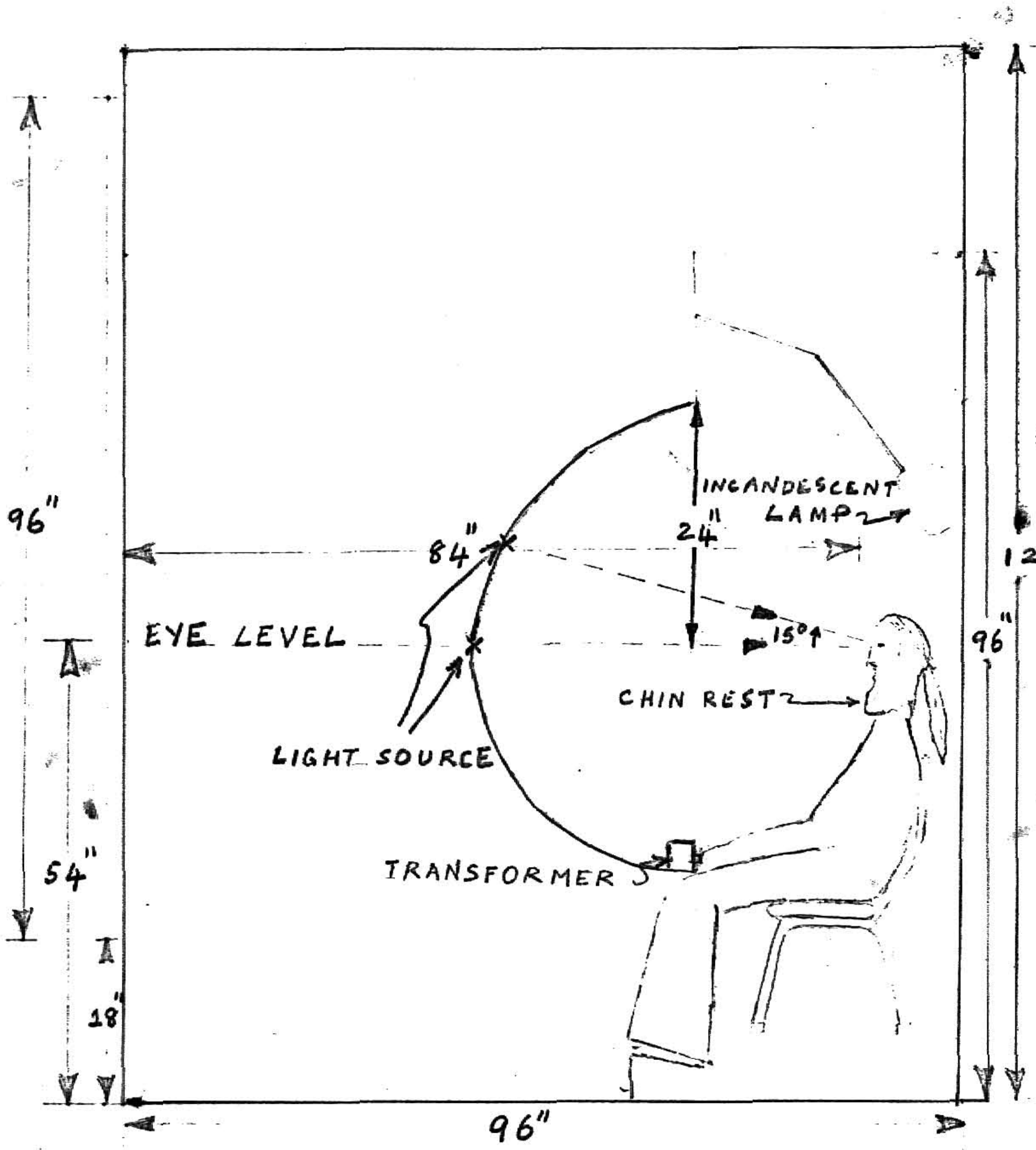

Figure 5. Experimental booth.

The observer adjusted the luminance of the glare source by means of a transformer and a selected neutral-density filter placed in front of the aperture. A stop on the transformer knob limited its lower value to 35 volts to eliminate operation of the source in the "red" region. The transmission factors of the filters were 100% (a hole), 7.9%, 0.53% and 0.05%.

A pilot study with three subjects had indicated that different "off" times did not have any significant effect on BCD. Hence the "off" time was kept fixed at three seconds which is the "off" time of the current Bennett (1976) study.

The size of the light source was 3.14×10^{-5} steradian. The background had a luminance of 0.1 foot lambert (0.343 nits). These are intermediate values of Bennett study.

Experimental Design

Independent variables. Different experimental conditions were obtained by varying the duration for which the source is "on", with the source placed along the horizontal line of sight (0°) and at 15° above the horizontal.

The durations -- 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1.0, 2.0, 5.0 and 10.0 seconds were chosen to give a wide range of values. The smallest duration (0.01 second) was the smallest value obtainable with the apparatus. A duration of ten seconds was felt to be long enough to approximate continuous exposure to the light source.

Since the response to a light along the line of sight is of interest, the glare source was placed at this angle (0^{o}). It was also presented at 15^{o} above the line of sight since 15^{o} is an intermediate value in the range of angles obtainable with the apparatus.

Dependent variables. BCD was the dependent variable. For each of the different experimental conditions, two BCD readings were taken and averaged.

Subjects and Recruitment Procedures

The 24 observers were recruited at student registration at the beginning of the semester. Interested persons filled out a background information blank (Figure 6) and a schedule. People were called to participate upon their availability.

Data Form

Name ______________________ Local Phone ______________

This date ______________ Time ____:____ Major ______________

Your birthdate ______________ Sex M F Fr Soph Jr Sr Gr

Consider the overall urban area where you have lived the longest. What was its population?

- Less than 10 ________
- More than 10 but less than 100 ________
- More than 100 but less than 1000 ________
- More than 1000 but less than 10,000 ________
- More than 10,000 but less than 100,000 ________
- More than 100,000 but less than 1,000,000 ________
- More than 1,000,000 ________

What is your principal occupation? ______________________

Do you spend more than half your work indoors? Yes ____ No ____

If you are associated with the field of lighting in what capacity and for how long? ______________________

____

What is your eye color? blue or green _____ brown _____

What is your original hair color? black _____ dark brown _____

light brown _____ blond _____

red _____

Do you wear eye glasses? Yes _____ No _____

Are these of some special type, such as tinted, bifocals contact lenses? ______________________

If you are aware of it, what is the nature of your visual problem? ______________________

____

____

Do you wear eye make-up? Yes _____ No _____

Have you been exposed to any other conditions which might irritate your eyes. Please describe. __________

____

____

Figure 6. Data Form

RESULTS

The BCD readings obtained covered a wide range of values. The lowest value of BCD was 7.3 foot-lamberts (25.01 nits) and the highest was 560,000 foot-lamberts (1,918,560 nits). The overall mean was 55,950 foot-lamberts (191,687 nits). The raw data is contained in the Appendix.

Mean values of BCD for different subjects, different angles and different durations are shown in Tables 1 and 2. A plot of the mean BCD values for different durations for each of the two angles is shown in Figure 7 (duration on a linear scale) and Figure 8 (duration on a logarithmic scale).

Analysis of variance

The results of an analysis of variance are shown in Table 3.

The analysis of variance indicated that there were significant differences among subjects, between the two angles at which the glare source was presented and among the ten durations for which the light was on, all significant at the 1% level. The interactions that produced significant differences at the 1% level were subject-duration and subject-angle.

Regression Analysis

Since there was a significant difference in the response

TABLE 1

Mean BCD Values for Subjects

Subject No.	BCD (foot-lamberts)	Subject No.	BCD (foot-lamberts)
1	1614.	13	4194.
2	7568.	14	149397.
3	14867.	15	9461.
4	26480.	16	1667.
5	238664.	17	138886.
6	24.	18	83820.
7	4421.	19	11226.
8	47353.	20	4335.
9	91724.	21	131919.
10	2392.	22	187872.
11	38508.	23	32817.
12	10373.	24	2230.

TABLE 2

Mean BCD Values for Angles and Durations

a) Angles

Angle	BCD (foot-lamberts)
0°	25060.
15°	86839.

b) Durations

Duration (seconds)	BCD (foot-lamberts)
0.01	86100.
0.02	67302.
0.05	63121.
0.1	74215.
0.2	65262.
0.5	40938.
1.0	38827.
2.0	36330.
5.0	38147.
10.0	49254.

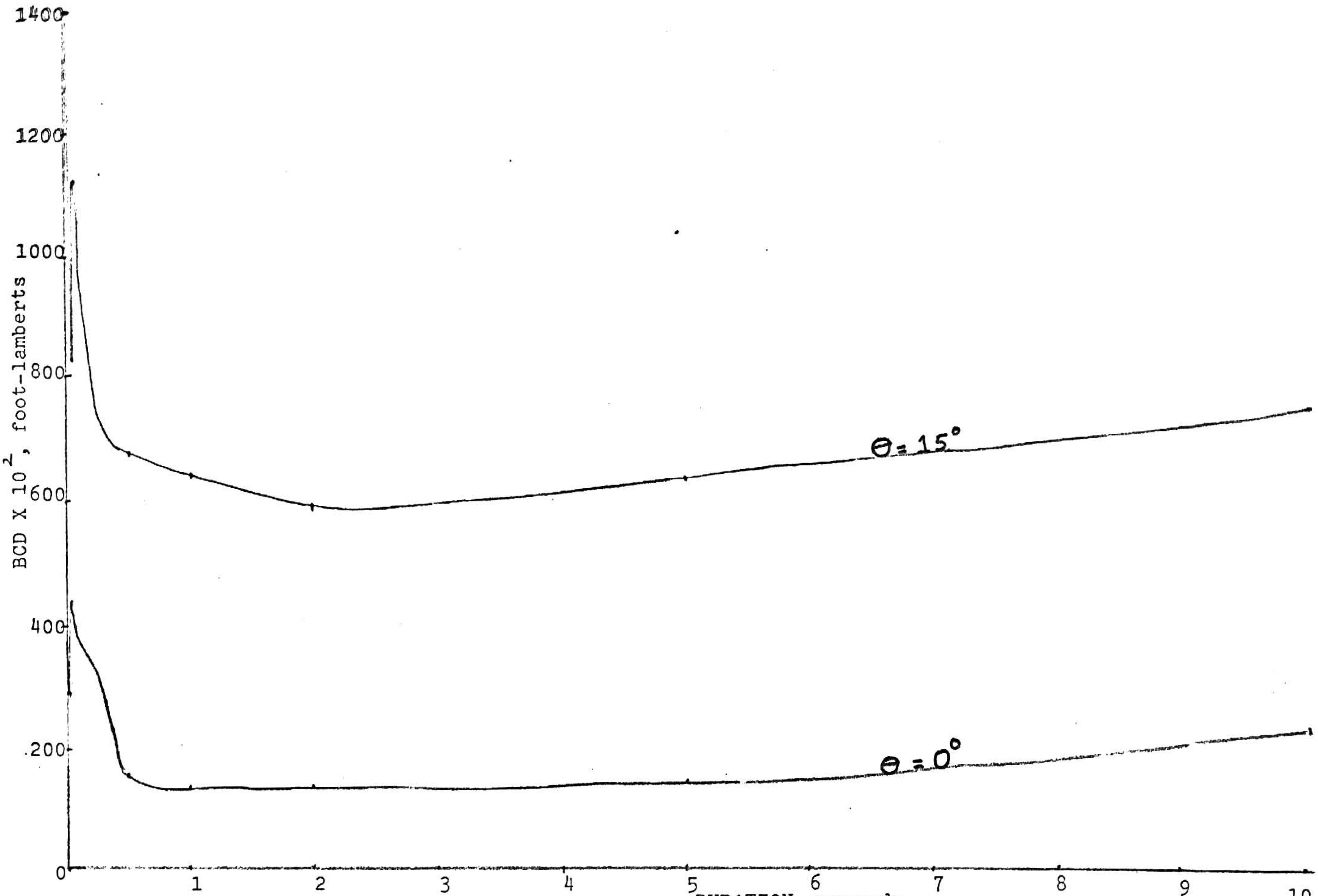

Figure 7. Plot of BCD (means) vs. duration

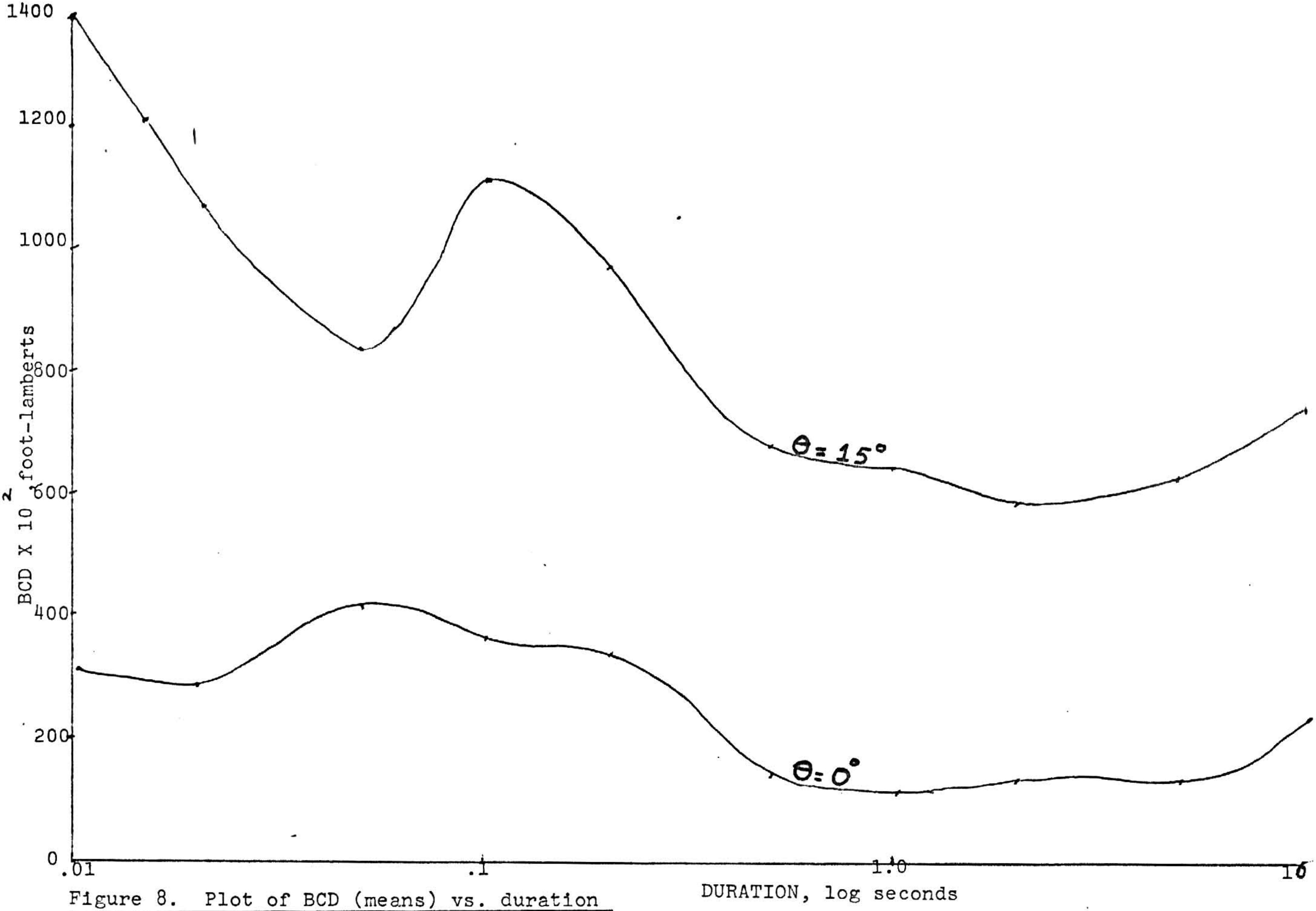

Figure 8. Plot of BCD (means) vs. duration

TABLE 3

Analysis of Variance

Source	Degrees of Freedom	Mean Squares	F (calculated)	F (table) significance level= 0.01
Subjects (S)	23	9583820.	36.53	1.90
Angles (A)	1	45800511.	12.69	7.88
Durations (D)	9	1479971.	3.97	2.50
S·A·	23	3609024.	13.75	1.90
S D	207	372950.	1.42	1.39
A·D	9	525123.	2.00	2.50
Error	207	262387.		
Total	479	1041329.		

to light at different angles, regression analyses as well as the calculation of correlation coefficients were done separately for each of the two angles.

In an attempt to find a model which would explain the variation of BCD with "on" time, the data was first fitted to an equation of the form:

$$BCD(\text{foot-lamberts}) = A_0+A_1\ t+A_2\ t^2+A_3\ t^3$$

where t is the duration in seconds, and A_0, A_1, A_2, A_3 are empirical constants.

This regression analysis yielded an "R^2" value of 0.0187 where

$$R^2 = \frac{\text{regression sum of squares}}{\text{total sum of squares}}$$

The estimated value of significance level was 21.6%.

This model was clearly inadequate.

In an attempt to get a better fit, a segmented lines program developed in the Statistical Laboratory at Kansas State University was utilized. Essentially, the program divided the BCD-duration curve into segments and fitted each segment with a separate linear equation. The results are summarized in Tables 4 and 5.

As shown in Tables 4 and 5 all the "R^2" values are extremely small. Increasing the number of segments into which the BCD-duration curve is divided into does not improve the goodness of fit appreciably.

TABLE 4

Regression Analysis Using the "Segmented Lines Program"; angle = 0^{o}.

No. of lines	R^2	Join Points	Linear Equations for BCD x 10^2 (foot-lamberts)
1	0.0035		272.987 - 11.855 (duration)*
2	0.0235	0.64	370.216 - 398.653 (duration) 108.914 + 11.105 (duration)
3	0.0279	0.05 0.55	252.594 + 3394.295 (duration) 433.309 - 573.464 (duration) 108.914 + 11.105 (duration)
4	0.0282	0.05 0.50 9.30	252.594 + 3394.295 (duration) 433.309 - 574.464 (duration) 118.298 + 10.794 (duration) 35.694 + 19.679 (duration)
5	0.0289	0.02 0.04 0.53 2.00	337.339 - 2537.832 (duration) ,501.755 - 1419.435 (duration) 472.789 - 663.191 (duration) 118.298 + 10.794 (duration) 35.694 + 19.679 (duration)

*where duration is in seconds

TABLE 5

Regression Analysis Using the "Segmented Lines Program"; angle = 15°.

No. of lines	R^2	Join Points	Linear Equations for BCD x 10^2 (foot-lamberts)
1	0.0071		931.886 - 33.626 (duration)*
2	0.0320	0.57	1153.811 - 971.039 (duration) 587.708 + 16.711 (duration)
3	0.0385	0.02 0.68	1760.626 - 35057.515 (duration) 1037.294 - 647.476 (duration) 587.708 + 14.711 (duration)
4	0.0423	0.03 0.10 0.58	1760.626 - 35057.515 (duration) 538.810 + 5856.845 (duration) 1156.792 - 958.442 (duration) 587.708 + 14.711 (duration)
5	0.0426	0.03 0.10 0.50 2.00	1760.626 - 35057.515 (duration) 538.810 + 5856.845 (duration) 1156.792 - 958.442 (duration) 708.184 - 60.730 (duration) 505.108 + 24.749 (duration)

*where duration is in seconds

The reason for the extremely small values of "R^2" observed in trying to fit the data to the different models mentioned is the tremendous range of the BCD values which results in serious calculational errors of the regression and reduction of the correlation. Longley (1967) demonstrated this when there is variability among several predictors. Arthur D. Dayton of the Kansas State University Statistics Department (personal communication) feels that this same effect takes place when there is extreme variability within one predictor (in this case, BCD).

In an attempt to eliminate subject differences and thereby ascertain the overall effect of duration on BCD, regression analysis was now done on the mean BCD values.

The results of a segmented lines regression analysis are shown in Tables 6 and 7.

When the number of segments into which the curve is broken up is increased,"R^2" increases, indicating a better fit. But increasing the number of segments also increases the number of equations needed to represent the curve, since each segment needs a separate equation i.e., the greater the number of segments the curve is broken up into, the more cumbersome is the model representing the relationship between BCD and duration. Compromising between accuracy and simplicity, the model which divides the BCD-duration curve into two segments is chosen as the best of the five models shown in Tables 6 and 7,

TABLE 6

Regression analysis on Means Using the "Segmented Lines Program"; angle = 0^{o}.

No. of Lines	R^2	Join Points	Linear Equations for BCD x 10^2 (foot-lamberts)
1	0.1206		272.986 - 11.856 (duration)*
2	0.8133	0.57	370.215 - 398.651 (duration) 108.913 + 111.056 (duration)
3	0.9636	0.03 1.28	252.593 + 3394.289 (duration) 433.307 - 573.461 (duration) 108.913 + 11.106 (duration)
4	0.9737	0.03 0.10 0.58	252.593 + 3394.289 (duration) 433.307 - 573.461 (duration) 118.297 + 10.795 (duration) 35.695 + 19.679 (duration)
5	0.9171	0.03 0.10 0.50 2.00	337.336 - 2537.700 (duration) 501.754 - 1419.441 (duration) 472.788 - 663.190 (duration) 118.297 + 10.795 (duration) 35.695 + 19.679 (duration)

*where duration is in seconds

TABLE 7

Regression Analysis on Means Using the "Segmented Lines Program"; angle = 15°

No. of Lines	R^2	Join Points	Linear Equations for BCD x 10^2 (foot-lamberts)
1	0.1668		931.883 - 33.626 (duration)*
2	0.7502	0.64	1153.808 - 971.033 (duration) 587.708 + 14.711 (duration)
3	0.9033	0.05 0.55	1760.630 - 35057.994 (duration) 1037.292 - 647.474 (duration) 587.708 + 14.712 (duration)
4	0.9911	0.05 0.50 9.30	1760.630 - 35057.994 (duration) 538.814 + 5856.763 (duration) 1156.790 - 958.440 (duration) 587.708 + 14.711 (duration)
5	0.9974	0.02 0.04 0.53 2.00	1760.630 - 35057.994 (duration) 538.814 + 5856.764 (duration) 1156.791 - 958.440 (duration) 708.183 - 60.730 (duration) 505.108 + 24.750 (duration)

*where duration is in seconds

for both the angles. Details of results obtained with the two segment regression analysis are shown in Table 8 (angle $=0^{\circ}$) and Table 9 (angle = 15°).

Regression analysis was done on the mean BCD values using polynomial models. The results are summarized in Tables 10 and 11.

A comparison of the "R^2" values in Tables 10 and 11 indicates that the best fit for both angles was obtained when the mean values of BCD were fitted to the equation:

$$BCD = A_0 + A_1 \text{ (duration) } + A_2 \text{ (duration)}^{\frac{1}{2}} + A_3 \text{(duration)}^{\frac{1}{4}}$$

The detailed results of the analysis with the above model are given in Tables 12 and 13.

Subject Effects

The subjects were now incorporated as dummy variables into a regression analysis of the raw data. The model was of the form:

$$BCD \text{ (foot-lamberts)} = A_0 + A_1 d + B_1 C + B_2 D + --- B_{24} Z$$

where A_0, A_1, B_1, B_2 - - - B_{24} are empirical constants

d is duration in seconds

C, D, - - Z are the subjects

This analysis yielded an "R^2" value of 0.5701. The estimated value of significance level was 0.0%. This "R^2" value is relatively much higher than the "R^2" value of 0.0187 obtained with the model:

TABLE 8

Regression Analysis on Means Using the "Segmented Lines Program"; angle = 0°, segments = 2.

95% confidence limits

Line	Coefficient	Lower Limit	Estimate	Upper Limit	Linear Equation
1	Intercept	301.079	370.215	439.351	BCD=370.215-398.651 (duration)
	Slope	-706.301	-398.651	-91.000	
2	Intercept	4.419	108.913	213.408	BCD=108.913+11.106 (duration)
	Slope	7.224	11.106	29.435	

Join Point	Lower Limit	Estimate	Upper Limit
1	0.183	0.683	1.092

$R^2 = 0.8133$

TABLE 9

Regression Analysis on means Using the "Segmented Lines Program"; angle = 15°, segments = 2.

95% confidence limits

Line	Coefficient	Lower Limit	Estimate	Upper Limit	Linear Equation
1	Intercept	461.005	1153.808	1346.610	BCD=1153.808-971.033 (duration)
	Slope	-1828.992	-971.033	-113.074	
2	Intercept	296.299	587.708	879.116	BCD=587.708+14.712 (duration)
	Slope	-36.405	14.712	65.828	

Join Point	Lower Limit	Estimate	Upper Limit
1	0.090	0.574	1.059

$R^2 = 0.7502$

TABLE 10

Regression Analysis on Means Using Different Models; angle = 0^{o}.

Model: Equation for BCD x 10^2 (foot-lamberts)	A_0	A_1	A_2	A_3	R^2
$A_0 + A_1 t + A_2 t^2$ *	312.960	-91.930	8.535	-----	0.5241
$A_0 + A_1 t + A_2 t^2 + A_3 t^3$	343.955	-225.077	52.716	-3.133	0.7085
$A_0 + A_1 t + A_2 t^{\frac{1}{2}} + A_3 t^{\frac{1}{4}}$	276.019	126.205	-640.874	414.990	0.7202

*where t is duration in seconds

TABLE 11

Regression Analysis for Means Using Different Models; angle = 15^{o}.

Model: Equation for BCD x 10^2 (foot-lambert)	A_0	A_1	A_2	A_3	R^2
$A_0 + A_1 t + A_2 t^2$ *	1015.444	-201.013	17.840	-----	0.4702
$A_0 + A_1 t + A_2 t^2 + A_3 t^3$	1092.738	-532.691	127.902	-7.805	0.6671
$A_0 + A_1 t + A_2 t^{\frac{1}{2}} + A_3 t^{\frac{1}{4}}$	1775.844	-5.154	738.818	-1859.692	0.7980

*where t is duration in seconds

TABLE 12

Regression Analysis on means;

model used: $BCD = A_0 + A_1(\text{duration}) + A_2 (\text{duration})^{\frac{1}{2}} + A_3 (\text{duration})^{\frac{1}{4}}$

$\times 10^2$
(foot lamberts)

angle = 0°

Parameters	Estimate	Standard Deviation	Alpha Hat
A_0	276.019	201.985	.223
A_1	126.205	76.082	.152
A_2	-640.874	541.297	.283
A_3	414.990	671.187	.560

$R^2 = 0.7202$

TABLE 13

Regression Analysis on Means

Model Used: $BCD \times 10^2$ (foot-lamberts) $= A_0 + A_1 \text{ (duration)} + A_2 \text{ (duration)}^{\frac{1}{2}} + A_3 \text{ (duration)}^{\frac{1}{4}}$;

angle = 15^o

Parameters	Estimate	Standard Deviation	Alpha Hat
A_0	1775.844	413.745	.010
A_1	-5.154	155.846	.975
A_2	738.818	1108.790	.531
A_3	-1859.692	1374.857	.227

$R^2 = 0.7980$

$$BCD\ (\text{foot-lamberts}) = A_0 + A_1 d + A_2 d^2 + A_3 d^3$$

This indicates that most of the variation between subjects (and the analysis of variance indicated a considerable variation between subjects) is due to reliable subject differences.

In attempting to explain these differences, correlation coefficients relating BCD to sex, eye color and residential population of the subjects, were computed. Since 23 of the 24 observers were in the age group 19-29 years, a somewhat narrow range, the correlation coefficient relating BCD to age was not computed. The results are presented in Table 14, as are also the results of Bennett's (1976) study for comparison.

As Table 14 shows, none of the correlations are significant when the light is at the horizontal line of sight (0°). At 15°, a correlation of -0.44 between BCD and eye color indicates that blue/green-eyed observers were more resistant to discomfort glare (obtained higher BCD values) than brown-eyed observers. This is in conflict with Bennett's (1976) conclusion (see Table 8) that brown-eyed observers are more resistant to discomfort glare. The level at which these results are significant is the same in both cases, viz, 0.05. The other two correlation coefficients computed at 15° were non-significant.

TABLE 14

Correlations and Related Data

Parameter	Eye Color		Residential Population		Sex	
Type of coefficient	point biscrial		serial		point biscrial	
Present Study:	0°	15°	0°	15°	0°	15°
Correlation	-0.24	-0.44	-0.14	-0.07	-0.03	0.22
Significance	non-significant	0.05	non-significant	non-significant	non-significant	non-significant
Sample size	24	24	24	24	24	24
Bennett's Study:	0°		0°		0°	
Correlation	0.16		-0.04		0.09	
Significance	0.05		non-significant		non-significant	
Sample size	199		199		160	

DISCUSSION

It has been seen (Tables 10 and 11) that the best fit (largest "R^2") for both angles, using a single equation over the entire range of duration was obtained when the mean of BCD were fitted to the equation:

$$BCD = A_0 + A_1 \text{ (duration)} + A_2 \text{ (duration)}^{\frac{1}{2}} + A_3 \text{ (duration)}^{\frac{1}{4}}$$

Tables 12 and 13 contain the detailed results of the analysis with this model. Those results are used to plot BCD versus duration as represented by the above model (Figure 9). Crosses represent actual mean BCD values.

It has also been seen that when a segmented lines regression analysis was carried out on the means, the best fit (taking both the "R^2" value and the number of segments into account) for both angles was when the BCD-duration curve was divided into two segments (Tables 6 and 7). Tables 8 and 9 contain the detailed results. These results are used to plot BCD versus duration for the two angles (Figure 10). Crosses represent actual mean BCD values.

Figures 9 and 10 indicate that the overall effect on BCD of increasing duration is as was hypothesized. As duration increases, BCD decreases, reaches a minimum, then decreases.

A comparison of Figure 10 with Figure 1 indicates a certain similarity between the behavior of BCD and that of threshold luminance with increasing duration. Over a certain range of duration, the function is linear in both cases. This indicates

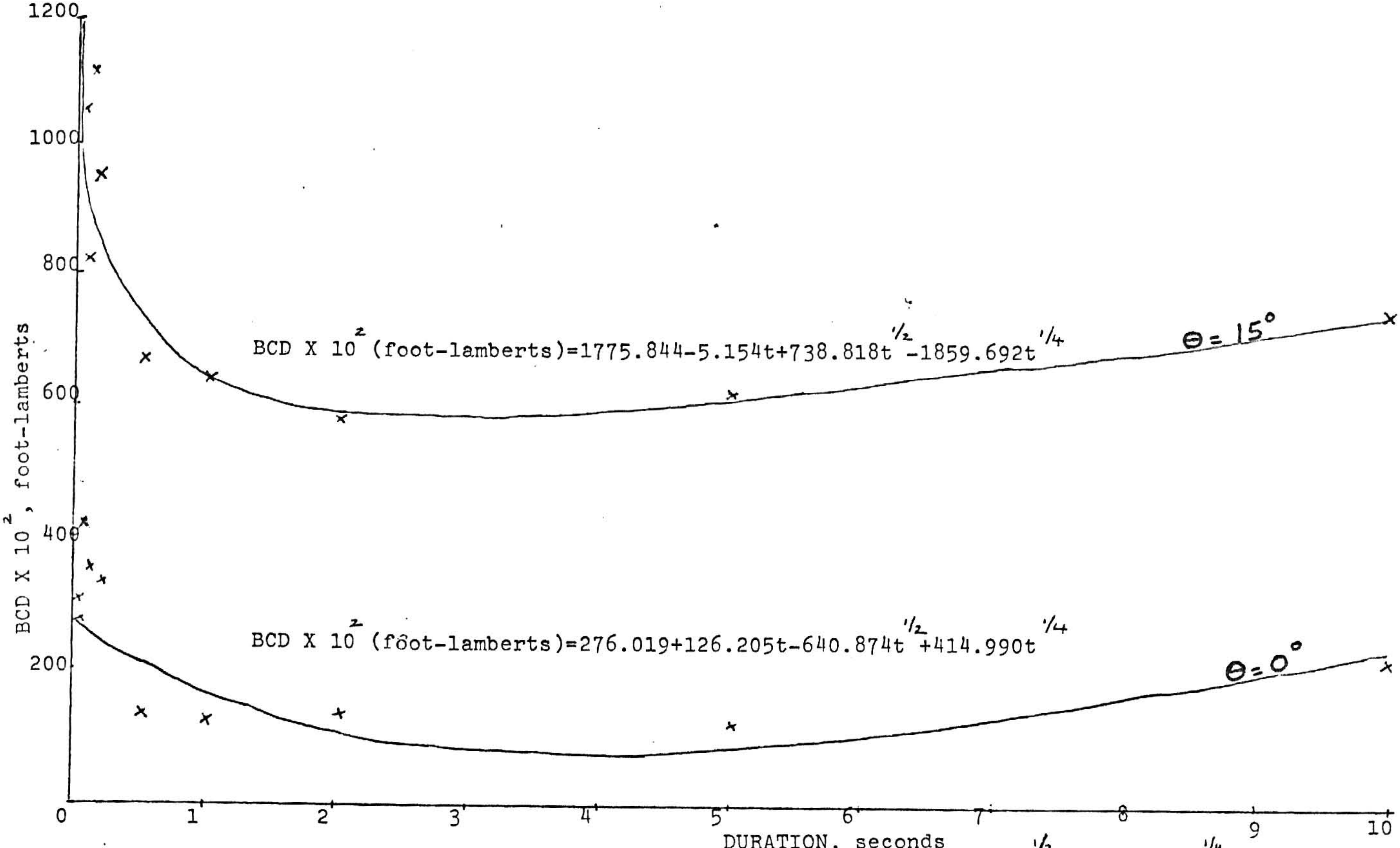

Figure 9. BCD-duration curves for model: $BCD=A_0+A_1(\text{duration})+A_2(\text{duration})^{1/2}+A_3(\text{duration})^{1/4}$.

X's represent actual mean values.

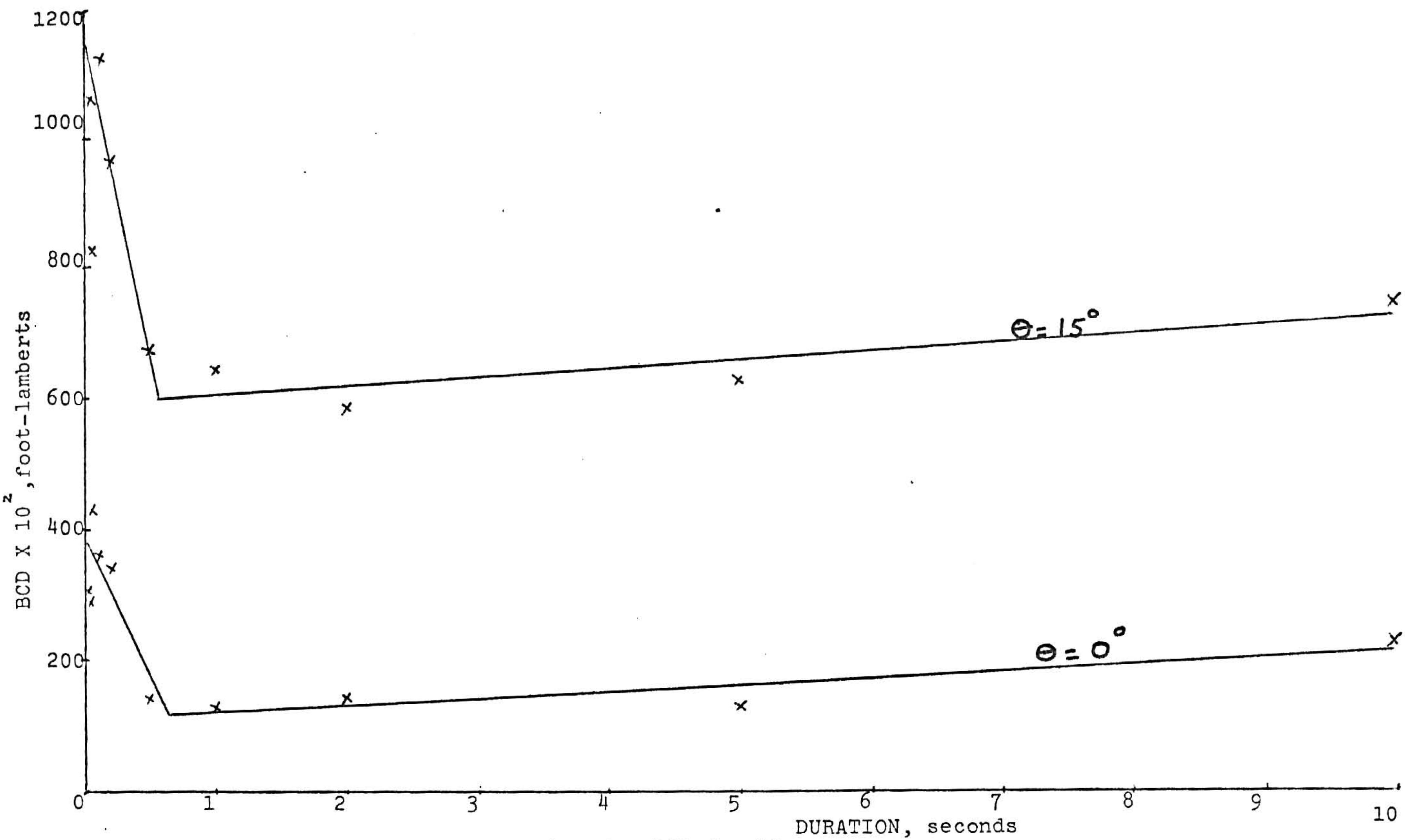

Figure 10. Segmented lines regression for BCD-duration.

No. of segments=2; X's represent actual mean values.

that BCD (like threshold luminance and estimated brightness) more or less obeys Bloch's Law in that for a certain range of durations the relationship between BCD and duration can be represented by:

BCD x duration = a constant.

The two important aspects in which Figures 1 and 10 differ are:

1. The critical duration for threshold luminance (Figure 1) is 0.1 second. For BCD (Figure 10) it is approximately 0.6 second for both angles.
2. At durations greater than the critical duration, threshold luminance is independent of duration (Figure 1). BCD however shows an increase with duration at durations greater than the critical duration (Figure 10).

It is interesting to note that for both angles (Figure 10) the magnitude of the critical duration is approximately the same, viz. 0.6 second. If this were not so, it would indicate that for BCD, no critical duration existed and Bloch's Law would not apply to BCD.

For the functions shown in Figure 9 however, the BCD-duration curve reaches a minimum at a duration of four seconds (angle = 0^{o}) and three seconds (angle = 15^{o}). These results which are got by differentiating the functions can be verified from Figure 9. Through the BCD-duration curve reaches a minimum at approximately the same value of duration for both angles, these critical durations (four seconds for 0^{o} and three seconds for 15^{o}) differ markedly from the critical durations obtained with the two segment regression (approximately 0.6 second for both angles).

The reason for the increase in BCD with increasing duration for durations greater than the critical duration may be because the eye has sufficient time to partially adapt itself to the glare at the larger durations and consequently finds it less uncomfortable than when the light is on for a relatively shorter duration. Also, if the larger durations (viz. 5 seconds and 10 seconds) are considered to approximate a continuous exposure, the rise of the curve validates Hopkinson and Collins' (1970) contention that momentary and continuous exposure to a glare source evoke different responses. From Tables 8 and 9 it should be noted that the control limits (95% confidence level) on the slope of the BCD curve for durations greater than the critical duration encompass a wide range and that for 15^{o}, a slope of zero (BCD independent of duration) is between the lower and upper limits. If Bloch's Law is to apply to BCD, the slope of the second segment should be zero.

In order to show the initial portion of the curve more clearly, Figure 7 was reproduced but with duration on a log scale (Figure 8). The inconsistency of the curve for durations less than 0.1 second (falls, then rises, then falls for 0^{o};

falls and rises for 15°) is clearly shown. One possibility for this inconsistency is that the duration for which the light is on was so small that it did not give the observer the opportunity to make a reasonably good judgment. Some subjects even volunteered that they were unsure of their judgments at durations of 0.01 and 0.02 second.

The analysis of variance (Table 3) indicated a significant variation among subjects. A regression analysis with subjects as dummy variables indicated that this variation (which was considerable) was due to reliable subject differences. Correlation coefficients relating BCD to sex, eye color and residential population of the subjects were computed in an attempt to explain this variation. The only correlation that was significant (see Table 14) was that for eye color (blue/green-eyed observers more resistant to discomfort glare than brown-eyed observers) at 15°. This correlation only partially explains the considerable variation among subjects. In large part, the variation is due to the different subjective criteria that observers base their judgments upon.

From Figure 9 (or Figure 10) it can be concluded that there is a certain duration which produces greater discomfort than durations greater than or less than it. Results of the pilot study done by Gupta and Ahmed (1975) indicated that the critical duration was in the range one to ten seconds, when the glare source was presented at an angle of 15^{o} above the horizontal line of sight. Since no data was collected in this range, it was difficult to pinpoint the critical duration more precisely. The two segment regression analysis indicated that the critical duration was approximately 0.6 second for both angles (Table 8 and 9) whereas the function

$$BCD = A_0 + A_1 \text{ (duration)} + A_2 \text{ (duration)}^{\frac{1}{2}} + A_3 \text{ (duration)}^{\frac{1}{4}}$$

(where A_0, A_1, A_2, A_3 evaluated by regression analysis are empirical constants) upon differentation gave a minimum BCD at a duration of approximately four seconds for 0^{o} and three seconds for 15^{o}.

A comparison of the two curves in Figure 8 seems to indicate that the effect of varying durations affects BCD differently for the different angles at which the glare source is presented. However, the analysis of variance (Table 3) shows that the "F" value for the interaction of angle and duration is not significant at the 1% level. From this it can be concluded that though the angle at which a glare source is presented affects the magnitude of the BCD, which accounts for the fact that the BCD-duration curve for 15^{o} is at a higher level than that for 0^{o} (see Figures 9 and 10), the manner in which BCD varies with duration is the same for both angles. Putnam and Gillmore (1957) also arrived at the conclusion that the angle at which a glare source is presented affects the magnitude of BCD, the higher the light is above the horizontal line of sight, the greater is the BCD.

As mentioned earlier, a study of Fry and Allen (1952) indicated that the magnitude of pupillary constriction produced by a 1.12° patch of constant luminance is the same when the patch is at acting at different angles, ranging from 0° to 20°. There has been some speculation (Fugate and Fry, 1956) as to the usefulness of pupillary constriction as an index of discomfort glare. The fact that BCD does depend on the angle at which the glare source is presented (BCD higher for an angle of 15° than for an angle of 0°), considered in conjunction with Fry and Allen's (1952) conclusion seems to indicate that pupillary constriction, per se, cannot be used as an index of discomfort glare.

CONCLUSION

As duration increases, BCD decreases, reaches a minimum, then increases. This is true when the glare source is placed along the horizontal line of sight as well as when it is 15° above the line of sight.

There is evidence to believe that the effect of increasing duration on BCD for durations less than a critical duration is similar to Bloch's Law. This critical duration for BCD is much higher than the critical durations for other visual functions (like "threshold luminance" and "estimated brightness") which obey Bloch's Law.

The angle at which a glare source is presented affects the degree of discomfort it produces in an observer.

Though there is considerable variation among subjects, the basis for the different responses of different people is unknown.

Pupillary constriction, per se, cannot be used as an index of discomfort glare.

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APPENDIX

APPENDIX A

Raw data

ON THE FOLLOWING PAGES, THE INFORMATION BELOW THE WORDS "SUBJECT NO." WAS REMOVED BY THE CUSTOMER LEAVING SPECKLED REMAINS OF THE ORIGINAL TEXT.

THIS IS AS RECEIVED FROM THE CUSTOMER.

DATA TABLE

Subject no. 1

duration(s.)	BCD*10^3 (foot-lamberts) θ=0°		θ=15°	
		mean		mean
0.01	1. 0.1272 2. 0.2862	0.2067	1. 3.3970 2. 2.0540	2.7255
0.02	1. 0.5300 2. 0.1272	0.3286	1. 3.7130 2. 5.2140	4.4635
0.05	1. 0.2120 2. 0.5432	0.3776	1. 6.6360 2. 7.1100	6.8730
0.10	1. 0.3498 2. 0.4558	0.4028	1. 2.6860 2. 1.7380	2.2120
0.20	1. 0.4558 2. 0.5035	0.4797	1. 2.4490 2. 4.2660	3.3375
0.50	1. 0.5830 2. 0.3498	0.4664	1. 1.7380 2. 1.3430	1.5405
1.00	1. 0.2120 2. 0.2650	0.2385	1. 1.8960 2. 1.3430	1.6195
2.00	1. 0.2650 2. 0.1749	0.2200	1. 2.4490 2. 1.5010	1.9750
5.00	1. 0.1749 2. 0.2862	0.2306	1. 3.0740 2. 2.0670	2.5705
10.00	1. 0.1590 2. 0.0901	0.1246	1. 1.3430 2. 2.4490	1.8960

DATA TABLE

Subject no. 2

duration(s.)	BCD*10^3 (foot-lamberts)			
	$\theta=0^\circ$		$\theta=15^\circ$	
		mean		mean
0.01	1. 6.3990 2. 3.1600	4.7795	1. 25.2800 2. 37.1300	31.2050
0.02	1. 32.3900 2. 28.4400	30.4150	1. 3.3970 2. 7.4260	5.4115
0.05	1. 3.3970 2. 2.3700	2.8835	1. 8.6900 2. 3.3970	6.0435
0.10	1. 7.9000 2. 5.6090	6.7545	1. 5.8460 2. 5.8460	5.8460
0.20	1. 6.3990 2. 9.4800	7.9395	1. 3.1600 2. 6.3200	7.6630
0.50	1. 4.2660 2. 3.3970	3.8315	1. 3.3970 2. 4.2660	3.8315
1.00	1. 2.3700 2. 2.6070	2.4885	1. 4.8980 2. 3.9500	4.4240
2.00	1. 2.6070 2. 1.7380	2.1725	1. 4.5820 2. 5.2140	4.8980
5.00	1. 1.7380 2. 3.3970	2.5675	1. 10.2700 2. 7.1100	8.6900
10.00	1. 5.6090 2. 4.8980	5.2535	1. 3.9500 2. 4.5820	4.2660

DATA TABLE

Subject no. 3

duration(s.)	BCD*10³ (foot-lamberts) θ=0°		θ=15°	
		mean		mean
0.01	1. 23.7000 2. 25.2800	24.4900	1. 29.2300 2. 31.6000	30.4150
0.02	1. 9.8750 2. 12.6400	11.2575	1. 15.0100 2. 18.9600	16.9850
0.05	1. 16.5900 2. 18.1700	17.3800	1. 14.2200 2. 19.7500	16.9850
0.10	1. 16.5900 2. 15.8000	16.1950	1. 22.9100 2. 27.6500	25.2800
0.20	1. 15.8000 2. 15.0100	15.4050	1. 15.0100 2. 8.6900	11.8500
0.50	1. 12.2450 2. 12.2450	12.2450	1. 6.6360 2. 9.4800	8.0580
1.00	1. 14.2200 2. 9.0850	11.6525	1. 7.9000 2. 10.2700	9.0850
2.00	1. 21.3300 2. 18.1700	19.7500	1. 7.4260 2. 7.1100	7.2680
5.00	1. 11.0600 2. 9.4800	10.2700	1. 12.2450 2. 11.8500	12.0475
10.00	1. 14.2200 2. 12.2450	13.2325	1. 7.9000 2. 7.1100	7.5050

DATA TABLE

Subject no. 4

duration(s.)	BCD*10^3 (foot-lamberts)			
	θ=0°		θ=15°	
		mean		mean
0.01	1. 25.2800 2. 37.1300	31.2050	1. 10.2700 2. 16.5900	13.4300
0.02	1. 34.7600 2. 34.7600	34.7600	1. 9.4800 2. 6.9520	8.2160
0.05	1. 33.1800 2. 32.3900	32.7850	1. 15.0100 2. 12.6400	13.8250
0.10	1. 34.7600 2. 37.9200	36.3400	1. 22.9100 2. 25.2800	24.0950
0.20	1. 35.5500 2. 35.5500	35.5500	1. 13.4300 2. 14.2200	13.8250
0.50	1. 30.0200 2. 41.0800	35.5500	1. 24.4900 2. 33.1800	28.8350
1.00	1. 19.7500 2. 30.0200	24.8850	1. 15.0100 2. 15.0100	15.0100
2.00	1. 26.0700 2. 37.9200	31.9950	1. 26.0700 2. 26.0700	26.0700
5.00	1. 21.3300 2. 41.0800	31.2050	1. 27.6500 2. 26.0700	26.8600
10.00	1. 35.5500 2. 35.5500	35.5500	1. 28.4400 2. 30.8100	29.6250

DATA TABLE

Subject no. 5

duration(s.)	BCD*10^3 (foot-lamberts)			
	$\theta=0°$		$\theta=15°$	
		mean		mean
0.01	1. 470.0000 2. 240.0000	355.0000	1. 620.0000 2. 480.0000	550.0000
0.02	1. 43.0000 2. 94.0000	68.5000	1. 440.0000 2. 320.0000	380.0000
0.05	1. 360.0000 2. 440.0000	400.0000	1. 33.1800 2. 31.6000	32.3900
0.10	1. 640.0000 2. 480.0000	560.0000	1. 520.0000 2. 320.0000	420.0000
0.20	1. 330.0000 2. 200.0000	265.0000	1. 260.0000 2. 270.0000	265.0000
0.50	1. 94.0000 2. 113.0000	103.5000	1. 210.0000 2. 140.0000	175.0000
1.00	1. 62.0000 2. 72.0000	67.0000	1. 112.0000 2. 190.0000	146.0000
2.00	1. 128.0000 2. 72.0000	100.0000	1. 127.0000 2. 190.0000	158.5000
5.00	1. 100.0000 2. 120.0000	110.0000	1. 94.0000 2. 80.0000	87.0000
10.00	1. 240.0000 2. 160.0000	200.0000	1. 360.0000 2. 350.0000	355.0000

DATA TABLE

Subject no. 6

duration(s.)	BCD*10³ (foot-lamberts)			
	θ=0°		θ=15°	
		mean		mean
0.01	1. 0.0070 2. 0.0078	0.0074	1. 0.0085 2. 0.0060	0.0073
0.02	1. 0.0085 2. 0.0070	0.0078	1. 0.0075 2. 0.0075	0.0075
0.05	1. 0.0270 2. 0.0390	0.0330	1. 0.0105 2. 0.0060	0.0083
0.10	1. 0.0083 2. 0.0180	0.0117	1. 0.0070 2. 0.0070	0.0070
0.20	1. 0.0083 2. 0.0180	0.0132	1. 0.0070 2. 0.0070	0.0070
0.50	1. 0.0850 2. 0.0785	0.0818	1. 0.0140 2. 0.0085	.0113
1.00	1. 0.0565 2. 0.0750	0.0658	1. 0.0140 2. 0.0085	0.0113
2.00	1. 0.0150 2. 0.0085	0.0118	1. 0.0120 2. 0.0085	0.0103
5.00	1. 0.1000 2. 0.1150	0.1075	1. 0.0085 2. 0.0070	0.0078
10.00	1. 0.0500 2. 0.0390	0.0445	1. 0.0075 2. 0.0330	0.0203

DATA TABLE

Subject no. 7

duration(s.)	BCD*10^{3} (foot-lamberts)			
	θ=0°		θ=15°	
		mean		mean
0.01	1. 6.4780 2. 9.0850	7.7815	1. 3.9500 2. 4.5820	4.1600
0.02	1. 14.2200 2. 30.8100	22.5150	1. 3.1600 2. 4.5820	3.8710
0.05	1. 2.9680 2. 1.5010	2.2345	1. 6.3200 2. 4.2660	5.2930
0.10	1. 4.2660 2. 6.1620	5.2140	1. 3.3970 2. 3.6340	3.5160
0.20	1. 1.7490 2. 1.7490	1.7490	1. 3.6340 2. 3.3970	3.5160
0.50	1. 0.6095 2. 1.8550	1.2323	1. 2.6860 2. 3.1600	2.9230
1.00	1. 2.3700 2. 3.1600	2.7650	1. 1.1850 2. 2.0540	1.6195
2.00	1. 3.1600 2. 4.2660	3.7130	1. 3.6340 2. 3.6340	3.6340
5.00	1. 1.6430 2. 1.9875	1.8156	1. 3.1606 2. 2.9230	3.0418
10.00	1. 3.6340 2. 3.6340	3.6340	1. 3.1606 2. 5.2140	4.1873

DATA TABLE

Subject no. 8

duration(s.)	BCD*10^3 (foot-lamberts)			
	θ=0°		θ=15°	
		mean		mean
0.01	1. 9.4800 2. 14.2200	11.8500	1. 50.0000 2. 31.0000	40.5000
0.02	1. 14.2200 2. 11.0600	12.6400	1. 62.0000 2. 62.0000	62.0000
0.05	1. 19.7500 2. 16.5900	18.1700	1. 117.0000 2. 310.0000	213.5000
0.10	1. 6.1620 2. 14.2200	10.1910	1. 90.0000 2. 125.0000	107.5000
0.20	1. 9.8750 2. 5.6880	7.7815	1. 100.0000 2. 100.0000	100.0000
0.50	1. 7.5840 2. 9.2430	8.4135	1. 66.0000 2. 46.0000	56.0000
1.00	1. 5.2140 2. 7.5840	6.3990	1. 46.0000 2. 31.0000	38.5000
2.00	1. 4.8980 2. 2.8440	3.8710	1. 66.0000 2. 74.0000	70.0000
5.00	1. 14.2200 2. 15.8000	15.0100	1. 94.0000 2. 46.0000	70.0000
10.00	1. 22.1200 2. 17.3800	19.7500	1. 70.0000 2. 80.0000	75.0000

DATA TABLE

Subject no. 9

duration(s.)	BCD*10^3 (foot-lamberts) $\theta=0^\circ$	$\theta=0^\circ$ mean	$\theta=15^\circ$	$\theta=15^\circ$ mean
0.01	1. 15.8000 2. 15.8000	15.8000	1. 220.0000 2. 200.0000	210.0000
0.02	1. 16.5900 2. 16.5900	16.5900	1. 270.0000 2. 210.0000	240.0000
0.05	1. 14.2200 2. 12.6400	13.4300	1. 155.0000 2. 260.0000	207.5000
0.10	1. 11.8500 2. 15.8000	13.8250	1. 260.0000 2. 160.0000	210.0000
0.20	1. 22.9100 2. 16.5900	19.7500	1. 190.0000 2. 240.0000	215.0000
0.50	1. 15.0100 2. 7.4260	11.2180	1. 150.0000 2. 140.0000	145.0000
1.00	1. 7.0310 2. 4.2660	5.6485	1. 290.0000 2. 150.0000	220.0000
2.00	1. 28.4400 2. 30.8100	29.6250	1. 94.0000 2. 74.0000	84.0000
5.00	1. 15.0100 2. 8.6900	11.8500	1. 58.0000 2. 100.0000	79.0000
10.00	1. 12.2450 2. 10.2700	11.2575	1. 50.0000 2. 100.0000	75.0000

DATA TABLE

Subject no. 10

duration(s.)	BCD*10^3 (foot-lamberts) θ=0°	mean	θ=15°	mean
0.01	1. 1.2720 2. 1.1130	1.1925	1. 1.3430 2. 3.3970	2.3700
0.02	1. 0.8480 2. 1.1130	0.9805	1. 4.5820 2. 3.3970	3.7535
0.05	1. 0.9540 2. 1.4310	1.1925	1. 2.4490 2. 1.6590	2.8045
0.10	1. 1.5370 2. 1.4310	1.4840	1. 1.8960 2. 1.6590	1.7775
0.20	1. 1.5370 2. 0.9010	1.2190	1. 5.2140 2. 3.3970	4.3055
0.50	1. 0.9540 2. 1.2720	1.1130	1. 0.9480 2. 1.0665	1.0073
1.00	1. 1.0070 2. 0.6890	0.8480	1. 2.6860 2. 4.2660	3.4760
2.00	1. 1.2720 2. 1.2190	1.2455	1. 3.9500 2. 3.3970	3.6735
5.00	1. 0.9540 2. 1.4310	1.1925	1. 5.5300 2. 5.2140	5.3720
10.00	1. 0.9010 2. 1.3780	1.1395	1. 5.5300 2. 9.8750	7.7025

DATA TABLE

Subject no. 11

duration(s.)	BCD*10^3 (foot-lamberts) θ=0°		θ=15°	
		mean		mean
0.01	1. 1.5370 2. 2.2260	1.8815	1. 105.0000 2. 125.0000	115.0000
0.02	1. 2.4910 2. 2.5970	2.5440	1. 54.0000 2. 50.0000	52.0000
0.05	1. 2.1465 2. 2.7560	2.4513	1. 130.0000 2. 100.0000	115.0000
0.10	1. 2.5705 2. 3.0210	2.7958	1. 46.0000 2. 84.0000	65.0000
0.20	1. 1.9875 2. 2.0670	2.0273	1. 74.0000 2. 94.0000	84.0000
0.50	1. 1.7490 2. 2.3850	2.0670	1. 40.0000 2. 54.0000	47.0000
1.00	1. 2.3850 2. 2.6500	2.5175	1. 40.0000 2. 54.0000	47.0000
2.00	1. 2.9150 2. 3.3920	3.1535	1. 120.0000 2. 70.0000	95.0000
5.00	1. 2.5705 2. 1.8550	2.2128	1. 50.0000 2. 54.0000	52.0000
10.00	1. 3.3920 2. 2.6500	3.0210	1. 58.0000 2. 100.0000	79.0000

DATA TABLE

Subject no. 12

duration(s.)	BCD*10³ (foot-lamberts)			
	θ=0°		θ=15°	
		mean		mean
0.01	1. 1.5900 2. 1.4840	1.5370	1. 12.2450 2. 11.0600	11.6525
0.02	1. 1.1130 2. 1.5370	1.3259	1. 38.7100 2. 21.3300	30.0200
0.05	1. 2.0670 2. 2.5970	2.3320	1. 12.2450 2. 31.6000	21.9225
0.10	1. 2.6500 2. 1.3780	2.0140	1. 2.6860 2. 4.8980	4.8980
0.20	1. 2.8620 2. 1.5900	2.2260	1. 37.1300 2. 48.9800	43.0550
0.50	1. 1.3780 2. 1.0600	1.2190	1. 26.0700 2. 10.2700	18.1700
1.00	1. 2.6500 2. 1.0070	1.8285	1. 24.4900 2. 35.5500	30.0200
2.00	1. 0.8215 2. 0.7950	0.8083	1. 13.4300 2. 16.5900	15.0100
5.00	1. 2.1730 2. 1.5370	1.8550	1. 15.0100 2. 4.2660	9.6380
10.00	1. 1.9875 2. 1.4840	1.7358	1. 5.5300 2. 9.0850	7.3075

DATA TABLE

Subject no. 13

duration(s.)	BCD*10³ (foot-lamberts) θ=0°		θ=15°	
		mean		mean
0.01	1. 0.9540 2. 0.6095	0.7818	1. 46.5000 2. 58.0000	52.2500
0.02	1. 0.1166 2. 0.1590	0.1378	1. 3.6735 2. 2.2120	2.9428
0.05	1. 0.5088 2. 0.6625	0.5857	1. 3.6735 2. 3.3970	3.5353
0.10	1. 0.6095 2. 0.9010	0.7553	1. 2.2120 2. 3.6735	2.9428
0.20	1. 0.2650 2. 0.2650	0.2650	1. 2.4490 2. 2.4490	2.4490
0.50	1. 0.5300 2. 0.2438	0.3869	1. 1.8960 2. 1.8960	1.8960
1.00	1. 0.4028 2. 0.2862	0.3445	1. 2.6860 2. 2.9230	2.8045
2.00	1. 0.2120 2. 0.3074	0.2597	1. 4.2660 2. 2.4490	3.3575
5.00	1. 0.7420 2. 1.2190	0.9805	1. 2.4490 2. 3.3970	2.9195
10.00	1. 0.3498 2. 0.3074	0.3286	1. 3.6735 2. 4.2660	3.9698

DATA TABLE

Subject no. 14

duration(s.)	BCD*10³ (foot-lamberts) θ=0°		θ=15°	
		mean		mean
0.01	1. 42.6600 2. 26.8600	34.7600	1. 230.0000 2. 400.0000	315.0000
0.02	1. 16.5900 2. 19.7500	18.1700	1. 150.0000 2. 320.0000	235.0000
0.05	1. 240.0000 2. 260.0000	250.0000	1. 250.0000 2. 310.0000	280.0000
0.10	1. 30.0200 2. 17.3800	23.7000	1. 400.0000 2. 310.0000	355.0000
0.20	1. 200.0000 2. 250.0000	225.0000	1. 230.0000 2. 230.0000	230.0000
0.50	1. 19.7500 2. 33.1800	26.4650	1. 112.0000 2. 162.0000	137.0000
1.00	1. 66.0000 2. 94.0000	80.0000	1. 90.0000 2. 100.0000	95.0000
2.00	1. 24.4900 2. 20.5400	22.5150	1. 130.0000 2. 200.0000	165.0000
5.00	1. 17.3800 2. 38.315	27.8475	1. 200.0000 2. 150.0000	175.0000
10.00	1. 125.0000 2. 190.0000	157.500	1. 120.0000 2. 150.0000	135.0000

DATA TABLE

Subject no. 15

duration(s.)	BCD*10³ (foot-lamberts) $\theta=0°$	mean	$\theta=15°$	mean
0.01	1. 3.3970 2. 9.4800	6.4385	1. 31.6000 2. 34.7600	33.1800
0.02	1. 1.5370 2. 1.9875	1.7623	1. 18.9600 2. 15.0100	16.9850
0.05	1. 1.2720 2. 0.6360	0.9540	1. 15.0100 2. 28.4400	21.7250
0.10	1. 1.5900 2. 1.4310	1.5105	1. 18.9600 2. 24.4900	21.7250
0.20	1. 1.4310 2. 2.1200	1.7755	1. 26.0700 2. 24.4900	25.2800
0.50	1. 1.3780 2. 1.8550	1.6165	1. 25.2800 2. 18.9600	22.1200
1.00	1. 2.1200 2. 2.2260	2.1730	1. 3.7130 2. 5.8460	4.7795
2.00	1. 0.5035 2. 1.1130	0.8083	1. 7.1100 2. 11.8500	9.4800
5.00	1. 1.5370 2. 1.4310	1.4840	1. 9.4800 2. 8.8480	9.1640
10.00	1. 0.8321 2. 1.6695	1.2508	1. 3.3970 2. 6.6360	5.0165

DATA TABLE

Subject no. 16

duration(s.)	BCD*10^3 (foot-lamberts) $\theta=0°$	$\theta=0°$ mean	$\theta=15°$	$\theta=15°$ mean
0.01	1. 0.0742 2. 0.0456	0.0599	1. 6.6360 2. 4.8980	5.7670
0.02	1. 0.0583 2. 0.0822	0.0703	1. 1.5010 2. 3.3970	2.4490
0.05	1. 0.0456 2. 0.0456	0.0456	1. 3.9500 2. 3.3970	3.6735
0.10	1. 0.0636 2. 0.1007	0.0822	1. 3.3970 2. 1.1850	2.2910
0.20	1. 0.0901 2. 0,0822	0.0862	1. 7.5050 2. 6.6360	7.0750
0.50	1. 0.4770 2. 1.0600	0.7685	1. 1.6590 2. 1.6590	1.6590
1.00	1. 0.0636 2. 0.0583	0.0610	1. 2.4490 2. 1.3430	1.8960
2.00	1. 0.1458 2. 0.0822	0.1140	1. 2.0540 2. 2.2120	2.1330
5.00	1. 0.1590 2. 0.1749	0.1670	1. 2.2120 2. 4.2660	3.2390
10.00	1. 0.0514 2. 0.0456	0.0485	1. 2.2120 2. 1.1060	1.6590

DATA TABLE

Subject no. 17

duration(s.)	BCD*10^3 (foot-lamberts)			
	θ=0°		θ=15°	
		mean		mean
0.01	1. 44.2400 2. 52.1400	48.1900	1. 640.0000 2. 640.0000	640.0000
0.02	1. 50.5600 2. 45.0300	47.7950	1. 340.0000 2. 340.0000	340.0000
0.05	1. 44.2400 2. 48.9800	46.6100	1. 400.0000 2. 290.0000	345.0000
0.10	1. 33.1800 2. 31.60000	32.3900	1. 450.0000 2. 530.0000	490.0000
0.20	1. 39.5000 2. 37.1300	38.3150	1. 240.0000 2. 125.0000	235.0000
0.50	1. 21.7250 2. 37.1300	29.4275	1. 140.0000 2. 125.0000	132.5000
1.00	1. 17.3800 2. 24.4900	20.9350	1. 50.0000 2. 40.0000	45.0000
2.00	1. 16.5900 2. 15.8000	16.1950	1. 80.0000 2. 90.0000	85.0000
5.00	1. 7.1100 2. 7.1100	7.1100	1. 90.0000 2. 84.0000	87.0000
10.00	1. 22.9100 2. 24.4900	27.2550	1. 58.0000 2. 70.0000	64.0000

DATA TABLE

Subject no. 18

duration(s.)	BCD*10^3 (foot-lamberts)			
	$\theta=0^\circ$		$\theta=15^\circ$	
		mean		mean
0.01	1. 18.9600 2. 10.2700	14.6150	1. 220.0000 2. 125.0000	172.0000
0.02	1. 7.9000 2. 7.5050	7.7025	1. 89.0000 2. 200.0000	144.5000
0.05	1. 7.5050 2. 11.0600	9.2825	1. 115.0000 2. 160.0000	137.5000
0.10	1. 15.0100 2. 16.5900	15.8000	1. 76.0000 2. 46.0000	61.0000
0.20	1. 17.3800 2. 10.2700	13.8250	1. 300.0000 2. 300.0000	300.0000
0.50	1. 16.5900 2. 23.7000	20.1450	1. 180.0000 2. 220.0000	200.0000
1.00	1. 11.8500 2. 9.8750	10.8625	1. 115.0000 2. 100.0000	107.5000
2.00	1. 25.6750 2. 25.6750	25.6750	1. 82.0000 2. 120.0000	101.0000
5.00	1. 20.5400 2. 23.7000	22.1200	1. 130.0000 2. 150.0000	140.0000
10.00	1. 13.4300 2. 21.3300	17.3800	1. 160.0000 2. 150.0000	155.0000

DATA TABLE

Subject no. 19

duration(s.)	BCD*10³ (foot-lamberts) θ=0°		θ=15°	
		mean		mean
0.01	1. 30.0000 2.100.0000	65.0000	1. 120.0000 2. 200.0000	160.0000
0.02	1.240.0000 2.150.0000	195.0000	1. 200.0000 2. 350.0000	275.0000
0.05	1. 89.0000 2.190.0000	139.5000	1. 112.0000 2. 130.0000	121.0000
0.10	1. 43.0000 2. 95.0000	69.0000	1. 230.0000 2. 140.0000	185.0000
0.20	1.120.0000 2.150.0000	135.0000	1. 90.0000 2. 140.0000	115.0000
0.50	1. 17.0000 2. 43.0000	30.0000	1. 112.0000 2. 140.0000	126.0000
1.00	1. 23.7000 2. 27.6500	25.6750	1. 130.0000 2. 150.0000	140.0000
2.00	1. 22.9100 2. 23.7000	23.3050	1. 50.0000 2. 74.0000	62.0000
5.00	1. 9.8750 2. 12.6400	11.2575	1. 250.0000 2. 200.0000	225.0000
10.00	1. 16.5900 2. 15.0100	15.8000	1. 120.0000 2. 128.0000	124.0000

DATA TABLE

Subject no. 20

duration(s.)	BCD*10^3 (foot-lamberts)			
	θ=0°		θ=15°	
		mean		mean
0.01	1. 6.5570 2. 2.6070	4.5820	1. 9.4800 2. 14.2200	11.8500
0.02	1. 6.0830 2. 6.0830	6.0830	1. 7.9000 2. 15.8000	11.8500
0.05	1. 1.0600 2. 0.7950	0.9275	1. 9.8750 2. 9.4800	9.6775
0.10	1. 0.2438 2. 1.1130	0.6784	1. 8.6900 2. 9.4800	9.0850
0.20	1. 0.9540 2. 0.9010	0.9275	1. 6.6360 2. 9.4800	8.0580
0.50	1. 0.8215 2. 0.9540	0.8878	1. 1.6590 2. 3.1600	2.4095
1.00	1. 0.1007 2. 0.2650	0.1829	1. 5.2140 2. 4.8980	5.0560
2.00	1. 0.9010 2. 0.2862	0.5936	1. 3.9500 2. 3.1600	3.5550
5.00	1. 0.4399 2. 0.4399	0.4399	1. 1.8960 2. 4.2660	3.0810
10.00	1. 0.8480 2. 0.4028	0.6254	1. 3.6340 2. 8.6900	6.1620

DATA TABLE

Subject no. 21

duration(s.)	BCD*10^3 (foot-lamberts)			
	θ=0°		θ=15°	
		mean		mean
0.01	1. 20.5400 2. 9.4800	15.0100	1. 330.0000 2. 375.0000	352.0000
0.02	1. 46.6100 2. 26.8600	36.7350	1. 74.0000 2. 54.0000	64.0000
0.05	1. 34.7600 2. 50.5600	42.6600	1. 66.0000 2. 92.0000	79.0000
0.10	1. 9.4800 2. 30.8100	20.1450	1. 250.0000 2. 210.0000	230.0000
0.20	1. 12.2450 2. 7.9000	10.0725	1. 160.0000 2. 240.0000	200.0000
0.50	1. 11.0600 2. 19,7500	15.4050	1. 330.0000 2. 150.0000	240.0000
1.00	1. 19.7500 2. 22.1200	20.935	1. 240.0000 2. 300.0000	270.0000
2.00	1. 12.2450 2. 6.0040	9.1245	1. 210.0000 2. 300.0000	255.0000
5.00	1. 37.1300 2. 46.6100	41.8700	1. 440.0000 2. 390.0000	415.0000
10.00	1. 11.0600 2. 30.8100	20.9350	1. 250.0000 2. 350.0000	300.0000

DATA TABLE

Subject no. 22

duration(s.)	BCD*10^3 (foot-lamberts)			
	θ=0°		θ=15°	
		mean		mean
0.01	1. 62.0000 2.110.0000	86.0000	1. 380.0000 2. 580.0000	480.0000
0.02	1.125.0000 2.210.0000	167.5000	1. 400.0000 2. 530.0000	465.0000
0.05	1. 18.9600 2. 25.6750	22.3175	1. 270.0000 2. 360.0000	315.0000
0.10	1. 42.6600 2. 35.5500	39.1050	1. 440.0000 2. 400.0000	420.0000
0.20	1. 23.7000 2. 30.8100	27.2550	1. 320.0000 2. 450.0000	385.0000
0.50	1. 10.2700 2. 7.5050	8.8875	1. 270.0000 2. 270.0000	270.0000
1.00	1. 11.8500 2. 9.8750	10.8625	1. 450.0000 2. 250.0000	350.0000
2.00	1. 22.1200 2. 18.9600	41.0800	1. 230.0000 2. 250.0000	240.0000
5.00	1. 6.1620 2. 8.6900	7.4260	1. 74.0000 2. 84.0000	79.0000
10.00	1. 3.3970 2. 12.6400	8.0185	1. 290.0000 2. 380.0000	335.0000

DATA TABLE

Subject no. 23

duration(s.)	BCD*10^3 (foot-lamberts)			
	θ=0°		θ=15°	
		mean		mean
0.01	1. 12.6400 2. 8.6900	10.6650	1. 37.0000 2. 260.0000	148.5000
0.02	1. 6.0040 2. 2.2120	4.1080	1. 155.0000 2. 200.0000	177.5000
0.05	1. 26.0700 2. 13.4300	19.7500	1. 31.0000 2. 43.0000	37.0000
0.10	1. 3.3970 2. 3.9500	3.6735	1. 37.0000 2. 46.0000	41.5000
0.20	1. 3.3970 2. 3.9500	3.6735	1. 46.0000 2. 66.0000	56.0000
0.50	1. 26.0700 2. 19.7500	22.9100	1. 11.0000 2. 9.0000	10.0000
1.00	1. 7.9000 2. 9.8750	8.8875	1. 16.5900 2. 11.8500	14.2200
2.00	1. 16.5900 2. 26.0700	21.3300	1. 7.5050 2. 14.2200	10.8625
5.00	1. 12.6400 2. 11.0600	11.8500	1. 8.2950 2. 17.3800	12.8375
10.00	1. 7.9000 2. 16.5900	12.2450	1. 24.4900 2. 37.1800	28.8350

DATA TABLE

Subject no. 24

duration(s.)	BCD*10^3 (foot-lamberts)			
	θ=0°		θ=15°	
		mean		mean
0.01	1. 9.4800 2. 4.2600	6.8730	1. 1.5010 2. 0.7110	1.1060
0.02	1. 0.9480 2. 0.7940	0.8710	1. 0.8690 2. 0.7110	0.7900
0.05	1. 9.8750 2. 6.0830	7.9790	1. 0.7110 2. 0.7110	0.7110
0.10	1. 1.7380 2. 1.2245	1.4813	1. 16.5900 2. 5.8460	11.2180
0.20	1. 0.9480 2. 1.1060	1.0270	1. 0.9480 2. 0.7110	0.8295
0.50	1. 0.9480 2. 1.1060	1.0270	1. 0.7110 2. 0.7110	0.7110
1.00	1. 3.1600 2. 1.9750	2.5675	1. 0.8690 2. 0.8690	0.8690
2.00	1. 1.2245 2. 1.1060	1.1653	1. 0.7110 2. 0.7110	0.7110
5.00	1. 0.9480 2. 0.9480	0.9480	1. 0.7110 2. 0.8690	0.7900
10.00	1. 2.1725 2. 1.5010	1.8368	1. 1.5010 2. 0.7110	1.1060

VARIATION OF DISCOMFORT GLARE WITH "ON" TIME OF GLARE SOURCE

by

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B. Tech., Indian Institute of Technology

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1976

ABSTRACT

An empirical approach was adopted to evaluate the effect that different durations of a glare source have on discomfort glare. The concept of "borderline between comfort and discomfort" or "BCD" was used as a measure of discomfort glare. Twenty-four subjects, twelve male and twelve female were asked to adjust the luminance of a light source to their BCD for twenty different experimental conditions. The experimental conditions were obtained by using the two different angles at which the glare source was placed and ten different durations for which it was "on". BCD declined with increasing duration over a certain interval (it is similar to Bloch's Law in this interval), then increased. This was true when glare source was placed along the horizontal line of sight as well as when it was 15^{o} above the line of sight. However, the degree of discomfort was greater when the light was along the line of sight. Pupillary constriction, per se, cannot be used as an index of discomfort glare.