RANGE EFFECTS IN DISCOMFORT GLARE

by

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Approved by:

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To my Parents

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INTRODUCTION

Light is the basis of life and order as opposed to darkness, chaos, disorder and death. Light is defined as a "visually evaluated radiant energy" or simply a form of energy that permits humans to see.

The "quality" of a lighting system is a description of the visual comfort and visual adequacy of the system, other than the quantity of illumination. It is a term used to describe all the factors in a lighting installation such as luminance ratios, uniformity and chromaticity. The luminances of areas in a space and the luminance ratios between them contribute favourably or unfavourably to the seeing conditions. It is often misunderstood that satisfactory quality of a lighting system can be achieved merely by providing the recommended illumination level for a particular task in a space. However, the provision of proper luminances in the entire visual field is of great importance. Thus, the ultimate goal in lighting practice is to provide luminances in the entire visual environment that would produce the most satisfactory seeing conditions. If the luminance of a part of the visual scene is too high for the state of adaptation of the eye, then the source of luminance is a glare source.

Glare

Light that produces discomfort and sometimes interference with vision is known as glare. Very high luminances or contrasts will produce glare. The glare caused by light sources in the field of vision is known as direct glare, where as the glare caused by reflection of a light source on a viewed surface is known as reflected glare or veiling reflection. The two undesirable effects of glare are disability and discomfort. These two effects need not occur at the same time. The main difference between disability glare and discomfort glare is that, disability glare affects performance by reducing the visual efficiency to see, whereas in discomfort glare there is no necessary direct interference with vision but annoyance, irritation or distraction. In interior lighting the common complaint is discomfort rather than disability. If the illumination close to the line of sight were to be increased then disability effects might result.

Borderline Between Comfort and Discomfort

Somewhere between the two sensations of comfort and discomfort of light there is a point of change, a threshold where the light is at the borderline between comfort and discomfort, which is termed the "Borderline between comfort and discomfort" or "BCD".

Experiments have been conducted to arrive at the BCD levels for various combinations of parameters, for example Luckiesh and Guth, 1949, Putnam and Faucett, 1951, and Bennett, 1977. Bennett (1977) in his study on discomfort glare had as parameters: A, the source angle (in degrees) above the line of sight, the background luminance, L_B (in foot lamberts), and S, the source size in steradians. He determined a relationship for the borderline between comfort and discomfort (BCD) in foot lamberts, as a function of these three parameters.

$$BCD = \frac{40\ (L_B)^{0.3} \cdot \exp(0.05A)}{S^{0.6}}$$

The research by Putnam and by Bennett used small source sizes with primary applications to exterior lighting such as for roadways.

Range effects

Comparing the results of the three studies conducted by Luckiesh and Guth (1949), Putnam and Faucett (1951) and Bennett (1977), for certain common conditions, it was found that they had differing outcomes. The BCD levels obtained by Bennett (1977) are higher than those of Putnam and Faucett (1951), which in turn are higher than those of Luckiesh and Guth (1949). (Figure 1). Parts of the three experiments were conducted under similar physical conditions. The eye position of the observer was fixed by means of an adjustable head rest, so that the glare source was in the line of sight. The observer adjusted the luminance of the glare source by means of a transformer. The observer was asked to adjust the luminance until in his judgment the borderline between comfort and discomfort (BCD) was reached. The three experiments had different luminance ranges of the glare source available to the subjects. The maximum luminance in the study by Bennett (1977) was 900,000 foot lamberts, Putnam and Faucett (1951) had 60,000 foot lamberts and Luckiesh and Guth (1949) had 30,000 foot lamberts. There is a possibility that the differing luminance ranges might have contributed to varying BCD levels. Studies have shown that subjective assessments tend to be close to the middle of the available range. This is known as a "range effect".

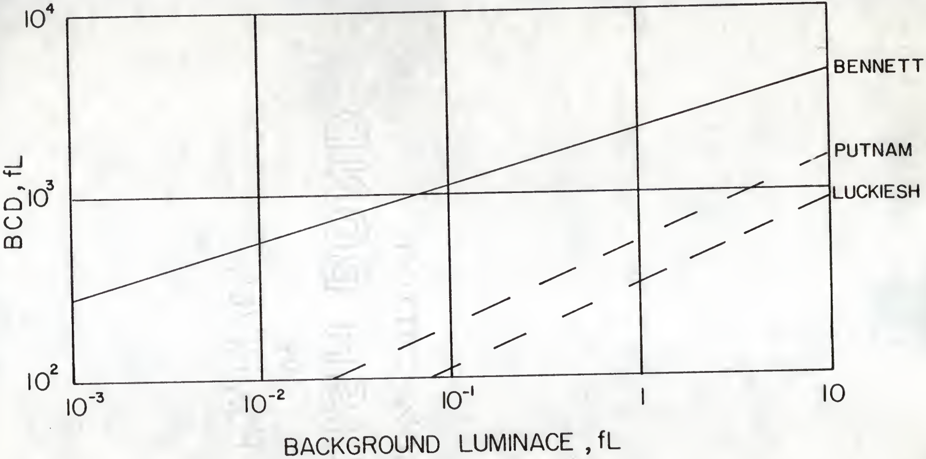

Figure 1. Comparison of different researchers, for a single glare source of size 1.1×10^{-3} steradians at 0^{o}.

Kennedy and Landesman (1963) illustrated the range effect in an experiment to determine the optimum table height for manual performance. In their study, two groups of 18 undergraduates performed a simple manipulation task on a table at six different heights. Four of the heights were common to both groups, but the means of the two ranges differed by 20 centimeters (Figure 2). It was concluded that the group with the higher range had maximum performance at an average height of 20 centimeters - 8 inches - above the average height of the other group.

Robinson, Copeland and Rennie (1961) showed that the just acceptable noise level depends upon the range of noises heard. Unpracticed observers sat beside the London to Brighton road. They estimated the noisiness of vehicles climbing a hill using a six category rating scale. The greatest noise made by each vehicle was measured, but the observers were not told the noise levels. The middle row of Table 1, shows that the peak noise levels ranged from 66 to 97 dB(A). The average transition point between the two middle ratings "acceptable" and "noisy" was found to lie at 82 dB. This is halfway between 66 and 97.

A Swiss experiment by Weber and Lauber (1961) had less intense noise levels. The top row of Table 1, shows that they ranged from 52 to 84 dB. The middle rating lies at 72 dB. This is a little above the middle of the range, which lies at 68. But 73 is a good deal less than 82 found by Robinson with more intense noise levels.

The other investigation quoted by Robinson is an American experiment by Andrews and Finch (1952).

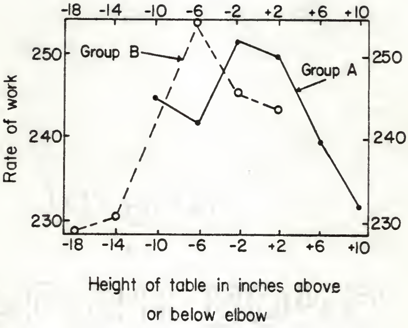

Figure 2. A range effect with a within-subject experimental design.

TABLE 1

The just Acceptable Noise made by Road Vehicles and the Range of Noises heard (Data from Robinson, Copeland and Rennie ,1961).

Investigator	Intensity in dB(A) Lowest	Acceptable	Highest
Weber	52	73	84
Robinson	66	82	97
Andrews	86	90	97

Acceptable Noisy

The bottom row of Table 1 shows that Andrews had extreme levels of 86 and 97 dB. Here the middle rating was found at 90 dB. This is a little below the middle of the range, which lies at 92. But 90 is a good deal more than the values found in the other two investigations.

Table 1 shows that the mid-point of the subjective estimates depends upon the physical range of noises used in the experiment. Intense noises raise the intensity of the just acceptable noise level. Noises of low intensity lower the intensity of the just acceptable noise level. The observer centers his range of responses near to the middle of the range of noise intensities.

A similar range effect is reported by Bowsher, Johnson and Robinson (1966) at the 1964 Farnborough Air show. One group of observers judged the noisiness of an aircraft from the assembly hall, which was 500 meters from the landing end of the runway and 100 meters from the glide path. Another group made similar judgments at the same time from a church hall which was 1000 meters from the landing end of the runway and 900 meters from the glide path. Table 2, shows that the transition point between the two middle ratings "moderate and noisy", significantly differ for the two groups.

Babiker (1977) in an experiment to arrive at the borderline between comfort and annoyance (BCA) due to noise, had a sound range of 50 to 100 dB available to 100 subjects. He obtained a mean of 78.36 dB and a median of 80.00 dB. This result and range is consistent with the evaluations made by the subjects close to the glide path in the Bowsher, Johnson and Robinson experiment (1966), (Table 2).

TABLE 2

The Transition Between Aircraft Noises Judged Moderate and Range of Noises Heard. (Data from Bowsher, Johnson and Robinson, 1966)

Distance from glidepath	Intensity in dB(A) Lowest	Moderate	Highest
Far	45	69	83
Near	55	79	101
	Moderate		Noisy

One of the objects of this study is to find out whether discomfort glare is subject to the range phenomenon.

Adaptation level

"Adaptation" in simple words can be referred to as an adjustment. The concept of adaptation as adjustment to environing conditions has been used by biologists as well as psychologists for many years. The restriction of the concept of adaptation to effects of long continued stimulation neglects the important, transient stages of adaptation, that must be taken into account when considering sensory phenomena. Adaptation is affected by reaction of the organism to stimulation, as well as by action of stimulation upon the organism.

Helson's theory of "Adaptation Level" (1964) has relevance to the "range effect". He describes behavior as bipolar with neutral, indifferent or zero responses, as indicators of stimuli and situations to which the organism is adapted. The borderline between comfort and discomfort is an example of this neutral response. On one side of the neutral response is the "approach or pleasant" response and on the other side is the "avoid or unpleasant" response. The neutral zone between pleasantness and unpleasantness and the absence of emotion in the face of stimulation represent effective adaptation levels. He states that "adaptation level tends to assume some intermediate value between extremes of stimulation".

The diversity of forms, structures, and functions in the plant and animal kingdoms is evidence of the great variety of ways in which organisms have adapted to the conditons of life in which they have evolved. Both lasting and transient changes in the environment require constant readjustments on the part of living things to maintain and advance life in the individual and in the species. Almost all types of animals can function within fairly wide limits provided certain vital supports, such as oxygen, food and water are not withdrawn. Similarly, the sensory sensitivity in human beings to stimuli like glare or noise tends to adjust or adapt itself within a fairly wide range. Harris (1950) as cited by Helson (1964), pointed out that sense organs have no ture zero; the state of balance of receptor systems shifts with changes in level of stimulation. Following intense or prolonged stimulation decline in sensitivity may be noticeable for days if the original intensity is very great for example exposure to 110-130 dB for eight minutes may result in a hearing loss of 60 dB, for a week. Thus, it is felt that exposure to high luminance, might result in a higher adaptation level or a higher BCD. This variation in the adaptation levels could cause a shift in the BCD level.

Differential sensitivity as measured by the just noticeable increment or decrement in wave lengths (hue discrimination) and in frequency (pitch discrimination) is a complex function, representing specialized adaptations which are as yet imperfectly understood. Sensory adaptations involve interaction of a number of variables in the receptor processes as well as further complications in the central nervous system.

Multiple Sources

Practical situations and prior research show the importance of multiple sources. Also, street or roadway lighting arouses an interest in the study of multiple glare sources.

Luckiesh and Guth (1949) conducted a study to determine, relationships that can be used to establish the BCD brightnesses of multiple sources.

They used the simple approach of comparison, that will determine the characteristics of two or more sources in terms of a single source, which produces the same sensation of comfort or discomfort. They found that, two sources of equal brightness and area located symmetrically on either side of the line of vision are equivalent to a single source of the same brightness having a total area of both sources and located at the point, where one of the two sources was located.

Guth and McNelis (1961) studied the discomfort glare caused by multiple sources. They described that the usual procedure for obtaining discomfort glare ratings for a complete lighting system is to sum up the computed glare ratings of the individual luminaires or luminous elements. These individual ratings can be expressed as indices of sensation 'M', computed by means of an equation:

$$M = \frac{B}{PF^{0.44}\,(w^{-0.21} - 1.28)}$$

where 'B', is the source brightness in foot lamberts, 'w', the source size in steradians, 'F', the field brightness in foot lamberts and 'P', the position index - a measure of the effect of location of the sources in the visual field. The position index for overhead luminous sources is "one".

In their experiment, the brightness of a luminous ceiling consisting of several luminaires or luminous elements was determined by using the "Comparison Method". In this method, the observers adjusted the brightness of a source, located in the line of sight until it produced the same sensation, as a specific brightness of the simulated luminous ceiling. The Guth research was carried out with moderate size sources with primary applications to interior lighting, whereas Bennett's research was a study of one glare source at a time. Since most lighting installations consist of more than one source, it is desirable to study the effect of multiple glare sources. Also, it is of interest to find, whether the areas or the number of sources determine the effects of multiple sources.

Individual Differences

It is a well known fact that "no two people are the same". It has been a common experience and concern of glare researchers to find very wide individual differences in sensitivity to glare.

Luckiesh and Guth (1949) conducted a study to find the BCD brightness in foot lamberts of a standard circular source (subtending 0.0011 steradian) located on the line of vision, with a background luminance of ten foot lamberts. A group of 50 subjects varying in age from 20 to 40 years participated in the experiment. The BCD settings ranged from 315 to 1600 foot-lamberts. The geometric mean was 830 foot lamberts. An analysis of the data showed that the BCD evaluations of the 50 subjects were normally distributed (approximately). They concluded that the variation between individuals is not unexpected nor extraordinary because of the many physiological and psychological factors that may influence the subjective appraisal of bright areas. Furthermore, the standards of comfort or discomfort vary greatly among individuals.

Alphin (1961) reported the results of his study in which 109 inexperienced observers adjusted luminaire brightness in a simulated office to BCD. It was reported that there was no relation between age, and the brightness chosen for BCD. Neither eye color, nor the wearing of glasses showed any correlation with the brightness selected for BCD.

Bennett (1977) conducted a correlation study between discomfort glare judgments (BCD's) and age, eye color, occupation, sex, population, place of residence, hair color and wearing of glasses, he found small correlation between BCD and age, eye color and occupation. Age was negatively correlated with BCD, brown eyed observers tolerated higher luminances and those with outdoor occupations tolerated higher luminances.

Bennett (1977) in his study to construct a model for predicting BCD from source size, source angle and background luminance found that individual differences among observers were very large and of equal importance in predictiveness to the physical parameters.

Babiker (1977) conducted a study to test human sensitivity to noise and glare using the concepts of borderline between comfort and annoyance (BCA) and borderline between comfort and discomfort (BCD), respectively. He studied, whether individual differences rather than the physical characteristics of noise and glare might be responsible for much of the variation in sensitivity for this stimulation. Originally he found that 75 percent of the explained variation was due to the sets of personal factors. However, upon cross-validation, the predictiveness dropped close to zero.

Visual acuity. If one were to test sensitivity to annoyance due to noise, one might expect that the results of the usual hearing sensitivity tests would be related, and might find that individuals with reduced hearing would be less annoyed by a given noise level. One might look for an analogous effect for vision and sensitivity to discomfort from glare. While not strictly analogous to hearing sensitivity, visual acuity might be relevent.

Visual acuity is described as fineness of vision. The four basic characteristics that govern visual acuity are size, luminance, contrast and time exposure of the object or area being viewed. The other factors that affect visual acuity are pattern of the background, pupil accommodation and chromaticity.

In view of the lack of success in predicting glare sensitivity previsouly, visual acuity is felt to be worthy of consideration.

Pupil Size

Light impinging upon the eye enters through the pupil, the size of which is controlled by the iris, thereby controlling the amount of light entering the eye.

Fugate and Fry (1956) investigated the relationship of pupil size and the borderline between comfort and discomfort (BCD). They attempted to determine the role played by constriction of the pupil size of the human eye as associated with exposures of light in producing discomfort. They found that the contraction of the iris and the BCD level are related. By paralyzing one eye by means of the drug hematropine, and thus stopping the flexibility of one iris, Fugate and Fry found that there was no significant change in the BCD level of the other eye. Paralysis of both eyes at the same time greatly decreased the threshold of discomfort. The subjects found it quite intolerable under paralysis of both irises to walk outside and even face ordinary daylight.

PROBLEM

The primary objective of this study is to determine whether the "range effect" has any bearing on the subjective assessments of the borderline between comfort and discomfort of glare. The scope of this research is extended to study glare due to multiple sources. The hypothesis being that the borderline between comfort and discomfort is the same for sources of equal total areas, irrespective of the number but the BCD increases as the total area decreases. It is also desired to study individual differences and the correlation of pupil size, visual acuity and BCD.

METHOD

When the observer reported to the laboratory he was asked to read a description of the experiment entitled "Instructions for determining the range effect on the borderline between comfort and discomfort of glare"; (Figure 3). He was later handed a form to sign, indicating his willingness to participate in the study. Every subject was given a vision test, using a "Titmus Vision tester" (Model OV-7, Titmus Optical Co., Inc., Petersburg, Virginia). The Titmus vision tester is a standard screening device that has a display of Landolt rings for testing visual acuity.

After the completion of the vision test, the subject was seated in front of a two foot radius hemisphere and the subject's head was positioned on a head rest provided in the pupillometer (Series 1900 eye view monitor and TV pupillometer, GW Applied Science Laboratories, Wallham, MA) (Figure 4). The hemisphere was constructed of poster board, painted white. The luminance of the hemispherical surface of 0.1 foot lambert was achieved by means of a CTT 125 volt, 1000 watt projector bulb located above and behind the subject. This luminance is termed the background luminance. Two glare sources each a CTT 125 volt, 1000 watt projector bulb were mounted behind circular openings in the surface of the hemisphere. One source was along the horizontal line of sight, and the other at an angle of 22^{0} above the horizontal line of sight. Tape recorded instructions were played before the start of the experiment. These instructions were as follows.

This research is to study various factors that effect the evaluation of the borderline between comfort and discomfort of glare or BCD. In this study you will be asked to raise the intensity of light to the highest level. Most people would say that this level of light is uncomfortably glaring. Next you will be asked to lower the level of light to its lowest intensity. Most people would say that this level is not glaring. Some where in between these two extremes there should be a point of change, a threshold, where the light is at the borderline between comfort and discomfort. This point should be sucn that the light is not annoying or uncomfortable for you, but if it were any brighter it would be uncomfortable.

Figure 3. Instructions.

Figure 4. The glare apparatus, seen are the two foot radius hemisphere, pupillometer and transformer.

"There is a concept called borderline between comfort and discomfort or BCD. First take the control and increase the intensity to the highest level. Look horizontally. Most people would say that this level of light is uncomfortably glaring. Now take the control and turn the light down until it is at the lowest level. Look horizontally, most people would say that this level is comfortable, that is not glaring. Now, somewhere, in between these two extremes there 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 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 pleasant -- comfort criteria, 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. When you have completed your adjustment, signal the experimenter to record the setting. Now go ahead".

Every subject was exposed to a total of six conditions, they were designated as conditions A, B, C, D, E and F. Conditions A, B, C, D and E were at an angle of 22^{o} above the horizontal line of sight, where as condition F, was along the line of sight. Condition A, was a single source of size 0.715×10^{-3} steradian*. Condition B, consisted of two glare sources, the total area of the sources was 0.715×10^{-3} steradian. Condition C, had three glare sources, the total area of the three sources was 0.715×10^{-3} steradian. Thus, in a two source condition the areas were $0.5\ (0.715 \times 10^{-3})$ steradian, and in the three source condition, the areas were $0.33\ (0.715 \times 10^{-3})$ steradian (Figure 5).

Condition D consisted of two glare sources of $0.33\ (0.715 \times 10^{-3})$ steradian in area and condition E had one glare source each of 0.33 (0.715×10^{-3}) steradian in area (Figure 6). All the conditions from A to E were presented to the subject by mounting a circular plate with holes of the required areas and configurations for each of the five conditions. The plate was pivoted at its center behind the hemisphere, such that each

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*The original nominal size of the glare source was 10^{-3} steradian. The change took place, since the subjects eye was positioned at a distance of 29 inches from the hemisphere's center against an earlier distance of 24 inches. This was done so that the pupillometer could be accommodated in the hemisphere. This change in distance led to a change in source sizes of conditions A to F. Each of the conditions A, B and C had the total area of the sources changed to 0.715×10^{-3} steradian, as against a nominal of 10^{-3} steradian. Conditions D and E, had each source of 0.236×10^{-3} steradian as against a specified nominal of 0.33×10^{-3} steradian. Condition F consisted of a source of 0.715×10^{-3} steradian against a nominal size of 10^{-3} steradian.

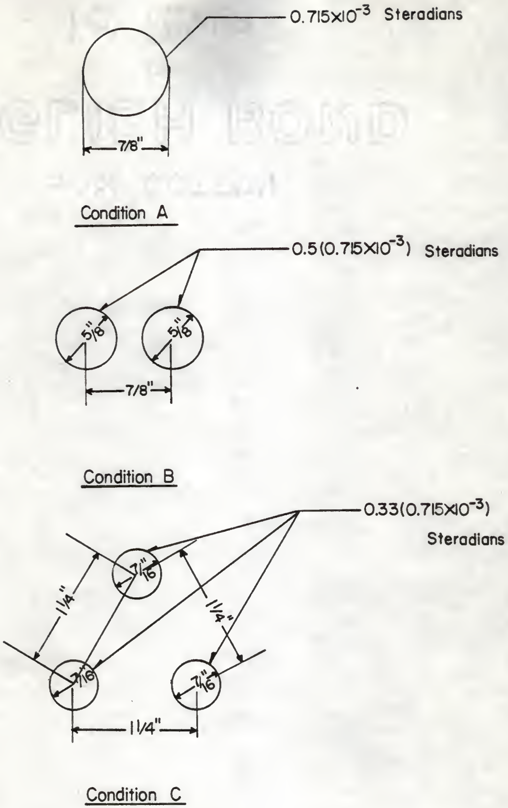
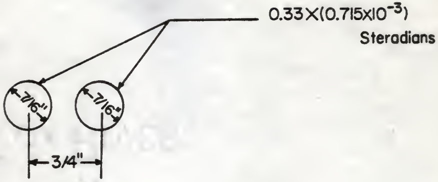
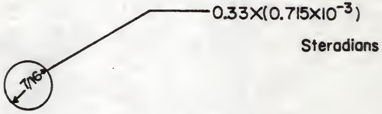


Figure 5. The one, two and three glare source conditions A, B and C.



Condition D



Condition E

Figure 6. The two and one glare source conditions D and E.

condition was visible through the upper aperture of the hemispherical surface. The plate was easily accessible by the experimenter from the back side of the booth, and could be rotated with ease to present each of the five conditions. Condition F, termed the "control condition", consisted of one glare source of size 0.715×10^{-3} steradian, positioned in the horizontal line of sight of the subject. This source was presented for one second and occluded for three seconds, by means of an electronically controlled tachistoscopic shutter. This condition F, was similar to a condition in the single glare source study of Bennett (1977).

Each of the two light sources were connected in series to a transformer. The transformer knob was at the disposal of the subject, and by rotating the knob, the luminance was either increased or decreased depending on the voltage applied. The voltage reading appeared on a voltmeter, which was connected across the secondary side of the transformer. A subject was exposed to only one of the two luminance ranges, both having a minimum of one foot lambert, one with a maximum of 300,000 foot lamberts and the other with a maximum of 30,000 foot lamberts. The transformer was set in its highest position, for a maximum luminance of 300,000 foot lamberts. To accomplish a maximum luminance of 30,000 foot lamberts with the same physical displacement of the control (as that of 300,000 foot lamberts) a Kodak wratten gelatin filter with 10% transmittance factor was placed in front of the glare source.

To maintain relative constancy of color of the source for a fairly large change in voltage, the subjects were given the choice of either using one or none of three filters, before making a setting. The three filters had transmittance factors of 10%, 1% and 0.1%. The optional use of any one of the three filters was offered for both the luminance ranges. The subjects made three adjustments with the voltage reset to the minimum value each time, for all the six conditions. For every setting made by the subject, the voltage in volts was recorded from the voltmeter, the pupil size in millimeters seen on the dial of the pupillometer, and the filter used. The voltage and pupil size readings were later averaged and the mean voltages subsequently converted to foot lamberts (fL).

Experimental Design

In this study, the independent variables were the two luminance ranges one to 30,000 foot lamberts and the other to 300,000 foot lamberts. The dependent variables were the BCD values and the pupil sizes obtained for each of the six conditions under both the luminance ranges.

Assignment and sequence of conditions

There were a total of 20 subjects run under each luminance range. The selection of the luminance range for subjects was at random with the help of a random table. Also, the sequence of presentation of the six conditions for every subject was selected at random.

Apparatus

Pupillometer. The series 1900 eye view monitor (Figure 7) is a system for measuring the subjects pupil diameter. The television camera views the left eye of the subject, which is illuminated by an infrared spot. The resulting picture of the eye is displayed on a 5 inch TV pupil monitor. Special recognition circuitry detects the pupil and the corneal reflection

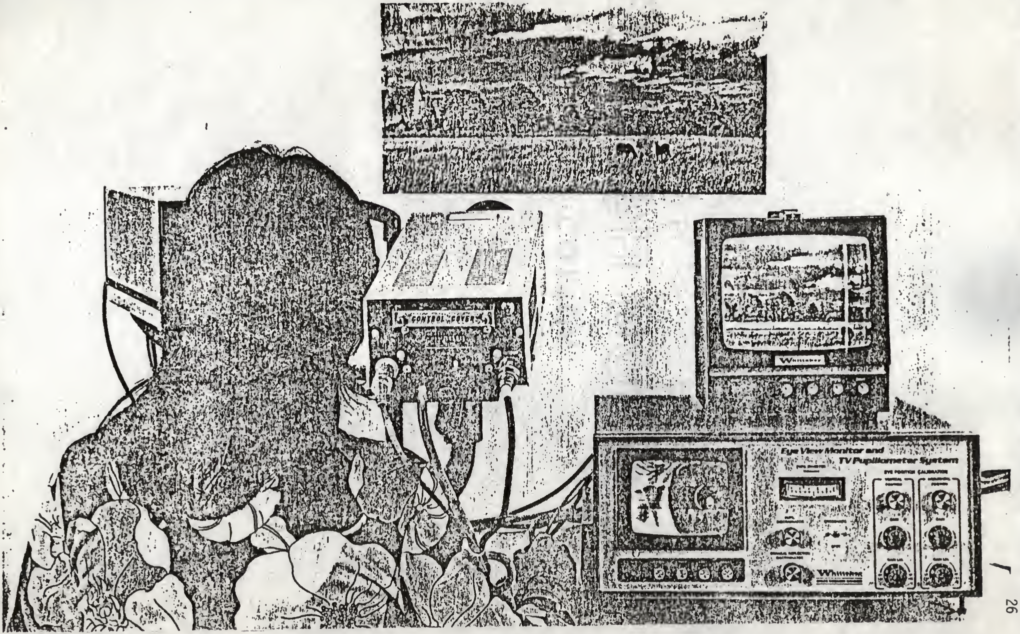


Figure 7. Series 1900 eye movement monitor showing a subject's point of view.

from the video signal. This recognition circuit allows operation for a broad range of subjects and under varying conditions with minimum operator adjustments. It superimposes "delineators" and other indicators on the image of the pupil, to indicate to the operator that the measurement is correct. The pupil diameter is indicated in millimeters on a dial provided next to the TV pupil monitor screen.

Spotphotometer. A Spectra brightness spotmeter (Photo Research Corp., Calif. Code - 1905 - SB) was used to measure the luminance of the glare source, for different voltages. A voltage, luminance relationship was measured and plotted. This calibration was later used to convert the voltage readings to arrive at the luminance value or the "BCD", for every transformer setting made by the subject.

Subjects and Recruitment Procedure

The subjects were signed up during student registration by means of an advertisement for people interested in earning money. Interested persons filled out their schedules indicating the day and time of the week they would be available to participate in the experiment. The subjects were later called during the course of the semester to participate in the experiment depending on their availability. Forty one subjects reported to the laboratory. One of them did not qualify to take part in the experiment due to poor visual acuity. Hence a total of 40 subjects were run, with 20 under each luminance range. Every subject was run for a period of half an hour. The subjects varied in age between 18 and 38 years with a mean of 23.2 years. 35 subjects were male and five female. Fifteen of them wore glasses. They were all students at the Kansas State University.

RESULTS

Table 3, gives the BCD, pupil size and the means for all the subjects under each of the six conditions A, B, C, D, E and F for both the luminance ranges.

Range

Table 4, shows that the overall means of the BCD level for the 300,000 foot lambert range is nearly seven times that of the 30,000 foot lambert range, and that the luminance range has a negligible effect on the pupil size. Table 5, shows that the difference between the mean BCD levels under the two ranges is statistically significant and Table 6, indicates that the luminance range does not have a significant effect on the pupil size.

Comparing the mean BCD level of 3,294 foot lamberts obtained under the 300,000 foot lamberts range for condition F, with the predicted value of 4,647 foot lamberts got by using the relationship found by Bennett, 1977 (refer to "Borderline between Comfort and Discomfort in the "Introduction"), it is seen that the difference between the two values is statistically significant at a level of 0.05.

Individual differences

The results under this criterion indicate that the individual differences among the subjects have a significant effect on the evaluation of the BCD (Table 5) and that the pupil size did vary significantly among the subjects (Table 6).

TABLE 3

The BCD Setting in Foot Lamberts and Pupil Size in Millimeters for all the Subjects.

Subject	Range Max. Luminance fL	A Luminance fL	A Pupil size mm	B Lumiance fL	B Pupil size mm	C Luminance fL	C Pupil size mm	D Luminance fL	D Pupil size mm	E Luminance fL	E Pupil size mm	Control Condition 'F' Luminance fL	Control Condition 'F' Pupil size mm	Overall Mean Luminance fL	Overall Mean Pupil size mm
1	300,000	128,000	4.5	82,000	5.1	103,000	5.0	250,000	5.0	86,000	5.0	10,750	4.0	84,800	4.8
2	300,000	16,500	4.0	20,500	4.0	18,000	4.0	28,000	4.3	25,500	5.0	720	4.0	21,700	4.2
3	300,000	124,000	5.1	66,000	4.0	35,000	5.0	82,000	4.5	53,000	4.7	1,280	4.7	72,000	4.6
4	300,000	8,200	3.4	7,150	3.8	9,800	4.0	14,000	3.5	11,000	3.2	580	3.1	24,790	3.5
5	300,000	22,000	2.2	33,000	3.2	34,500	2.5	60,000	3.0	27,500	2.3	1,500	2.0	35,400	2.6
6	300,000	540	4.2	620	4.5	990	4.8	2,600	5.0	24,000	4.5	190	4.0	5,750	4.5
7	300,000	2,100	3.8	2,500	3.9	3,500	4.0	5,800	3.6	2,250	4.0	520	3.4	3,230	3.8
8	300,000	190	5.4	170	5.1	560	5.7	520	5.0	245	5.2	430	4.0	337	5.3
9	300,000	110,000	4.5	58,000	2.7	120,000	3.0	113,000	2.9	62,000	2.7	540	3.4	92,600	3.1
10	300,000	180,000	3.6	64,000	4.0	76,000	4.1	128,000	5.3	180,000	4.2	900	4.0	125,600	4.2
11	300,000	390	4.2	800	4.1	1,050	4.4	900	4.2	2,100	4.8	420	2.4	1,048	4.3
12	300,000	9,800	4.3	12,800	4.4	10,500	4.0	18,000	4.0	7,900	4.0	820	2.0	11,800	4.1
13	300,000	78,000	4.0	50,000	4.0	24,000	5.0	47,000	5.0	24,000	5.4	4,000	3.2	44,600	4.6
14	300,000	1,500	5.3	1,900	5.1	4,500	6.0	12,000	6.2	3,300	5.4	46	3.2	4,640	5.6
15	300,000	580	4.5	1,400	4.8	450	4.9	1,700	4.3	720	4.9	940	3.3	970	4.7
16	300,000	960	4.4	2,400	4.2	1,900	4.8	2,400	4.8	4,600	4.0	130	2.6	2,452	4.4
17	300,000	6,500	3.0	43,000	3.5	50,000	4.0	28,000	3.0	14,000	3.0	1,800	2.0	20,560	3.2
18	300,000	20,500	3.0	1,600	2.8	6,400	3.0	24,000	3.0	2,000	3.5	39,000	2.0	10,900	3.0
19	300,000	5,600	3.0	43,000	4.5	11,000	4.6	1,300	3.2	9,500	3.2	210	4.0	14,080	3.7
20	300,000	20,500	4.5	8,600	4.3	15,000	4.2	19,000	4.1	18,000	4.2	1,100	3.0	16,220	4.3
21	30,000	2,350	5.0	1,850	4.0	2,900	3.0	5,150	4.0	3,100	4.1	1,950	4.0	3,070	4.0
22	30,000	3,500	4.0	3,400	4.4	4,800	4.0	6,600	4.0	4,500	4.0	280	4.0	4,560	4.0
23	30,000	40	5.4	4	5.2	140	6.0	6	5.3	2	5.4	15	4.0	38	5.5
24	30,000	7,000	3.0	1,200	3.2	1,100	3.0	4,500	2.5	3,250	3.2	350	3.8	5,410	2.9
25	30,000	950	3.0	620	3.6	3,450	5.1	950	4.1	690	3.3	900	3.6	1,332	3.8
26	30,000	3,300	5.4	3,800	6.0	3,800	5.8	6,800	5.6	3,250	5.5	3,000	6.4	4,190	5.7
27	30,000	1,800	3.0	7,000	3.3	7,800	3.1	3,000	3.0	6,800	3.0	560	3.8	5,280	3.1
28	30,000	240	3.2	228	3.0	330	2.8	350	3.0	1,050	3.0	20	3.0	440	3.0
29	30,000	1,200	4.0	4,100	4.4	2,100	4.2	2,700	4.2	3,700	3.7	14	3.8	2,760	4.1
30	30,000	450	4.0	560	5.4	2,100	3.8	2,700	3.8	6,600	3.8	14	3.8	2,482	4.2
31	30,000	11,200	4.1	7,600	3.8	9,800	4.0	1,200	4.2	4,900	4.0	43	4.2	6,940	4.0
32	30,000	1,200	5.0	1,120	5.4	2,000	4.8	1,630	6.0	2,600	6.0	330	3.0	1,710	5.4
33	30,000	19,000	4.0	17,000	4.0	19,000	4.4	12,200	4.8	11,700	4.4	725	2.6	15,780	4.3
34	30,000	7,600	5.0	6,000	4.8	12,000	5.0	7,000	5.0	6,800	4.6	900	4.0	7,880	4.8
35	30,000	1,900	3.3	1,150	2.5	4,000	3.1	6,200	3.2	1,400	3.2	1,100	3.0	2,930	3.0
36	30,000	2,200	4.7	3,100	4.8	1,800	5.0	3,600	4.0	6,200	5.0	860	2.5	3,380	4.7
37	30,000	1,800	4.8	5,200	5.1	20,000	5.1	4,100	4.6	760	4.7	240	4.0	6,372	4.9
38	30,000	1,600	4.6	2,100	4.6	2,000	4.0	3,400	4.0	3,400	4.2	230	2.0	2,500	4.2
39	30,000	3,100	3.6	3,100	4.0	3,600	3.5	4,300	2.6	5,000	3.4	2,000	2.1	3,820	3.4
40	30,000	6,600	5.0	5,300	5.0	7,500	5.1	11,200	5.1	11,200	5.0	6,400	5.0	7,400	5.0

TABLE 4

The Mean BCD in Foot Lamberts, the Pupil Size in Millimeters Under Each Condition and their Overall Means

Condition	Mean BCD level in foot lamberts under the given luminance range		Mean pupil size in millimeters under the given luminance range	
	1-300,000 foot lamberts	1-30,000 foot lamberts	1-300,000 foot lamberts	1-30,000 foot lamberts
A	36,793	3,851	4.1	4.2
B	24,972	3,721	4.1	4.3
C	26,307	5,661	4.2	4.3
D	41,911	4,729	4.1	4.2
E	27,880	4,190	4.1	4.2
F	3,294	996	3.2	3.6
Overall means	26,859	3,858	3.9	4.1

TABLE 5

Analysis of Variance of BCD

Source of Variance	df	MS	F
Range (R)	1	31,903,000,000	139.25*
Subjects (S)	38	3,274,000,000	14.29*
Conditions (A, B, C, D, and E)	4	423,000,000	1.84
Error	156	229,000,000	

*P < 0.01

TABLE 6

Analysis of Variance of Pupil

Source of Variance	df	MS	F
Range (R)	1	0.16	0.93
Subjects (S)	38	3.19	18.32*
Conditions (A, B, C, D, and E)	4	0.18	1.04
Error	156	0.17	

*P < 0.01

Conditions (A, B, C, D and E)

For comparing the five conditions the hypotheses were that the mean BCD levels, of conditions A, B and C (those sources with equal total areas) are equal and the directional hypotheses that the mean BCD level of condition C is less than that of D, which in turn is less than that of E, that is for sources of unequal total areas. Table 5, shows that the difference in the number of glare sources in conditions A, B and C, do not significantly effect the BCD level.

While comparing conditions C and D, by means of a one way t test, the t value is -2.16. This value proves to be significant. But, on conducting a similar t test for comparing conditions D and E and C and E, the test does not show any significance.

Correlation of BCD and Pupil Size

The correlation coefficient of the pupil with reference to BCD, is found to be -0.0437. The negative sign, indicates the fact that the pupil size decreases as the luminance increases. But, this correlation of BCD with the pupil size is not significant.

DISCUSSION

Range effect

Range definitely had an effect on the borderline between comfort and discomfort of glare. The mean BCD level obtained under a luminance range of one to 300,000 foot lamberts was 29,600 foot lamberts, and the mean BCD level under a luminance range of one to 30,000 foot lamberts was 4,410 foot lamberts (a ratio of seven to one). Statistical analysis indicated that the mean BCD levels under the two ranges differ significantly (Table 5). This finding confirms the earlier belief that the reason for varying results of the three experiments (Luckiesh and Guth, 1949, Putnam and Faucett, 1951 and Bennett, 1977) could be due to the varying luminance ranges made available to the subjects.

Range effects may be related to Helson's theory of "Adaptation Level". According to this theory, adaptation level is defined as a neutral region of response. Harris (1950) pointed out that sense organs have no true or fixed neutral response level. The state of balance or receptor system shifts with the changes in level of stimulation. In other words every organism possesses a mechanism that enables it to adjust itself to its surrounding environment in order to exist. Thus, higher stimulation results in a higher adaptation level. Complete adaptation to a stimulus is signalized by neutralization of the impinging energy. With steady sound or pressure stimulation, nerve impulses decline in rate and perhaps in amplitude, and there is a concomitant change in perceived intensity of the stimulus.

Following intense or prolonged stimulation, a decline in sensitivity may be noticeable for days if the original intensity is very great, for example, exposure to 110-130 dB for 8 minutes may result in a hearing loss of 60 dB, which is not fully regained for a week.

Therefore it is felt that this concept of different adaptation levels might be responsible for the evaluation of unique BCD levels, under different luminance ranges. This proved to be true also while comparing the mean BCD level of 3,294 foot lamberts obtained under the 300,000 foot lambert range for condition F, with the predicted value of 4,647 foot lamberts (Bennett, 1977). The difference between the two values is found to be statistically significant. The reason being, the varying luminance ranges. Bennett (1977), in his experiment had a maximum luminance range of 900,000 foot lamberts, whereas in this study the maximum luminance was 300,000 foot lamberts. Hence, it is summarized that range effects are a general characteristics of a man serving in an experiment with a "within subject design".

Referring to the experiment of Kennedy and Landesman (1963), to determine the optimum table height for maximum performance, Poulton (1973) concluded that the range effects fits a transfer of training model. The transfer of skill is greatest between heights of tables which are very similar, so heights in the middle of the range benefit most overall. The man learns a composite, manipulative skill, which is most appropriate to the middle of the range of table heights. From this and other examples it is clear that whatever stimuli or responses can be ordered consistently, they are capable of producing range effects if a within-subject design is used. This with-in subject design could effect a wide variety of human experimental psychology. Thus it is seen that range effects are a general characteristic of a man serving in an experiment with a within-subject design, rather than a special characteristic of particular areas of human behavior. Range effects are found also in experiments on animals which are capable of learning (Grice, 1966).

Range effects which are produced by learning the range of stimuli during the course of an experiment can be prevented by restricting each person to a single stimulus. This means using a separate groups design. For the Kennedy and Landesman experiment (1963), to determine optimum table height, the best solution is probably a two-stage experiment. First, use a within-subject design to find out where the optimum lies. Then check the results with two or three separate groups of subjects, who have not served in the previous experiment. With a separate-groups design, a comparison between conditions is confounded with relatively large individual differences. To ensure a reasonably small standard error, the experimenter may need larger numbers of men in each group than are needed in a complete within-subject design. But once the experimenter has accepted the need for more men, his statistical tests take care of the individual differences. A rejection of the null hypothesis indicates that the differences found are not likely to be due to the chance allocation of men to groups. The above procedure to avoid range effects could be applied to determine an appropriate BCD level of glare. It provides scope for further research in this field, particularly concerned with the finding of an appropriate BCD level of glare.

At this juncture, it is felt that this could be achieved by exposing every subject to only one, fixed luminance level and obtaining his response on a rating scale consisting of response levels such as "uncomfortable, moderate or acceptable and comfortable".

Since World War II, ergonomics has gradually been accepted by the armed services and by industry. Ergonomic recommendations are not frequently designed into equipment. So it is most important to ensure that the ergonomic recommendations are in fact correct. They should not be biased. This means checking the results of within-subject experiments, using separate groups of people for each key condition. Checks of this kind are not often made at the present time. This is because they do not realize that such checks are needed.

If many incorrect ergonomic recommendations are designed in to equipment, ergonomics will fall rapidly in to disrepute. Physicists and engineers will return to their old habits of ignoring ergonomics. All their prejudices will have been confirmed by the lamentable so-called ergonomic equipment. Therefore, there is a challenge to applied psychologists and ergonomists which they must accept. It means repeating many of the classical experiments, but using separate groups of people for each condition. At this stage it is not possible to tell how many changes will have to be made in ergonomic handbooks. But certainly some recommendations will need changing.

Multiple Sources

In this study, it was desired to explore whether the area or the number of glare sources have any effect on the borderline between comfort and discomfort.

Luckiesh and Guth (1949) found that the BCD level of two half area sources is approximately the same as the BCD level of a single full area source, located at the point where one of the half area sources was located. This finding of Luckiesh and Guth (1949) to a certain extent holds true with the result of comparison of the BCD levels of conditions A, B and C. Conditions A, B and C had glare sources of equal total areas. Although the single source of condition A was not positioned exactly at the point of location of one of the sources of conditions B and C, it was found that the BCD levels of conditions A, B and C did not differ significantly. Thus it is concluded that lighting installations consisting of varying number of glare sources with equal total areas, produce similar sensations of discomfort.

The comparison of conditions C, D and E (sources of unequal total areas) by statistical analysis indicated that the BCD level of condition C was less than that of condition D, but it did not show any significant difference in the BCD levels of conditions D and E, and also between conditions C and E. The reason for this inconsistent outcome is not known. Although it is felt that the reason for the similarity in the BCD levels of conditions C, D and E indicated in Table 5, might be due to the fact that the sources in conditions D and E were positioned close together, whereas Luckiesh and Guth (1949) had their two half area sources 10^{0} apart. Therefore a question is raised that, if the sources were placed far apart whether, the outcome might have been different. Anyhow this remains to be seen and it opens an area to be explored in the study of multiple glare sources.

Individual differences

The findings under this criterion are that the individual differences among the subjects had a significant effect on the evaluation of the BCD level. The outcome of varying performance of the subjects has found its presence even in earlier studies (Bennett, 1977, Babiker, 1977). Table 5, highlights the effect of individual differences by indicating that the evaluation of the BCD level differs significantly among the subjects. This variation among individuals is not unexpected nor extraordinary because of previous findings of wide individual differences.

All the subjects had satisfactorily passed through the visual acuity test. There was a very small variation in the visual acuity among them. Therefore it is felt that the correlation of visual acuity to BCD was not of much significance.

Pupil size

Table 6, shows that the pupil size differs among subjects. This result was expected due to long standing evidence on pupil reactions. It is worthy of note that the pupil size was recorded at the conclusion of a setting, but Fugate and Fry indicate that the time varying pattern is responsible for feelings of discomfort glare.

Implications

This study implies that range does have an effect on the evaluation of the BCD level. The three studies conducted by Luckiesh and Guth, Putnam and Faucett and Bennett to find the BCD level, had different luminance ranges, available to the subjects. But the three experiments had similar parameters. Table 7, shows that differing BCD's were obtained for a single source of 1.1 x 10^{-3} steradians with a background luminance of 0.1 foot lamberts in the three experiments possessing different luminance ranges.

Bennett (1970) states that "All applied research is simulation". This expresses the concept that the processes undergoing research study should be typical of the operations which are of interest in applied research. A researched process is set up either in the laboratory or by observation of an actual situation in such a fashion as to simulate the actual situation.

Burnswick (1956) set forth the concept of representative design of psychological experiments. He suggested that not only should subjects in experiments be representative samples of some interesting population, but also the stimuli should be representative of whatever the environment pertains to that population.

Therefore, concerning applied research for example in a study to determine the effects of roadway lighting it would be necessary to provide a maximum luminance similar to that of the roadway lighting.

In future research, it would be desirable to simulate roadway lighting luminances while studying the effects of multiple sources. Also, a need arises to study the effects of multiple glare sources, that are more physically separated.

TABLE 7

The Unique BCD Levels Obtained under Different Luminance Ranges in the Three Experiments, for a Source of 1.1×10^{-3} Steradians Positioned in the Line of Sight with a Background Luminance of 0.1 Foot Lamberts.

Experimenter's	Maximum Luminance in Foot Lamberts	BCD Level in Foot Lamberts
Luckiesh and Guth	30,000	156
Putnam and Faucett	60,000	362
Bennett	900,000	1375

CONCLUSIONS

1. The luminance range available to the subject does have an effect on the evaluation of the borderline between comfort and discomfort of glare. Range effects are a general characteristics of a man serving in an experiment with a within subject design. Therefore, the stimuli should be representative of the environment pertaining to that population.
2. Lighting installations consisting of varying number of glare sources with equal total areas, produce similar sensations of discomfort. Also, conditions of multiple sources that comprise of varying number of glare sources (with unequal total areas) closely clustered together have similar sensations of discomfort. It yet remains to be seen that if the sources are placed far apart, whether the effects would be different.
3. Individual differences among subjects have a significant effect on the evaluation of the BCD level. This variation among individuals is not unexpected because of previous findings of wide individual differences.

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RANGE EFFECTS IN DISCOMFORT GLARE

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ABSTRACT

Twenty different subjects performed under each of the two luminance ranges of one to 30,000 foot lamberts and one to 300,000 foot lamberts. Every subject made a setting of the BCD level for six conditions, one was along the horizontal line of sight and the rest at an angle of 22^0 above the line of sight. It was found that the luminance range made available to the subject does have an effect on the evaluation of the borderline between comfort and discomfort of glare. Range effects are a general characteristic of a man serving in an experiment with a within-subject design. Comparison of the conditions showed that those consisting of varying number of glare sources with equal total areas had similar BCD levels, and the conditions that comprised of varying number of closely clustered glare sources with unequal total areas had similar sensations of discomfort. It yet remains to be seen that lighting installations comprising of sources placed far apart might have differing effects. Individual differences among subjects had a significant effect on the evaluation of the BCD level. The pupil size among subjects proved to differ.