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PLAIN AND POLAROID SUNGLASSES AND VISUAL PERFORMANCE, DISABILITY GLARE, AND DISCOMFORT GLARE

by

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Last but not the least, the author feels deeply indebted to his wife, who spent four quiet months without a husband. It is to her that thesis is dedicated.

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INTRODUCTION

The eye is the primary link with the world around us. Without light, we cannot see; with inadequate light or excessive light or poor quality of light, seeing may be hazardous, inefficient, uncomfortable, or unpleasant. Any lighting system necessarily can be evaluated against two basic criteria, namely, "quantity of light" and "quality of light".

Quantity of light in any seeing situation is related to the ability to see or visual performance. There are multiple variables involved in determining the optimal level and conditions for any lighting system. Many researchers have investigated various factors involved in visual performance. The most common of these factors involved in visual performance for any visual activity can be described in terms of the task, size, contrast, luminance, and the age of the observer. Lack of performance in visual activity may arise, due to the inadequate or excessive luminance under a set of conditions of task difficulty, contrast, and age. A less difficult task needs lesser luminance as compared to a highly difficult task. Due to poor contrast, even under the best lighting conditions, the silver fox vanishes against the Arctic snow. Older people need more luminance for given tasks under the same conditions. When disability in any visual performance is due to excessive luminance in the vicinity of the task, it is termed as "disability glare".

The quality of lighting, on the other hand, pertains to the distribution of luminance in the entire visual field. When luminance in the field of view causes discomfort, but does not necessarily interfere with seeing, the sensation experienced by the observers is termed "discomfort glare".

Millions of people around the globe use sunglasses to reduce discomfort glare and probably most believe that they are improving their visual performance as well. Unfortunately, there is no experimental evidence to prove sunglass effectiveness in modifying glare or visual performance. However, some predictions about possible effects can be made.

Visual Performance

Visual tasks can be described fairly completely in terms of size, contrast, luminance, and the age of the observer. The luminance (L) of a perfectly diffusing reflected surface is dependent upon the illumination (E) incident on the surface and its reflectance (ρ) and is represented by:

$$L = E\rho \tag{1}$$

When illumination E is expressed in footcandles, the luminance, L, (sometimes called "brightness") is in footlamberts. ρ is a constant varying between zero and one. Luminance variation in a visual task occurs in the form of gradients or abrupt transitions which are called contrast borders. Blackwell (1946) defined the contrast (C) between two adjoining areas as:

$$C = \frac{|L_b - L_o|}{L_b} \tag{2}$$

where L_b and L_o are the luminances of the background and the object.

Luminance and performance. The relationship between luminance, contrast, and visual performance has been studied by many investigators.

Weston (1935, 1945, 1961) developed a series of visual tasks which consisted of a large number of Landolt rings printed in a pattern as shown in Figure 1. The charts of this type for rings of different sizes were printed in different contrasts by using papers of different reflectance. The task of the observer was to cancel the gap in each ring and the time the observers took in doing so was taken as the index of performance. The results, shown in Figure 2, indicates that, for tasks which differ in contrast and size, increasing the illumination does not improve the performance equally.

Blackwell (1959) studied the effect of size, contrast, and speed of vision on the threshold of detection. The threshold of detection was determined by presenting a luminance difference at the center of a field of uniform luminance. The luminance differences were presented in the form of transilluminated discs of various sizes between 0.8 to 51.2 minutes of arc subtended at the eye. These targets were illuminated for a time varying from 0.001 second to 1.0 second. The subjects (two in all) were told the size of the target to expect and the duration of the exposure. The position in which it was to appear was closely defined. The subjects decided in which of the four periods of time it actually appeared. Figure 3 shows the threshold curves (50% of judgments were currect) in terms of limiting contrast against background luminance for 1/30 second duration of presentation. The equal visibility curves show that lower contrast tasks need much more luminance as compared to the higher contrast tasks.

Bodmann (1961, 1962, 1967) devised a method which was similar to that of Weston, but which involved the measurement of speed for performance

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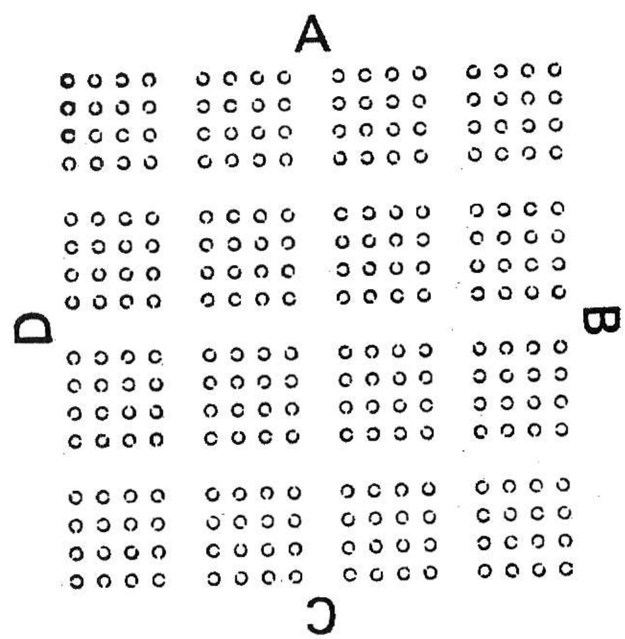


Figure 1. Weston's landolt ring performance chart.

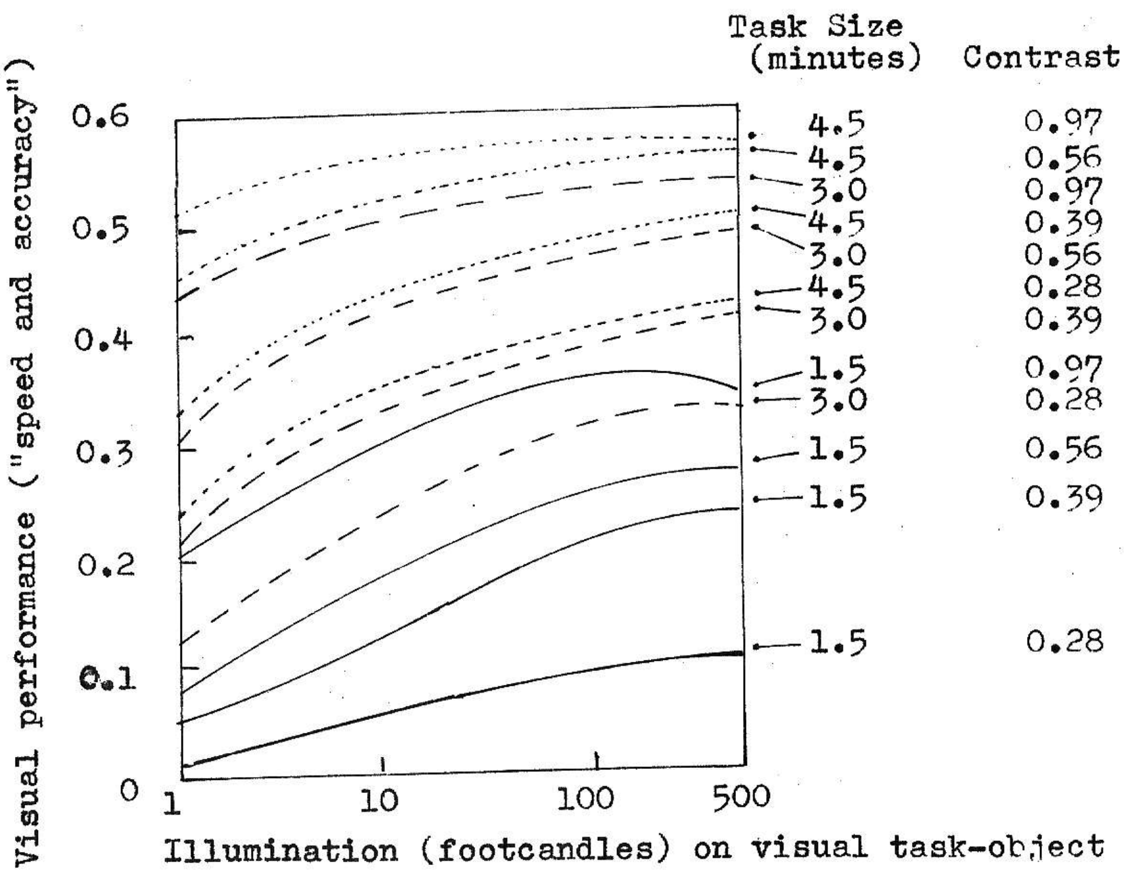


Figure 2. Experimental curves showing the relationship between speed and accuracy of visual discrimination and the illumination of the visual task-object (Weston 1962).

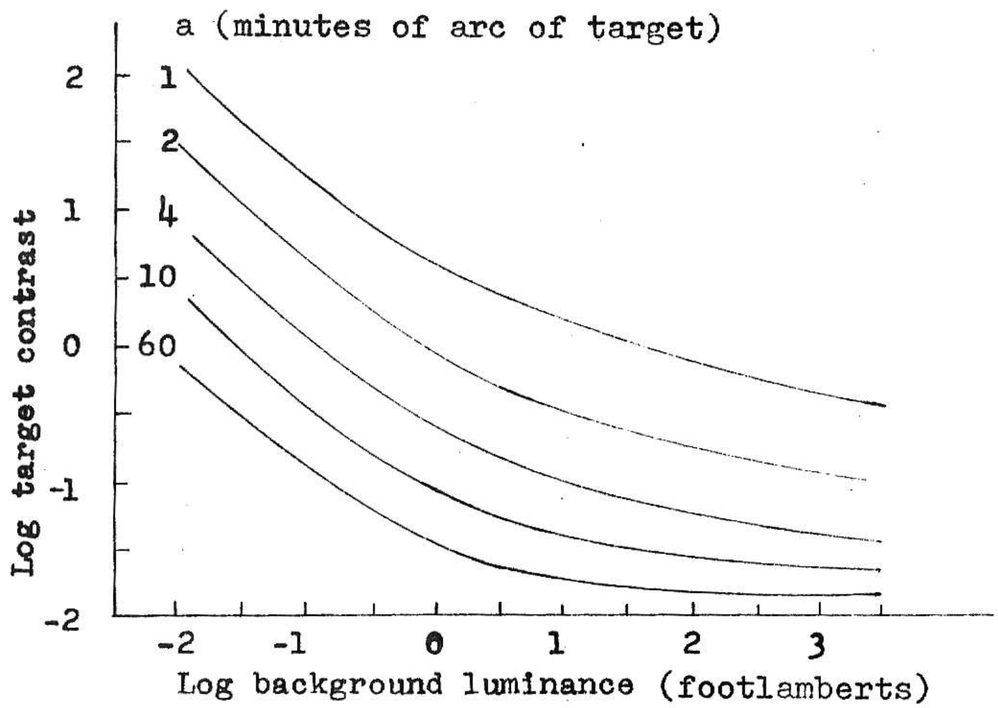


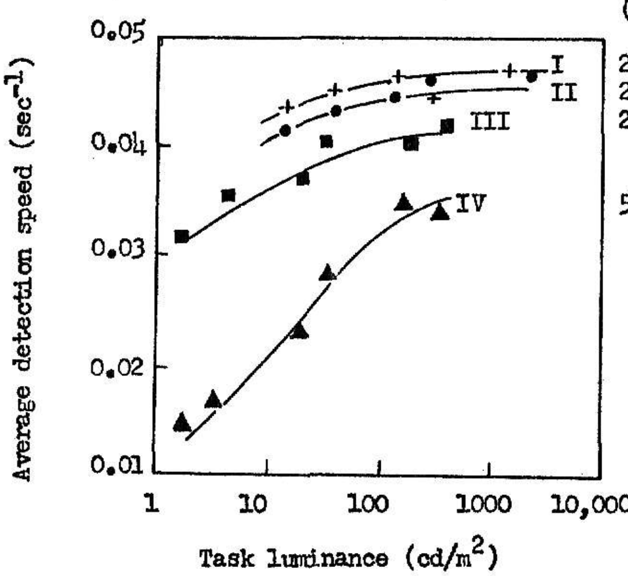
Figure 3. Blackwell's smoothed threshold contrast curves for a 1/30 second duration (50% accuracy). Each line gives conditions of equal performance.

at 100% accuracy and also for subjects of different age groups. The results (Figure 4) indicate that increased luminance benefited older people more in terms of increased visual performance, but performance levels off for both younger and older people, as some value of luminance is reached.

Blackwell's threshold data has been used for arriving at the recommended illumination levels in the United States. Results of Weston and Bodmann (1961, 1962) is a basis of lighting standards in Europe. Since Blackwell's task was very difficult, his work provides a basis for lighting standards requiring more illumination in the United States as compared to most European countries.

Fry (1962) made a detailed analysis of Blackwell's and Weston's work and recommended against the attempt to set too high a level of illumination, since this may cause (a) the possibility of direct visual discomfort through too high a task luminance, (b) the possibility that the visibility of some contrasts may be reduced at very high levels of luminance, and (c) the obvious fault of recommending levels of illumination beyond those which are economically acceptable.

Hopkinson (1965) analyzed the work of Bodmann (1961, 1962) and Balder (1957) and related it to similar work, and came to the conclusion that there is sufficient evidence for believing that there is an optimal level of illumination for given visual tasks, that increasing illumination beyond this level is of no value, and that in many cases it may be of distinct detriment in that glare discomfort from excessive brightness of the task itself may be introduced. This is contrary to Blackwell's findings. In general, in the analysis to be performed, it will be assumed



	Age range (years)	Background reflection factor (percent)	Object contrast
I	20-30	78.0	0.98
II	20-30	78.0	0.93
III	20-30	11.5	0.63
IV	50-60	11.5	0.63

Figure 4. Relation between luminance level and visual performance achieved in a search task for four conditions with different age groups, reflection factors, and object contrasts.

that performance continues to improve with increased luminance, although the improvement may be small.

Sunglasses and performance. Under conditions of high luminance, sunglasses are frequently worn. It is pertinent to consider, in terms of the aforementioned results, what effect this should have. For an object of two units of luminance in a field of 100 units, the contrast "C" is obtained from Equation 1.

$$C = \frac{100 - 2}{100} = 0.98$$

Assuming the transmission of sunglasses equals 0.10, the contrast with sunglasses will be

$$C = \frac{100 \times 0.10 - 2.0 \times 0.10}{100 \times 0.10} = 0.98$$

and the task luminance will now be (2 x 0.1) = 0.2 units. Figure 3 shows that as we move along an equal visibility contour towards lower luminance, the required contrast increases. Since contrast is not changed, visual performance must be reduced. The loss in visual performance, however, may not be very significant at high levels of luminance.

Richard (1953) found that visual acuity and contrast were not improved by yellow glasses at illumination levels found for night driving conditions. Measurements were made on 73 subjects (ages 16 through 72) using a "Snellen and a Calibrated Contrast Chart" at 11, 1, 0.1, and 0.01 footlamberts brightness for yellow glasses (overall visual transmission equals 0.85). Both acuity and ability to distinguish contrast decreased with age and with decreasing brightness.

Disability glare. When there are areas of very high luminance in the visual field, some form of glare will result. If there is direct interference with visual performance, this is called "disability glare". Holladay (1926) and Stiles (1928) have shown that a small source located at an angular distance θ in degrees from the line of sight produces an effect at the fovea which is equivalent to a veiling luminance, L_v, in footlamberts given by the following formula:

$$L_v = k\ E\ \theta^{-n} \qquad (3)$$

where E is the illumination produced by a glare source in the plane of the pupil in footcandles, and k and n are constants. Moon and Spencer (1943) used values of 10Π and 2 for the constants k and n. More recently, Christe and Fisher (1966) have shown that the value of k in Equation 3 can be related to the age of the observer in a manner which would be explained by the loss of clarity of optimal media with increasing age.

In the cases of roadway lighting, vehicle headlights, and direct light from sun on a highway, there may be a disability glare due to stray light. Stray light within the eye produces a veiling luminance which is superimposed upon the retinal image of the object to be seen. This alters the luminances of the image and its background and hence the contrast. The apparent luminances (L_b' and L_o') of the contrasting areas of the background (luminance L_b, footlamberts) and object (luminance L_v, footlamberts) are given by:

$$L_b' = L_b + L_v$$

$$L_o' = L_o + L_v$$

where L_v is added "veiling" luminance in footlamberts due to the glare source. Substituting these values in Equation 2, the resulting contrast is:

$$C' = \frac{L_b + L_v - L_o - L_v}{L_b + L_v} \text{ or}$$

$$C' = \frac{L_b - L_o}{L_b + L_v} \qquad (4)$$

Sunglasses and disability glare. Assuming that at threshold level a task of two units of luminance is just visible in 100 units of background luminance, the limiting contrast is obtained by substituting in Equation 2:

$$C = \frac{100 - 2}{100} = 0.98$$

Assuming that a veiling luminance (L_v) of 10 units is created due to a glare source in the field of view, the contrast C' is now given by Equation 4:

$$C' = \frac{100 - 2}{100 + 10} = 0.89$$

Since C' is less than the threshold contrast of 0.98, the object of two units will be below the threshold and, thus, would not be visible any more. As seen earlier, the effect of plain sunglasses (non-polaroid) will be to reduce both numerator and denominator in Equation 4 by an equal proportion and thus keep C' at 0.89. The use of sunglasses of transmission less than one, however, will reduce task luminance which in turn will impair visual performance. The impairment effect may not be very large at high luminance levels.

Blackwell (1953) measured the effect of yellow tinted night driving glasses on visual efficiency at low luminance levels, using contrast discrimination as the index. Conditions were selected to simulate the detection of low contrast pedestrians or obstacles occuring along the highway at night, with and without opposing headlights. It was found that yellow tinted glasses reduced simulated detection distance by as much as thirty-three percent compared with no glasses. Roper (1953) also reached on similar conclusions for tinted windshields.

Blackwell (1954) studied optical filters at low levels of luminance, with and without glare conditions. He predicted that optical filters would reduce visual discomfort due to direct glare, but losses in visual performance were to be expected. He experimentally tested two types of filters (transmissions; 0.87 and 0.69), for no glare and direct glare conditions. The criterion was detection distance of a contrast task. The results showed a loss of twenty-one percent of normal visual performance with glasses of 0.87 transmission, and forty-five percent of normal performance with glasses of 0.69 transmittance. There was no experimental evidence to show that loss in visual performance was insignificant at luminance levels higher than 11 footlamberts.

Reflected glare. In most of the outdoor activities as driving on a highway or sking, a prominant source of veiling luminance is the light reflected from a chrome plated surface, painted surface, windshield glass of an automobile, or from water or snow. The reflected light from a shining part may also constitute some kind of glare source in some industrial inspection tasks. In the case of reflected light, the situation becomes more involved since light rays reflected from a solid surface are partially polarized.

Polarization by reflection. According to electromagnetic theory, any type of light consists of transverse waves, in which the oscillating magnitudes are electric vectors. Assuming that in a beam of light traveling towards the observer, along the +Z axis in Figure 5, the electric vector at some instant executes random rotations with the direction and amplitude indicated. The net effect of such a vibration in the plane XY is as though there were two vibrations at right angles with equal amplitudes, but with no coherence of phase. Each vibration is the resultant of a large number of individual vibrations with random phases and, because of randomness, a complete incoherence is produced. Dots in Figure 6 represent the end on view of linear vibrations (vertical component) and the double pointed arrows are vibrations confined to the plane of the paper (horizontal component). Consider unpolarized light to be incident at an angle Φ on a dielectric such as glass as shown in Figure 6. Before reflection, the magnitude of both the components is the same. When $\Phi = 0$, the vertical and horizontal components are equal. With any increase in Φ, the vertical component increases until at the polarizing angle Φ' (approximately 57^{o} for glass), their values are 0 & 15 percent respectively. The characteristics of intensity of the vertical component (r_p) perpendicular to the plane of incidence, and the horizontal component (r_s) parallel to the plane of incidence, at different angles of incidence for glass, gold, and silver are shown in Figure 7 and Figure 8. A light wave with only a horizontal component is called horizontally plane polarized. It is evident from the reflection phenomenon that any kind of reflected light tends to be predominantly horizontally plane polarized,

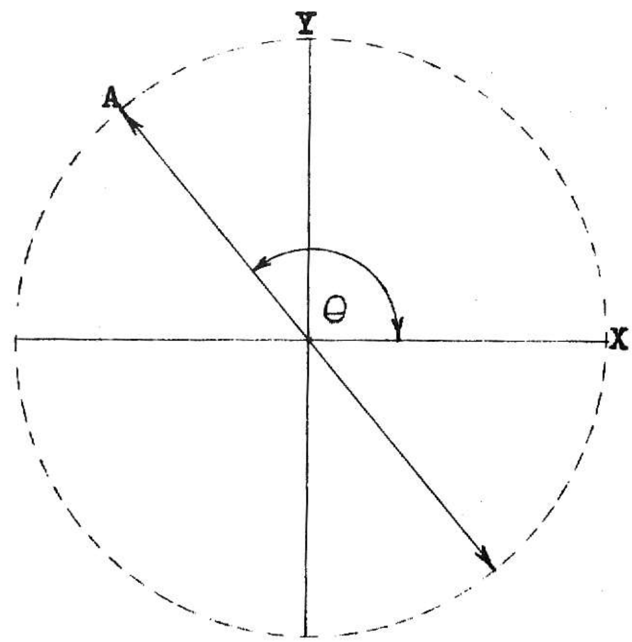


Figure 5. Vibrations in a beam of light viewed end on with amplitude A and phase angle θ.

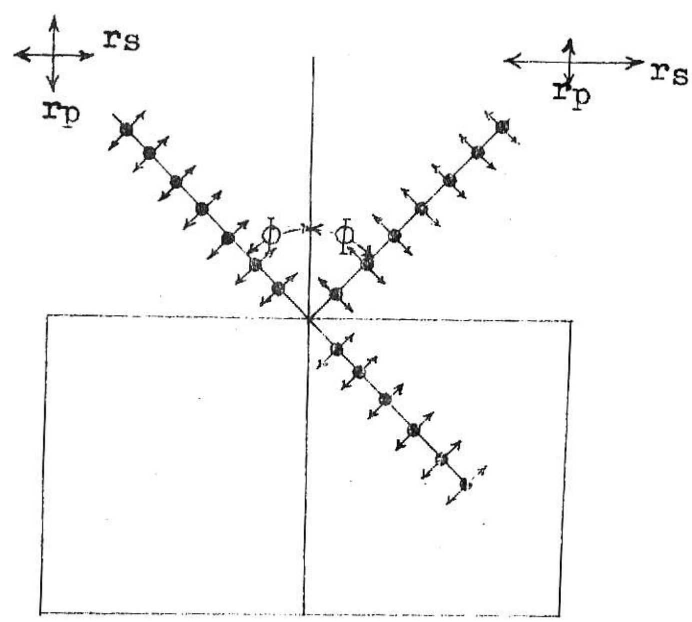


Figure 6. Polarization by reflection.

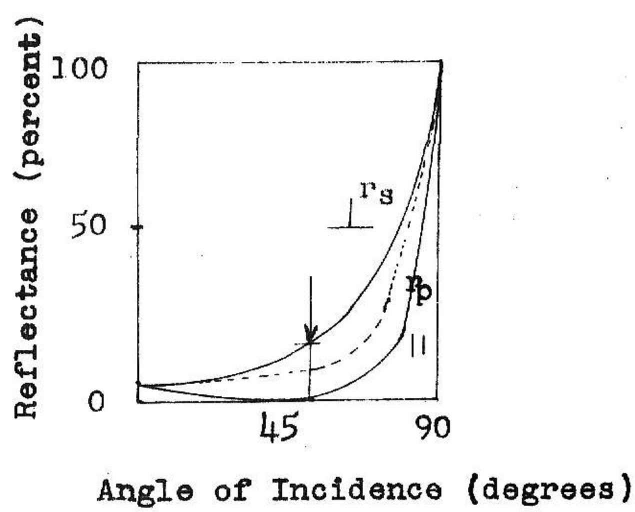


Figure 7. The characteristics of vertical component (r_p) and horizontal component (r_s) at different angles of incidence for glass (Jenkins and White, 1957).

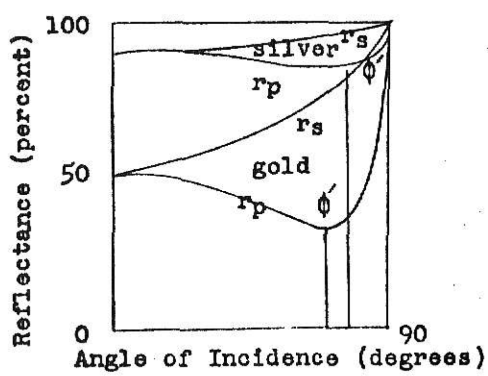


Figure 8. The characteristics of intensity of vertical component (r_p) and horizontal component (r_s) at different angles of incidence for silver and gold (Jenkins and White, 1957).

whereas, ordinary light is only partially horizontally and partially vertically plane polarized.

Reflected glare and polaroid sunglasses. Polaroid sunglasses have a film of organic crystals which have the property of absorbing the horizontal component and transmitting the vertical component with little or no loss, depending on the crystal's orientation. When an observer views through polaroid sunglasses (transmission 0.50), the veiling luminance (L_v) due to any reflected glare gets reduced to 0.5 z L_v, the value of z (polarization effect on transmission) being less than one. Any other light source will, however, be reduced only to one-half in luminance. With the naked eye, the apparent contrast due to a veiling luminance of 10 units from a reflected glare source, in the activity of viewing an object of two units in a field of 100 units, as given by equation 4 will be:

$$C' = \frac{100 - 2}{100 + 10} = 0.89$$

The contrast, C, if the observer is viewing through polaroid sunglasses will be:

$$C' = \frac{100 \times 0.5 - 2 \times 0.5}{100 \times 0.5 + 10 \times 0.5 \times z} \qquad \text{For } z = 0.2;\ C' = 0.96$$

So contrast increases and thus visual performance should be better. However, since luminance is also reduced to one-half, there will be some loss in performance. Nevertheless, at high levels of luminance, the loss due to reduced luminance should not be large (Figure 3) and thus polaroid sunglasses might help visual performance in high levels of luminance and might hurt in low levels of luminance.

Transient adaptation. Another factor which is relevant in visual performance is transient adaptation. When an observer briefly views areas that are much brighter or darker than the task, visual ability can be significantly reduced. Boynton and Miller (1963) and Boynton, Rinalducci and Sternheim (1969) studied the effects of transient adaptation. The studies were concerned with an index of visibility loss, called Φ, which was the ratio of a threshold for a test letter immediately after a transient adaptive change over that obtained after long term adaptation to the luminance. Both studies showed that at lower levels of luminance (less than 400 footlamberts) the value of ϕ depends most importantly on the ratio of the luminances involved in adaptation, and is relatively independent of the absolute levels that produced it and the performance loss is relatively small. At very high levels (4,000 footlamberts), Φ rises steeply.

If the observer is wearing ordinary sunglasses in luminances over 4000 fL., the transient adaptation will improve for the same contrasts. However, at luminance levels lower than 400 footlamberts, no gain in performance during transient adaptation can be predicted since the luminance ratio stays the same. However, since polaroid sunglasses, in addition to reducing absolute value of luminance, also increase contrast between very bright reflected light and ordinary light, their use may be more effective both in high and low luminances in reducing disability due to transient adaptation, if reflected light is involved. Due to the complicated experimental apparatus required for the precise study of transient adaptation, this phenomenon will not be considered further in the thesis.

Discomfort Glare

A form of glare can arise which may not have any accompanying disability, but which may be uncomfortable for the observer. This situation is called "discomfort glare". Discomfort glare may be caused by direct glare from light sources or luminaires, which are too bright, inadequately shielded, or of too great an area, or by reflected glare. For example, the light reflected from clouds or snow clad mountains and other surfaces may cause discomfort glare for a pilot. Another example could be in specular reflections of sunlight from a painted surface of other cars or a roadside sign. The overall discomfort glare found in a given environment by a given observer for one source can be specified by an index of glare sensation, M, given in the IES Handbook (Kaufman, 1966).

$$M = \frac{L\ (20.4\omega + 1.52\omega^{0.2} - 0.075}{F^{0.44} \qquad P} \tag{5}$$

where

L = luminance of the source (footlamberts)

F = field luminance (footlamberts)

P = a position index (of the source)

ω = solid angle subtended by the source (steradians)

The method of evaluation of discomfort glare has been to ask the observers for their direct subjective impression. Luckish and Guth (1949) used a single criterion of discomfort called the "borderline between comfort and discomfort" or "BCD". The procedure was to ask the observer to alter luminance of the glare source to give his judgment of BCD.

Bennett (1971) showed that direct magnitude estimation as a percentage of BCD to be reliable and comparable to observer adjustment. Depending upon various conditions such as position or size, discomfort glare occurs in situations when the luminance level against which human eye is exposed is between hundreds and thousands of footlamberts. Bennett (1971) found that overall mean BCD for six observers, viewing five source sizes subtending 17^{o} to 37^{o}, using continuous and momentary viewing techniques was 2700 footlamberts. This was somewhat higher than what was found by Guth (1963) and Atkinson (1966). Although experimental evaluation depends upon many variable conditions nevertheless, since the luminance encountered in practical outdoor situations in blazing sun is much higher, the use of dark sunglasses would reduce discomfort simply by reducing glare source luminance. For reflected glare, polaroid sunglasses might be more effective than the ordinary darkened sunglasses of the same transmittance because they absorb all the horizontally plane polarized light.

PROBLEM

As is seen in the Introduction, research has been done in the fields of visual performance, disability glare, and discomfort glare. The various variables involved have been defined and their inter-relationships have been investigated under different conditions.

Blackwell (1954) developed theoretical models and investigated the effect of plain sunglasses on visual performance and disability glare at low levels of luminance, but no theoretical models have been investigated for the effect of either ordinary or polaroid sunglasses on visual performance, disability glare, or discomfort glare. However, based upon the knowledge of the physical principles of optics, and the expected effects of variables like luminance, transient adaptation, contrast, veiling luminance, and BCD under different seeing situations with and without the use of ordinary or polaroid sunglasses, some directional hypothesis have been formulated in the earlier section. The purpose of this study was to experimentally test the significance of these hypothesis.

There is a theoretical basis to predict that both types of sunglasses reduce visual performance at all levels of luminance, but the effect may not be large at very high levels of luminance. Polaroid sunglasses should help to reduce disability glare when it is caused by a source of veiling luminance due to reflected glare at high levels of luminance. Neither the polaroid nor ordinary sunglasses can reduce disability glare if the source of glare (veiling luminance) is due to non-polarized light.

The last hypothesis was that polaroid and ordinary sunglasses reduce discomfort glare by the same amounts for non-polarized light in accordance with their transmission, but polaroid sunglasses are more effective than the ordinary sunglasses for reflected glare.

The present study determined experimentally whether there were differences in the functioning of polaroid sunglasses and ordinary sunglasses in direct visual performance, in reducing disability glare due to veiling luminances caused by reflected light and in reducing discomfort glare due to the same source. The two types of plain sunglasses (0.20 and 0.30 transmission) and polaroid sunglasses (0.15 transmission) were tested for light reflected from a painted steel surface for 45° angle of incidence under a background luminance of 100 footlamberts. The criteria were visual acuity and direct magnitude estimation of BCD.

METHOD

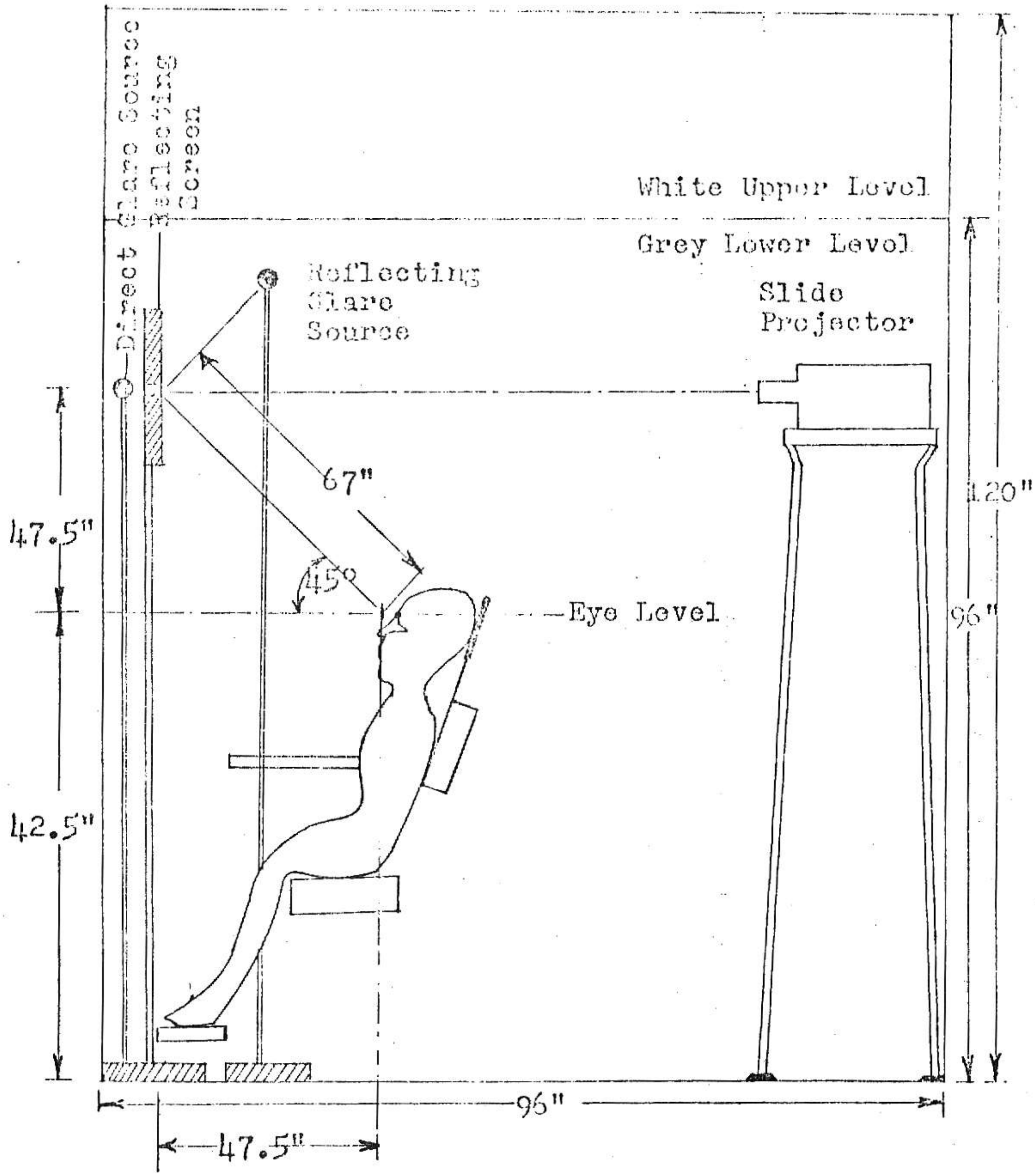
Overview

Two different experiments were conducted on six subjects. In the first experiment, visual acuity angle and subjective estimation of visibility was determined in a background luminance of 100 footlamberts with (a) direct viewing, (b and c) viewing through plain sunglasses (0.20 and 0.30 transmission) and (d) polaroid sunglasses (0.15 transmission). The three glare conditions were without a glare source, with a direct glare source (equivalent veiling luminance equals 6.8 footlamberts) and a reflected glare source (*1000 footlamberts*). The reflected glare was produced by reflection at an angle of incidence of 45^{o} from a flat steel sheet, painted Ermine white.

In Experiment Two, subjects were trained for glare judgment of BCD and estimated magnitude of BCD from a reflected glare source with direct viewing, viewing through two plain sunglasses (0.20 and 0.30 transmission) and polaroid sunglasses of 0.15 transmission.

Experimental Arrangement and Apparatus

The side view and plan of experimental arrangement are shown in Figure 9 and Figure 10. The apparatus for the experiment mainly consisted of an experimental booth, training booth, a slide projector for background luminance source, a variable transformer, a direct glare source, a reflected glare source, sunglasses, an adjustable chair, a vertically adjustable screen, and a light source for training the observers for BCD judgment.



Sketch not to scale.

Figure 9. Experimental booth (side view).

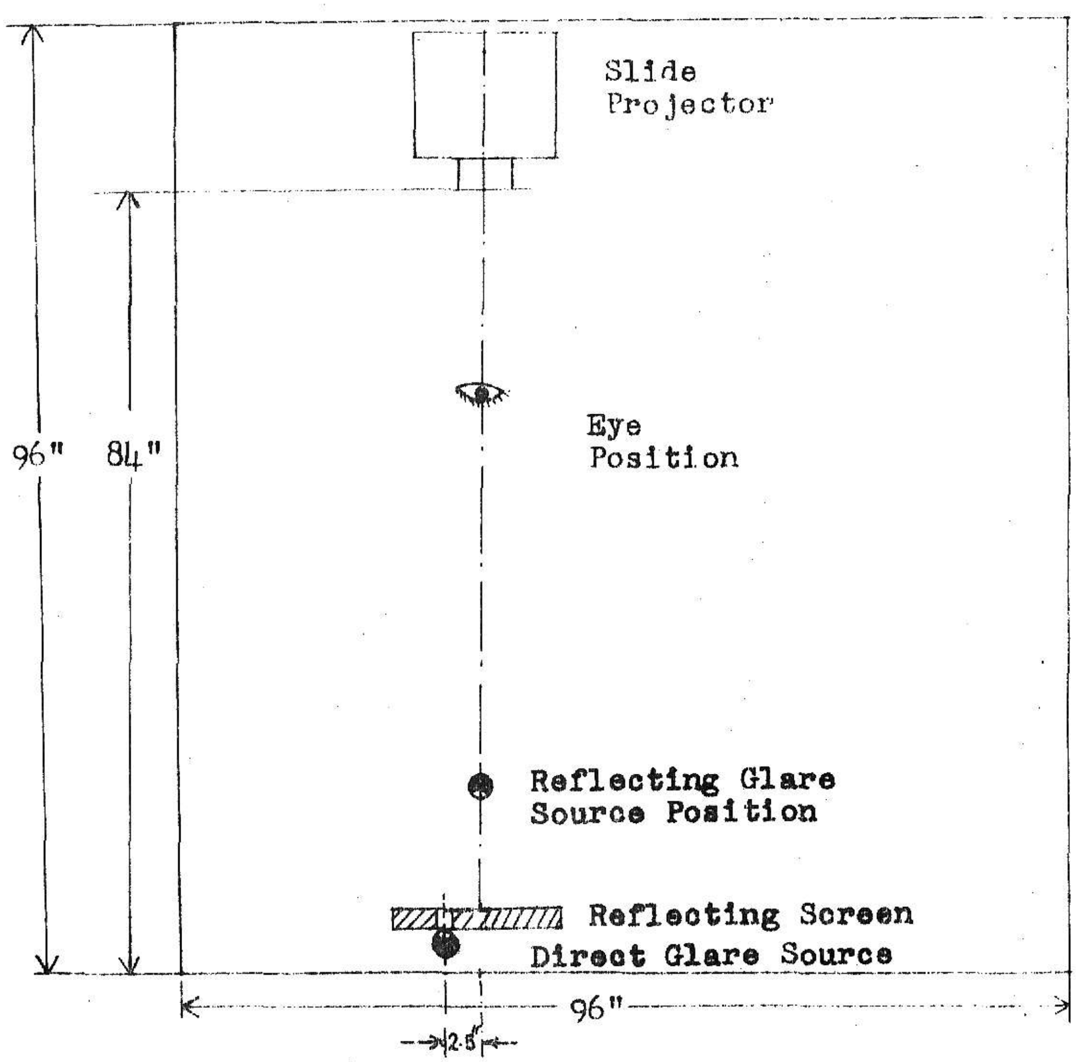


Figure 10. Experimental booth (plan).

Experimental booth. The experimental booth crosssection is shown in Figure 9. The upper walls and ceiling surfaces were plywood painted matte white (reflectance equals 0.75). The lower wall and subject table surfaces were masonite painted light grey (reflectance equals 0.65). Floor tiles were of mixed colors (reflectance equals 0.5). All light in the experimental booth was provided by the slide projector.

Training booth. The training booth is a room 6 x 3 x 6.5 feet. Inside surfaces are light grey poster board. At the end of the booth at seated eye level is an incandescent light source used for training. While the source is fifteen by fifteen inches with nine 150 watt incandescent bulbs, a one and one-quarter inch circular aperature cut in a black background, positioned opposite one bulb was used as a training source.

Slide projector. A Kodak slide projector with a remote control was used to project task slides.

Sunglasses. The sunglasses used in the study were grey 2 (plain), grey 3 (plain), and grey 3 (polaroid). All were manufactured by the Liberty Optical Company. The transmission of all sunglasses was measured by a photometer.

Reflecting material. A 18" by 14" steel plate painted Ermine white (Ditzler No. 8259) was used as the reflecting material for reflected glare. The angle of polarization (measured in the Department of Physics, Kansas State University) was 53°.

Glare sources. Two separate 200 watt, 250 volts bulbs, mounted on vertically adjustable stands were used as the sources for direct and reflected glare. The bulbs were completely shielded with aluminum foil except for a circular apperture of one and one-half inch diameter. The luminance was varied between 300 and 1000 fL. with a variable transformer.

Experimental Design and Procedure

Experiment One. The experimental design was a four (viewing conditions) by three (glare conditions) by six (subjects) by three (replications) factorial design.

The four viewing conditions were direct viewing, viewing through plain sunglasses of twenty percent and thirty percent transmission and polaroid sunglasses of fifteen percent transmission. The three glare conditions were no glare, direct glare (equivalent to 7.8 footlamberts), and reflected glare (equivalent to 1000 footlamberts). The direct glare was produced by light on the screen at a distance of 2.5" from the center of the Landolt ring to the center of a one and one-fourth inch diameter hole in the screen. The glare source was directly behind the hole.

Subjects served one hour a day, five days a week with one subject during a given session. On arrival the subject entered the experimental booth and was seated for five minutes with illumination set equal to one of the twelve conditions selected at random. He was then told about the purpose of the study and was given the following instructions about the task, "As the first part of your work as a subject, you will be participating in an experiment which I am running. In this experiment, you will see various conditions; some involving glare. You may view these directly or with a pair of sunglasses. There will be two major parts to this experiment. During the first part, your visual acuity will be tested. During the last part, you will be asked to make some glare judgment. The purpose of the first part is to evaluate visual acuity for various combinations of glare conditions and viewing conditions. In all these conditions, I want you to keep your eyes on the center of the circle on the screen and you are not to move your head at all." At this point, the experimenter projected a test slide.

Instructions to the subject were continued as follows, "You are going to take part in the experiment in five minutes. During these five minutes, I want you to simply look at the screen. At the end of five minutes, I shall project a slide similar to the one you now see on the screen. As you can see, it consists of a circle marked with numbers from one to eight around its periphery. Within this bigger circle, there is a smaller circle. Right in the center of both these circles, there is a small ring with a gap. The gap is pointed towards one of the eight positions marked on the outer circle. Your job is to try to find that number and speak it aloud. As you see it in this case, it is "five". If in some conditions you cannot see it at all, I want you to say "can't see", but I want you to guess on any occasion when you can see the ring. Then I shall project the next slide for which you have to tell me once again the number towards which the gap in the ring points. The projection of the slides will continue until I change the condition. Once again, I want to remind you that you are not to move your head to get away from the position of glare during any condition. After the end of conditions, in which you are wearing sunglasses, I want you to give me your judgment of effect of sunglasses on your ability to see. If you think it is no better, nor worse for seeing well than having no sunglasses, under no glare, call it "100". If however you think it is twice as good, call it "200". If ten percent more, call it "110" or "112" or whatever you think it is. Similarily if you think it is half as bad for seeing well than having no sunglasses, call it "50"; if eighty percent, call it "80" or call it "75" or whatever you think it is. Please feel free to ask any questions." At the end of five minutes, the experimenter projected the task slide with the smallest angle and had the subject's response recorded in Table I. The projection of slides continued in an ascending order of the size of the ring, until the subject gave correct responses for two consecutive ring sizes. For every size, four randomly sequenced slides were shown. After the completion of visual acuity task for the condition, the subject gave subjective judgment of visibility in that condition as compared to condition one.

At the completion of one condition, which took about three minutes, the experimenter changed conditions to another condition selected randomly and had the subject look at it while the experimenter was changing the sequence of task slides. The task was then projected for the new condition and this continued throughout the one hour session with all the twelve conditions being run for the subject. In the next experimental

TABLE 1

Data Sheet for Experiment One

Subject Name:________________ Replication 1 2 3

Condition No.________ Glare Source: None Direct Reflected

Sunglasses: None Grey 2 Grey 3 Polaroid Grey 3

Slide Size m.m.	PERFORMANCE DATA		No. of Slides	Number Correctly Read	% Correct	REMARKS
	Correct Reading	Subject Reading				
1.2			2			
1.6			4			
2.0			4			
2.4			4			
2.8			4			
3.2			4			
3.6			4			
4.0			4			
4.4			2			

Subjective Judgment of Visual Performance________________ session, the subject began a new randomized replication of all twelve conditions. (All randomizations were different for different observers.)

A Landolt ring (Figures 11 and 12) with its gap subtending angles from 0.48 minute to 1.76 minutes in increments of 0.16 was projected with the position of the gap at one of eight randomly selected positions on a 18" by 14" white screen. Numbers from one to eight in a circle of nine inches diameter were also projected.

The projected Landolt broken circle had its gap corresponding to one of the eight numbers in the circle on the screen. The subjects were allowed sufficient time to find the correct positioning of the gap and speak it aloud. The percentage of correct answers were plotted against the gap angles on a probability graph (Figure 13). The angle at fifty percent correct judgment on the curve was taken as the index of visual acuity angle for that condition.

Experiment two. Experimental design was a four (viewing conditions) by six (subjects) by three (replications) factorial design. The same four viewing conditions were used as in Experiment One.

Each subject was given one hour of training on low and high luminances. During the training session, subjects were shown the light source at a very high luminance (1500 footlamberts). They were told "You would probably consider this light uncomfortably glaring." The light was then lowered to a very low luminance (50 fL.). The subjects were told "You would probably find this light comfortable. Somewhere in between that first, uncomfortably glaring light and this comfortable light there must be a change point, a threshold, where the light is no longer uncomfortable. This is called, the Borderline between Comfort and Discomfort or "BCD."

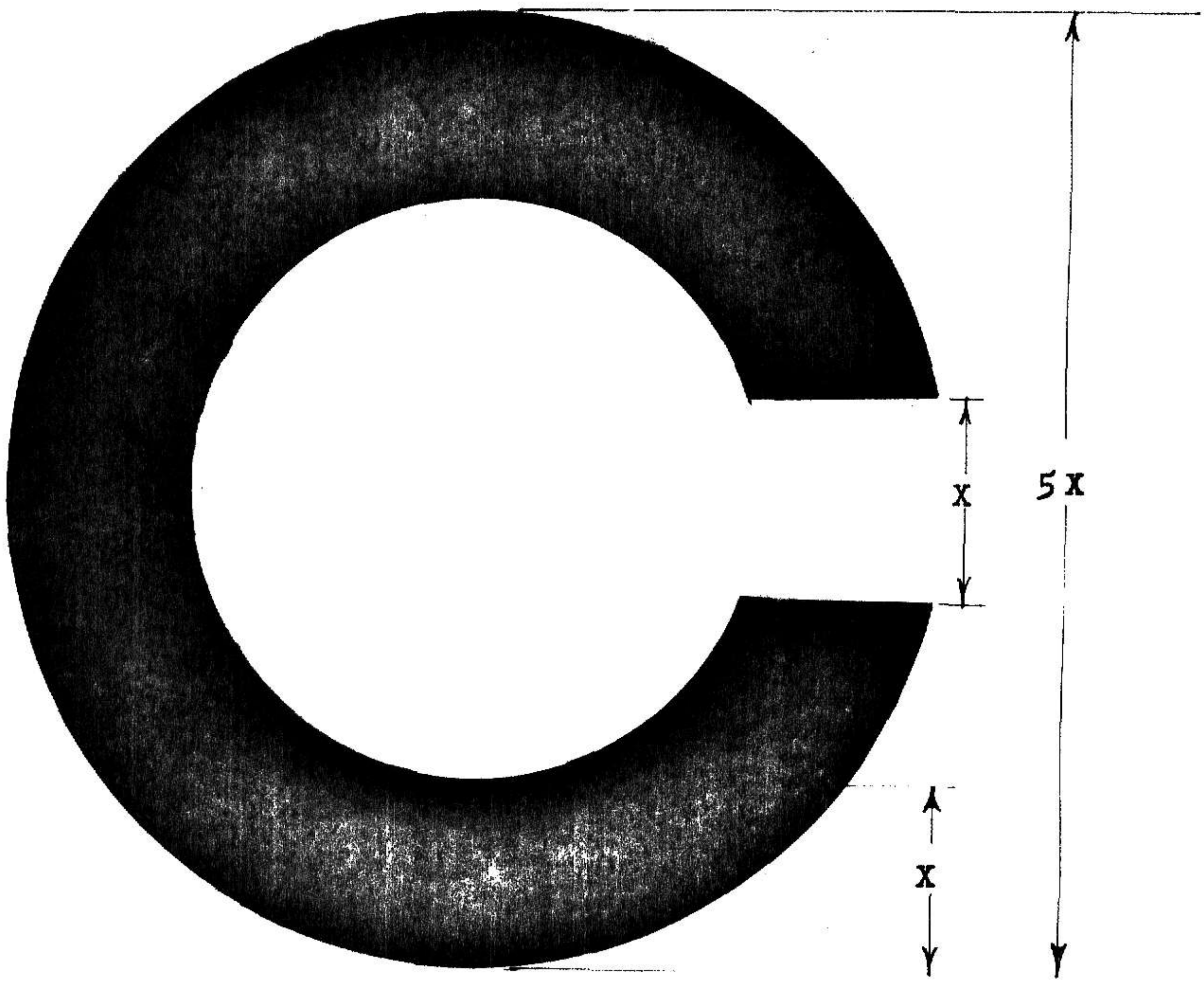


Figure 11. Dimensions of Landolt ring.

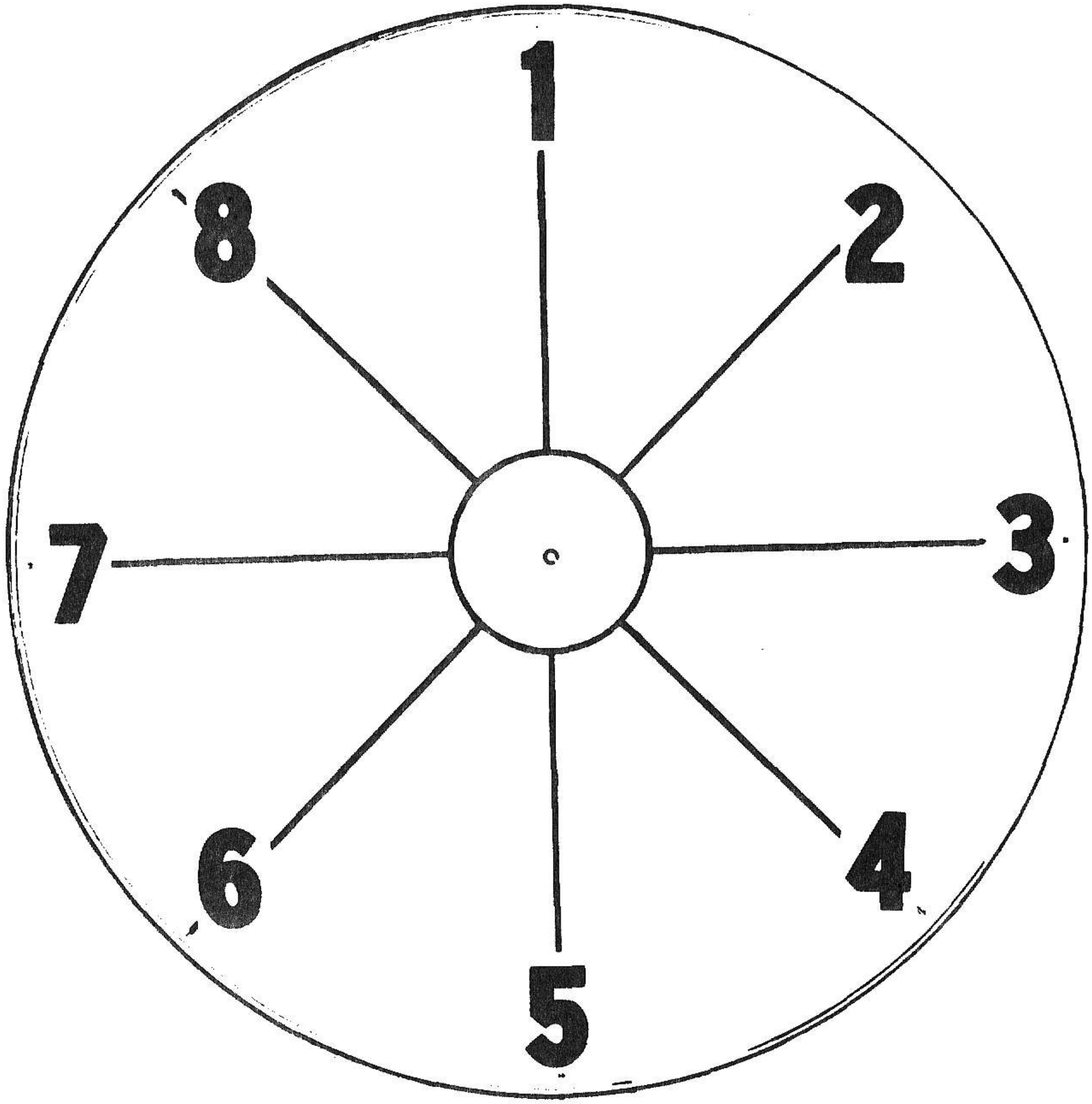


Figure 12. The task.

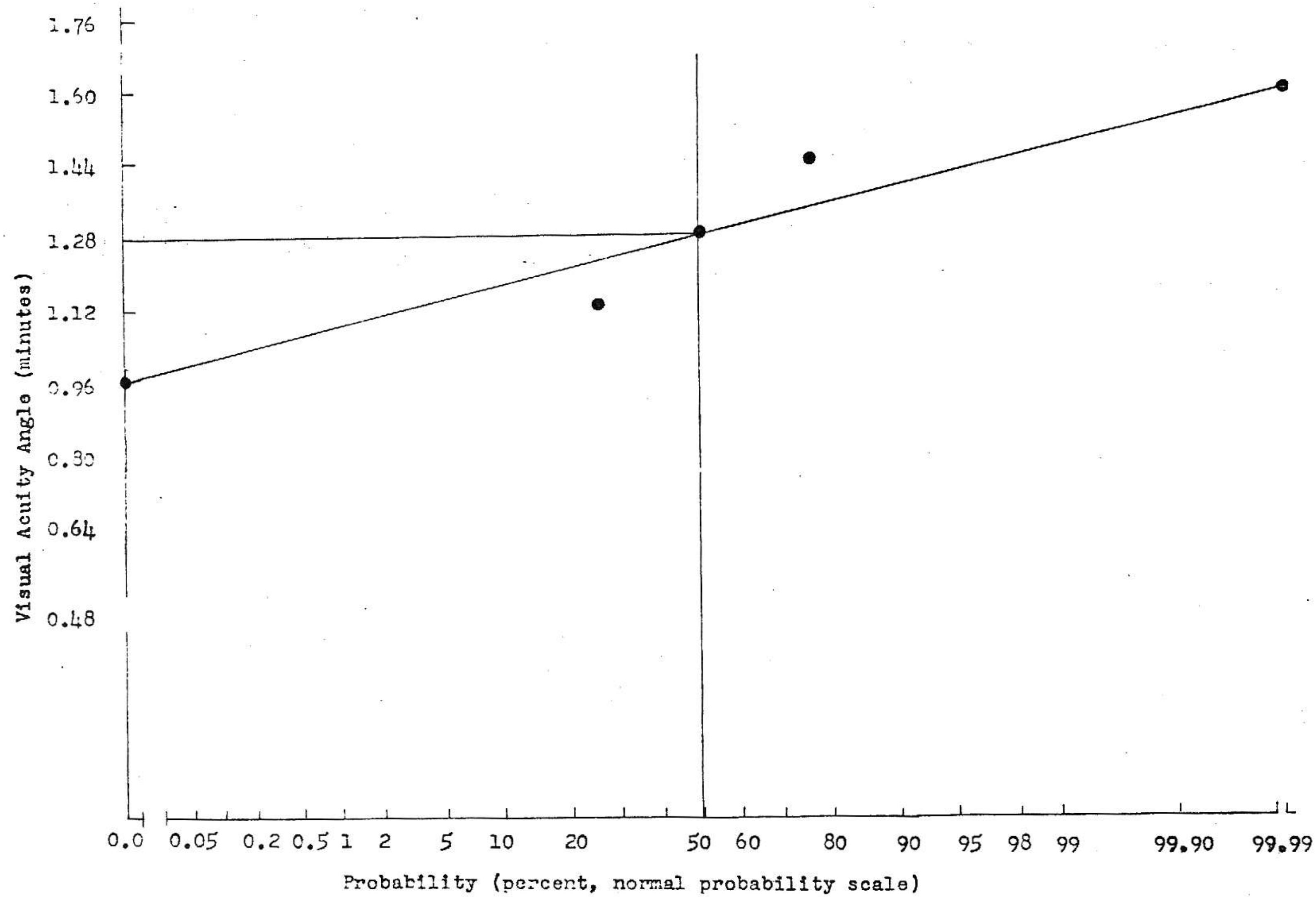


Figure 13. Index of visual acuity angle.

In response to any questions about the criterion, subjects were told that it was simply their judgment as to where BCD was, that the experimenter could not tell them whether they were "right" or "wrong" because there was no right or wrong to it - whatever they felt was BCD was BCD.

First, all subjects made BCD adjustments by light control switch. A median BCD was determined for each and shown to the subject. He was then instructed: "This is your median BCD. Look at it. Now, I want you to adjust the source to an arbitrarily higher level. If that level seemed to you to be twice as glaring a BCD, then you would call it "200"; it ten percent more, call it "110" or "112" or whatever you think it is. Then adjust the light back to BCD. Study it. Now adjust the light down to an arbitrarily lower level. If you think it is only half as glaring as BCD, call it "50"; if eighty percent, call it "80" or call it "73" or whatever you think it is."

In running the study, one of four viewing conditions was selected at random. One of the six luminances (produced by a variable transformer calibrated with a photometer) was selected at random and presented for judgment. After all the six luminances had been presented a second of the four conditions was selected. Only one subject at a time for one hour a day was run. The subject was seated in the experimental booth and completed all the four viewing conditions with a rest period of two minutes between conditions. The replications for each subject were randomized and different random replications were run for different subjects. The data was recorded in Table 2.

The task in experiment three was the subjective magnitude estimation

TABLE 2

Data Sheet for Experiment Two (Magnitude Estimation of BCD)

Subject Name:__________________ No.________ Replication No.________

1. Training Data:

Trial No.	1	2	3	4	5	6	7	8	9	10	Mean	Median
B.C.D.												
Order Of Magnitude												

2. Experiment No. 2: Random Sequence of Viewing Conditions____________

S. No.	Luminance Foot Lamberts	VIEWING CONDITIONS			
		Direct Viewing (1)	Plain Grey 2 Sunglasses (2)	Plain Grey 3 Sunglasses (3)	Polaroid Grey 3 Sunglasses (4)
1	300				
2	400				
3	500				
4	700				
5	950				
6	1,000				

of BCD. The subjects estimated magnitude of six luminances (300, 400, 500, 700, 950, & 1,000 footlamberts). A straight line was drawn by eye on a log - log plot for all these luminances against the BCD estimations (Figure 14). The luminance corresponding to one hundred per cent was taken as the index of BCD.

The Subjects

Six male students of Kansas State University worked as subjects in both experiments. None of the six subjects wore corrective lens. The subjects were paid on a hourly basis and were informed about the purpose of these studies before the starting of the experiments. The age of the subjects ranged from 23 to 31 years with a median of 24.

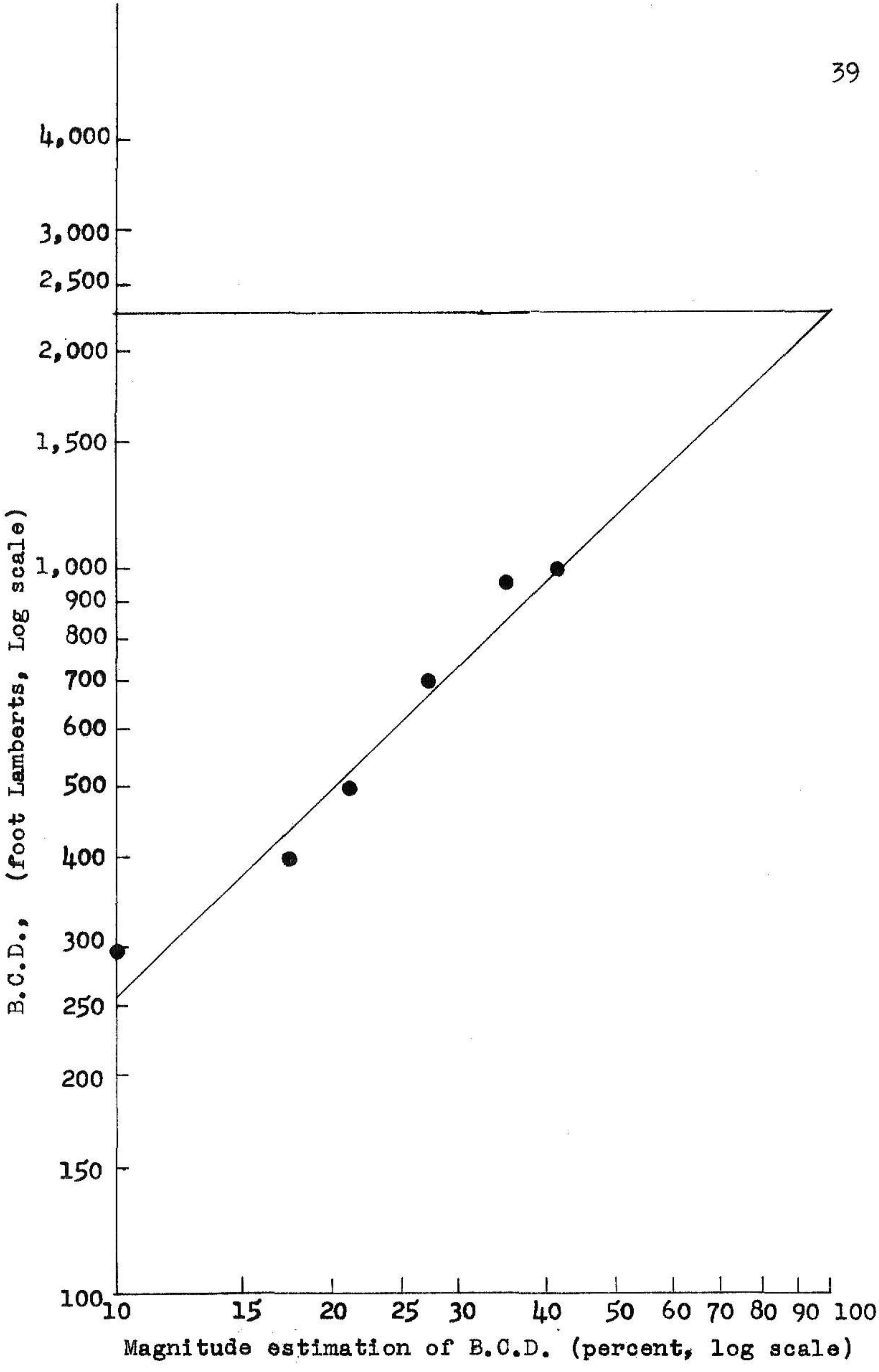


Figure 14. Magnitude estimation of B.C.D.

RESULTS

Data Analysis

All visual acuity angles, subjective judgment of visual performance, and magnitude estimation of BCD were calculated and are presented in Table 3 through Table 5. All the three variables were statistically analyzed by means of analysis of variance (ANOVA). The Kansas State University Department of Statistics and Computer Science "AARDVARK" Program was utilized. Using this fixed model analysis, significance was established at the 0.05 level. All the significant variables and their interactions were further tested by Duncan's multiple range test at the 0.05 level. For all measures, the ANOVA utilized two or more of the following variables:

	d.f.
G = (1) No glare, or (2) direct glare, or (3) reflected glare	2
V = (1) Viewing with no sunglasses, or (2) viewing through grey 2 (plain) sunglasses, or (3) viewing through grey 3 (plain) sunglasses, or (4) viewing through grey 3 (polaroid) sunglasses	3
S = Subjects (6)	5
R = Replications (3)	2

Visual Acuity Angle

In the case of visual acuity performance, the variables utilized for ANOVA were; three glare conditions (G), four viewing conditions (V), six subjects (S), and three replications (R). Table 6 gives the four

TABLE 3

Data, Means, Visual Acuity Angles, in Minutes

Viewing Conditions	Subject Number	No Glare Replications 1	No Glare Replications 2	No Glare Replications 3	No Glare Mean	Direct Glare Replications 1	Direct Glare Replications 2	Direct Glare Replications 3	Direct Glare Mean	Reflected Glare Replications 1	Reflected Glare Replications 2	Reflected Glare Replications 3	Reflected Glare Mean	Mean Of Means	GRAND MEANS
Direct Viewing	1	0.48	0.48	0.56	0.507	0.65	0.55	0.56	0.590	1.76	1.22	0.78	1.253	0.733	
	2	0.64	0.52	0.62	0.593	0.64	0.48	0.56	0.560	1.08	0.72	0.64	0.813	0.655	
	3	0.48	0.48	0.48	0.480	0.56	0.56	0.56	0.560	1.70	1.28	1.12	1.367	0.802	
	4	0.64	0.56	0.48	0.560	0.65	0.52	0.56	0.577	0.94	0.94	0.97	0.950	0.696	
	5	0.48	0.48	0.48	0.480	0.64	0.62	0.48	0.580	1.36	1.00	0.86	1.073	0.711	
	6	0.56	0.48	0.48	0.507	0.48	0.56	0.56	0.533	0.86	0.80	0.72	0.793	0.611	
	Mean	0.55	0.50	0.52	0.521	0.60	0.55	0.55	0.557	1.28	0.99	0.85	1.042		0.710
Viewing Through Grey 2 Plain Sunglasses (Transmission equals 0.30)	1	0.72	0.62	0.62	0.653	0.80	0.64	0.56	0.667	1.76	1.26	0.72	1.247	0.855	
	2	0.82	0.64	0.56	0.673	0.65	0.62	0.52	0.597	1.36	0.80	0.72	0.960	0.743	
	3	0.56	0.48	0.48	0.507	0.56	0.48	0.48	0.507	1.12	1.24	1.08	1.147	0.719	
	4	0.82	0.64	0.48	0.647	0.72	0.62	0.58	0.640	1.61	0.86	0.94	1.137	0.808	
	5	0.56	0.56	0.56	0.560	0.52	0.62	0.48	0.540	1.12	1.10	0.88	1.033	0.711	
	6	0.56	0.52	0.48	0.520	0.56	0.82	0.56	0.647	1.06	0.80	0.94	0.933	0.700	
	Mean	0.67	0.58	0.53	0.593	0.64	0.63	0.53	0.599	1.34	1.01	0.88	1.076		0.756
Viewing Through Grey 3 Plain Sunglasses (Transmission equals 0.20)	1	0.72	0.62	0.48	0.607	0.65	0.64	0.62	0.637	1.76	1.36	0.78	1.300	0.848	
	2	0.62	0.65	0.62	0.630	0.52	0.62	0.64	0.593	1.32	0.96	0.92	1.067	0.763	
	3	0.56	0.62	0.56	0.580	0.92	0.65	0.56	0.710	1.36	1.20	1.16	1.240	0.843	
	4	0.72	0.65	0.56	0.643	0.72	0.62	0.58	0.640	1.36	1.16	0.96	1.160	0.814	
	5	0.52	0.56	0.48	0.520	0.48	0.62	0.48	0.527	1.16	0.90	0.64	0.900	0.649	
	6	0.72	0.62	0.56	0.633	0.63	0.62	0.48	0.577	1.10	0.96	0.92	0.993	0.734	
	Mean	0.64	0.62	0.54	0.602	0.65	0.63	0.56	0.614	1.34	1.09	0.90	1.110		0.775
Viewing Through Grey 3 Polaroid Sunglasses (Transmission equals 0.15)	1	0.72	0.96	0.52	0.733	0.92	0.64	0.64	0.733	1.28	0.62	0.62	0.640	0.759	
	2	0.70	0.65	0.62	0.657	0.62	0.65	0.62	0.630	0.94	0.64	0.62	0.733	0.673	
	3	0.78	0.56	0.62	0.653	0.56	0.64	0.64	0.613	0.76	0.62	0.62	0.667	0.644	
	4	0.72	0.64	0.58	0.650	0.72	0.64	0.58	0.647	0.72	0.52	0.62	0.620	0.638	
	5	0.56	0.56	0.56	0.560	0.64	0.76	0.48	0.627	0.93	0.56	0.62	0.703	0.630	
	6	0.48	0.64	0.52	0.547	0.70	0.62	0.62	0.647	0.65	0.74	0.56	0.650	0.614	
	Mean	0.66	0.67	0.57	0.633	0.69	0.66	0.60	0.649	0.88	0.62	0.61	0.702		0.661
Mean Of Means		0.63	0.59	0.54		0.65	0.62	0.56		1.21	0.93	0.81			
GRAND MEANS					0.587				0.607				0.982		0.725

TABLE 4

Data, Means, Subjective Judgment of Visual Performance, Percent

Viewing Conditions	Subject Number	GLARE CONDITIONS: No Glare, Replications 1	2	3	Mean	Direct Glare, Replications 1	2	3	Mean	Reflected Glare, Replications 1	2	3	Mean	Mean of Means	GRAND MEANS
Direct Viewing	1	100	100	100	100	80	75	85	80	35	20	50	35	71.7	
	2	100	100	100	100	95	95	100	95	10	60	95	55	83.3	
	3	100	100	100	100	80	87	85	84	80	90	85	85	90.0	
	4	100	100	100	100	115	95	98	103	50	35	60	50	84.3	
	5	100	100	100	100	98	92	102	94	95	90	94	93	95.7	
	6	100	100	100	100	80	80	80	80	60	70	85	70	83.3	
	Mean				100.0				89.5				64.7		84.7
Viewing Through Grey 2 Plain Sunglasses (Transmission equals 0.30)	1	93	95	90	93	77	80	75	77	50	35	65	50	73.3	
	2	130	110	95	110	100	90	105	98	50	80	60	63	90.3	
	3	95	99	88	93	90	95	90	92	75	82	90	82	89.0	
	4	100	90	100	97	95	90	100	95	20	70	70	53	81.7	
	5	105	108	100	104	110	105	100	105	90	93	97	94	101.0	
	6	90	90	95	92	85	85	80	83	50	75	75	67	80.7	
	Mean				98.2				91.7				68.1		85.9
Viewing Through Grey 3 Plain Sunglasses (Transmission equals 0.20)	1	87	90	85	87	83	80	85	83	37	35	40	37	69.0	
	2	130	120	75	108	130	100	95	108	30	30	60	40	85.3	
	3	100	92	85	92	105	95	87	96	85	85	93	87	91.7	
	4	70	98	100	87	100	110	95	102	20	30	65	38	75.7	
	5	115	108	108	110	110	98	106	105	90	95	102	95	103.3	
	6	95	80	80	85	95	90	93	93	50	75	70	65	81.0	
	Mean				94.8				97.8				60.3		84.3
Viewing Through Grey 3 Polaroid Sunglasses (Transmission equals 0.15)	1	62	30	95	62	85	80	90	85	87	100	75	87	78.0	
	2	100	115	105	107	120	100	100	107	95	60	80	78	97.3	
	3	90	98	95	94	90	90	90	90	90	90	90	90	91.3	
	4	125	95	105	108	120	98	105	108	80	90	110	93	103.0	
	5	110	98	112	107	105	100	105	103	86	96	108	97	102.3	
	6	95	90	90	92	95	95	90	93	85	75	90	86	90.3	
	Mean				95.0				97.7				83.5		93.7
GRAND MEANS					96.9				94.2				70.4		87.1

TABLE 5

Data, Magnitude Estimation of B.C.D. (BCD's in Foot Lamberts)

Experiment Number 2:

Subject Number	VIEWING CONDITIONS			
	Direct Viewing (1)	Plain Grey 2 Sunglasses (2) (Transmission equals 0.30)	Plain Grey 3 Sunglasses (3) (Transmission equals 0.20)	Polaroid Grey 3 Sunglasses (4) (Transmission equals 0.15)
1	1,300	2,300	2,350	3,000
2	1,200	1,000	1,850	2,500
3	1,300	2,000	2,500	4,000
4	1,050	1,300	2,750	4,000
5	1,350	1,800	2,000	2,500
6	1,400	1,800	1,550	2,500

TABLE 6

Analysis of Variance of Visual Task Angle for Three Glare Conditions for Four Viewing Conditions

Source of Variance	df	MS	F
Glare Conditions (G)	2	3.5671	361.615**
Viewing Conditions (V)	3	0.1400	14.196**
Subjects (S)	5	0.1093	11.079**
Replications (R)	2	0.6868	69.520**
G x V	6	0.2830	28.580**
G x S	10	0.0578	5.763**
G x R	4	0.2194	22.237**
V x S	15	0.0182	1.840
V x R	6	0.0089	0.896
S x R	10	0.0425	4.312**
G x V x S	30	0.0154	1.563
G x V x R	12	0.0079	0.799
V x S x R	30	0.0074	0.745
G x S x R	20	0.0270	2.734**
G x V x S x R	60	0.0099	
Total	215		

*$p < .05$
**$p < .01$

way ANOVA of visual acuity angle. All variables and interactions are considered and all significant effects ($p < 0.05$) are identified.

There were significant effects for glare conditions, viewing conditions, subjects and replications. There were also significant interactions of glare by viewing conditions, glare by subjects, glare by replications, viewing conditions by replications, subjects by replications, and subjects by glare conditions by replications.

Glare conditions. Table 7 shows results of Duncan's multiple range test for the three glare conditions. Direct glare was not significantly different from no glare conditions. However, both are significantly better than reflected glare.

Viewing conditions. Table 8 presents the results of Duncan's multiple range test for the four viewing conditions. Polaroid sunglasses were significantly better than either of the two plain sunglasses. There was no significant difference between plain grey 2 and plain grey 3 sunglasses.

Subjects. There were individual differences among the subjects as shown in Table 9.

Replications. There were significant differences in all the replications. Acuity improved with every replication as shown in Table 10.

Glare conditions by viewing conditions. Table 11 gives the results of Duncan's multiple range test for the interaction of glare conditions by viewing conditions. For reflected glare, polaroid sunglasses significantly improved the visual acuity performance. There were no significant differences between direct glare viewing conditions. For no

TABLE 7

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Three Glare Conditions on Visual Acuity Angle

Entry	Means (Visual Acuity Angle, Minutes)	
Reflected Glare	0.9824	
Direct Glare	0.6073	*
No Glare	0.5873	*

* Non-significant groupings connected by column of asterisks

TABLE 8

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Four Viewing Conditions on Visual Acuity Angle

Entry	Means (Visual Acuity Angle, Minutes)	
Grey 3 Plain Viewing Transmission = 0.20	0.7753	*
Grey 2 Plain Viewing Transmission = 0.30	0.7562	*
Direct Viewing	0.7098	
Grey 3 Polaroid Viewing Transmission = 0.15	0.6614	

* Non-significant groupings connected by column of asterisks

TABLE 9

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Six Subjects on Visual Acuity Angle

Entry	Means (Visual Acuity Angle, Minutes)		
Subject 1	0.8138		
Subject 3	0.7524	*	
Subject 4	0.7388	*	
Subject 2	0.7088	*	*
Subject 5	0.6752		*
Subject 6	0.6649		*

* Non-significant groupings connected by column of asterisks

TABLE 10

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Three Replications on Visual Acuity Angle

Entry	Means (Visual Acuity Angle, Minutes)
Replication 1	0.8294
Replication 2	0.7120
Replication 3	0.6356

* Non-significant groupings connected by column of asterisks

TABLE 11

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Three Glare Conditions by Four Viewing Conditions on Visual Acuity Angle

Entry	Means (Visual Acuity Angle, Minutes)	
Reflected Glare x Grey 3 Plain Viewing Transmission = 0.20	1.1099	*
Reflected Glare x Grey 2 Plain Viewing Transmission = 0.30	1.0761	*
Reflected Glare x Direct Viewing	1.0416	*
Reflected Glare x Grey 3 Polaroid Viewing Transmission = 0.15	0.7022	*
Direct Glare x Grey 3 Polaroid Viewing Transmission = 0.15	0.6494	**
No Glare x Grey 3 Polaroid Viewing Transmission = 0.15	0.6327	***
Direct Glare x Grey 3 Plain Viewing Transmission = 0.20	0.6138	**
No Glare x Grey 3 Plain Viewing Transmission = 0.20	0.6022	**
Direct Glare x Grey 2 Plain Viewing Transmission = 0.30	0.5994	**
No Glare x Grey 2 Plain Viewing Transmission = 0.30	0.5933	**
Direct Glare x Direct Viewing	0.5666	**
No Glare x Direct Viewing	0.5211	*

* Non-significant groupings connected by column of asterisks

glare, viewing through all the sunglasses was worse than direct viewing. Reflected glare made visual acuity angle significantly worse in the case of direct viewing and viewing through grey 2 or grey 3 plain sunglasses. Effect of any glare condition was not significant for polaroid sunglasses.

Glare conditions by subjects. Table 12 gives the results of Duncan's multiple range test for the interaction of glare conditions by subjects. Reflected glare was significantly effective for reduced visual acuity for all the subjects. There was no significant difference between direct glare and no glare for any of the subjects.

Glare conditions by replications. Table 13 gives the results of Duncan's multiple range test for interaction of glare conditions by replications. There was a significant replication effect for reflected glare. There was no significant replication effect for either no glare condition or direct glare condition. Also the replication effect for reflected glare was significantly different from that of direct glare or no glare.

Viewing conditions by replications. Table 14 presents the results of Duncan's multiple range test. There was a significant difference between the first and the second replications for all the viewing conditions. However, only in the case of Grey 2 (Plain) and Grey 3 (Plain) viewing conditions was there a significant difference between the second and the third replications.

Subjective Judgment of Visual Performance.

The data for subjective judgment of visual performance was analyzed for the average subjective judgments as shown in Table 4. The ANOVA

TABLE 12

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Three Glare Conditions by Six Subjects on Visual Acuity Angle

Entry	Means (Visual Acuity Angle, Minutes)	
Reflected Glare x Subject 1	1.1599	*
Reflected Glare x Subject 3	1.1050	*
Reflected Glare x Subject 4	0.9666	*
Reflected Glare x Subject 5	0.9275	**
Reflected Glare x Subject 2	0.8933	**
Reflected Glare x Subject 6	0.8424	*
Direct Glare x Subject 1	0.6566	*
No Glare x Subject 2	0.6383	**
Direct Glare x Subject 4	0.6258	**
No Glare x Subject 1	0.6249	**
No Glare x Subject 4	0.6241	**
Direct Glare x Subject 6	0.6008	***
Direct Glare x Subject 3	0.5974	***
Direct Glare x Subject 2	0.5949	***
Direct Glare x Subject 5	0.5683	***
No Glare x Subject 3	0.5549	**
No Glare x Subject 6	0.5516	**
No Glare x Subject 5	0.5299	*

* Non-significant groupings connected by column of asterisks

TABLE 13

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Three Glare Conditions by Three Replications on Visual Acuity Angle

Entry	Means (Visual Acuity Angle, Minutes)	
Reflected Glare x Replication 1	1.2112	
Reflected Glare x Replication 2	0.9274	
Reflected Glare x Replication 3	0.8087	
Direct Glare x Replication 1	0.6462	*
No Glare x Replication 1	0.6308	*
Direct Glare x Replication 2	0.6175	**
No Glare x Replication 2	0.5912	***
Direct Glare x Replication 3	0.5583	**
No Glare x Replication 3	0.5399	*

* Non-significant groupings connected by column of asterisks

TABLE 14

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Three Replications by Four Viewing Conditions on Visual Acuity Angle

Entry	Means (Visual Acuity Angle, Minutes)	
Replication 1 x Grey 2 Plain Viewing Transmission = 0.30	0.8822	*
Replication 1 x Grey 3 Plain Viewing Transmission = 0.20	0.8799	*
Replication 1 x Direct Viewing	0.8111	*
Replication 2 x Grey 3 Plain Viewing Transmission = 0.20	0.7794	*
Replication 1 x Grey 3 Polaroid Viewing Transmission = 0.15	0.7444	**
Replication 2 x Grey 2 Plain Viewing Transmission = 0.30	0.7399	**
Replication 2 x Direct Viewing	0.6811	**
Replication 3 x Grey 3 Plain Viewing Transmission = 0.20	0.6666	*
Replication 2 x Grey 3 Polaroid Viewing Transmission = 0.15	0.6477	**
Replication 3 x Grey 2 Plain Viewing Transmission = 0.30	0.6466	**
Replication 3 x Direct Viewing	0.6372	**
Replication 3 x Grey 3 Polaroid Viewing Transmission = 0.15	0.5922	*

* Non-significant groupings connected by column of asterisks

utilized three variables: three glare conditions (G), four viewing conditions (V), and six subjects (S). Table 15 gives the three-way ANOVA of the subjective judgments of visual performance. All variables and interactions are considered and all significant effects ($p < 0.05$) are identified. There were significant interactions of glare by viewing conditions and glare by subjects. All these significant effects were further tested by Duncan's multiple range test at the .05 protection level for further analysis.

Glare conditions. Table 16 presents Duncan's multiple range test for glare effect. Only the reflected glare condition has a significantly lower mean value for subjective judgment of visual performance. There was no significant effect for direct glare as compared to the no glare condition.

Viewing conditions. Table 17 presents Duncan's multiple range test for viewing conditions effect. Only viewing through polaroid sunglasses was judged significantly better. There was no significant difference between direct viewing, viewing through grey 2 (plain) sunglasses, or viewing through grey 3 (plain) sunglasses.

Subjects. There was some subject variability as shown in Table 18.

Glare by viewing conditions. Table 19 presents Duncan's multiple range test for the interaction of glare by viewing conditions. Only in the case of reflected glare were grey 3 (polaroid) sunglasses judged to significantly improve visual performance. The improved visual performance by viewing through polaroid sunglasses was not significantly different from any viewing condition under no glare or direct glare

TABLE 15

Analysis of Variance of Subjective Judgment of Visual Performance for Three Glare Conditions for Four Viewing Conditions

Source of Variance	df	MS	F
Glare Conditions (G)	2	5,115.035	71.400**
Viewing Conditions (V)	3	350.015	4.885**
Subjects (S)	5	978.220	13.655**
G x V	6	364.573	5.089**
G x S	10	375.254	5.238**
V x S	15	65.385	0.913
G x V x S	30	71.638	
Total	71		

*$p < .05$

**$p < .01$

TABLE 16

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Three Glare Conditions on Subjective Judgment of Visual Performance

Entry	Means	
No Glare	96.99	*
Direct Glare	94.16	*
Reflected Glare	70.42	

* Non-significant groupings connected by column of asterisks

TABLE 17

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Four Viewing Conditions on Subjective Judgment of Visual Performance

Entry	Means	
Grey 3 Polaroid Viewing Transmission = 0.15	93.722	
Grey 2 Plain Viewing Transmission = 0.30	85.999	*
Direct Viewing	84.722	*
Grey 3 Plain Viewing Transmission = 0.20	84.333	*

* Non-significant groupings connected by column of asterisks

TABLE 18

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Six Subjects on Subjective Judgment of Visual Performance

Entry	Means	
Subject 5	100.583	
Subject 3	90.500	*
Subject 2	89.083	*
Subject 4	86.166	*
Subject 6	83.833	*
Subject 1	73.000	

* Non-significant groupings connected by column of asterisks

TABLE 19

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Three Glare Conditions by Four Viewing Conditions on Subjective Judgment of Visual Performance

Entry	Means		
No Glare x Direct Viewing	100.000	*	
No Glare x Grey 2 Plain Viewing Transmission = 0.30	98.166	*	
Direct Glare x Grey 3 Plain Viewing Transmission = 0.20	97.833	*	
Direct Glare x Grey 3 Polaroid Viewing Transmission = 0.15	97.666	*	
No Glare x Grey 3 Polaroid Viewing Transmission = 0.15	95.000	*	
No Glare x Grey 3 Plain Viewing Transmission = 0.20	94.833	*	
Direct Glare x Grey 2 Plain Viewing Transmission = 0.30	91.666	*	
Direct Glare x Direct Viewing	89.500	*	
Reflected Glare x Grey 3 Polaroid Viewing Transmission = 0.15	88.500	*	
Reflected Glare x Grey 2 Plain Viewing Transmission = 0.30	68.166		*
Reflected Glare x Direct Viewing	64.666		*
Reflected Glare x Grey 3 Plain Viewing Transmission = 0.20	60.333		*

* Non-significant groupings connected by column of asterisks

condition. There were no significant difference for any of the direct glare and no glare viewing conditions.

Glare by subjects. Table 20 presents Duncan's multiple range test for interaction of glare conditions by subject effect. The reflected glare condition was judged significantly worse for subjects one, two, and six as compared to both no glare and direct glare. There was no significant effect of glare conditions for subjects three and five.

Magnitude Estimation of BCD

Magnitude estimation of BCD data of Table 5 was analyzed for average magnitude estimation of BCD. The ANOVA utilized two variables: four viewing conditions (V) and six subjects (S). Table 21 gives the three-way ANOVA for the average estimated BCD. Both the subject effect and viewing condition effect are considered and significant effects ($p < .05$) are identified. There was a significant effect for viewing conditions.

Viewing conditions. Table 22 presents Duncan's multiple range test for viewing condition effect. Viewing through polaroid sunglasses resulted in significantly higher BCD than viewing directly, or viewing through grey 2 or grey 3 plain sunglasses. Viewing through grey 3 (plain) sunglasses resulted in significantly higher BCD than direct viewing. There was no significant increase in BCD for grey 2 (plain) than direct viewing. Also, there was no significant increase in BCD by viewing through grey 3 (plain) sunglasses rather than grey 2 (plain) sunglasses.

TABLE 20

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Three Glare Conditions by Six Subjects on Subjective Judgment of Visual Performance

Entry	Means	
No Glare x Subject 2	106.250	*
No Glare x Subject 5	105.250	*
Direct Glare x Subject 2	102.000	**
Direct Glare x Subject 4	102.000	**
Direct Glare x Subject 5	101.750	**
No Glare x Subject 4	98.000	***
No Glare x Subject 3	94.750	****
Reflected Glare x Subject 5	94.750	****
No Glare x Subject 6	92.250	****
Direct Glare x Subject 3	90.750	***
Direct Glare x Subject 6	87.250	**
Reflected Glare x Subject 3	86.000	**
No Glare x Subject 1	85.500	**
Direct Glare x Subject 1	81.250	**
Reflected Glare x Subject 6	72.000	*
Reflected Glare x Subject 2	59.000	*
Reflected Glare x Subject 4	58.500	*
Reflected Glare x Subject 1	52.250	*

* Non-significant groupings connected by column of asterisks

TABLE 21

Analysis of Variance of BCD for Four Viewing Conditions

Source of Variance	df	MS	F
Subjects (S)	5	307,916.375	1.637
Viewing Conditions (V)	3	3,508,193.999	18.657**
S x V	15	188,027.125	
Total	23		

*$p < .05$
**$p < .01$

TABLE 22

Duncan's Multiple Range Test at the 0.05 Level for the Effect of Four Viewing Conditions on Magnitude Estimation of B.C.D.

Entry	Mean B.C.D. (footlamberts)	
Grey 3 Polaroid Viewing Transmission = 0.15	3083.3	
Grey 3 Plain Viewing Transmission = 0.20	2166.7	*
Grey 2 Plain Viewing Transmission = 0.30	1800.0	**
Direct Viewing	1266.7	*

* Non-significant groupings connected by column of asterisks

DISCUSSION

Visual Acuity

The mean value of visual acuity angle for the no glare condition with direct viewing was found to be 0.52 minutes, which is appreciably larger than the 0.40, obtained by Moon and Spencer (1944) for the same background luminance (100 footlamberts). This may be due to the fact that in the present study, since it was imperative to view at an angle of 45^{o} to have a reflected glare effect, the task was rather difficult due to the visual distortions in the gap of the Landolt ring. Moreover, the index of visual acuity used in this thesis does not account for the probability of correct responses by the subjects due to chance. Since the gap of the Landolt ring was always positioned towards one of the eight positions and the subjects were encouraged to guess, the probability associated with such a chance factor was 1/8 or 0.125. For a random sample of 20 observations, accounting for this probability resulted in approximately eight percent higher values for the average visual acuity angle. Furthermore, the subjects selected to take part in this experiment had better than average visual acuity. Initially several potential subjects were eliminated based on self reports of poor acuity. On the first day of experimentation, five of the six subjects initially selected to participate in the study had to be rejected, because they failed to see even the largest available visual angle in glare conditions. Since the study was primarily designed to evaluate relative effects of different viewing and glare conditions, the absolute values of visual acuity angle were of little importance.

As seen in the Results, most of the effects of the experimental variables have been found to be significant. The mean visual acuity angle for reflected glare was 0.98 minutes as compared to 0.61 minutes for direct glare and 0.59 minutes for no glare conditions. Thus reflected glare significantly reduced visual acuity. Although statistically insignificant, direct glare apparently did reduce visual acuity. The insignificance of direct glare can be accounted for by the lack of severity of direct glare condition (6.8 footlamberts) as compared to the reflected glare condition (1000 footlamberts). It was desired to have an equal effect for both direct glare and reflected glare conditions, but, due to lack of availability of a point source of light of high luminance, the equivalent veiling luminance of direct glare could not be increased beyond 6.8 footlamberts. This value was obtained by the equation given by Halladay (1926).

$$L_v = \frac{10\Pi E}{\theta^2}$$

where

L_v = equivalent veiling luminance (footlamberts)

E = illumination produced by the glare source in the plane of the pupil (footcandles)

θ = angular displacement of glare source from the line of sight (degrees).

For the present study the experimenter could not increase the illumination due to the available glare source beyond 0.95 footcandles. The least displacement of glare source due to practical consideration was 2.5" at a distance of 67". This gave a value for $\theta = \frac{180}{\Pi} \times \frac{2.5}{67} = 2.1^{\circ}$, and $L_v = \frac{10\Pi \times 0.95}{(2.1)^2} = 6.8$ footlamberts. However, the insignificance of the direct glare effect did not defeat the main purpose of the present study which was to evaluate the effect of polarized sunglasses on reflected glare.

Viewing through Grey 3 polaroid sunglasses (transmission equals 0.15) gave the best overall mean visual acuity angle (0.66 minutes). This was significantly better than direct viewing (0.71 minutes). Both direct viewing and viewing through polaroid sunglasses gave better visual acuity than viewing through the plain sunglasses. This may be attributed to the fact that there was a drastic improvement in visual acuity due to polaroid sunglasses in adverse reflected glare conditions.

The results can best be understood by examining the interaction between glare and viewing conditions. Figure 15 gives mean visual acuity angles for four viewing conditions by three glare conditions.

The best acuity angle was in the no glare condition with direct viewing. In the absence of any glare, both polaroid and plain sunglasses, depending upon their transmissions reduced visual acuity. The loss in the visual acuity was not significant for transmissions up to 0.20. However, the polaroid sunglasses (transmission equals 0.15), there was a significant loss in the visual acuity for no glare condition. Since the background luminance was 100 footlamberts, polaroid sunglasses resulted in an effective

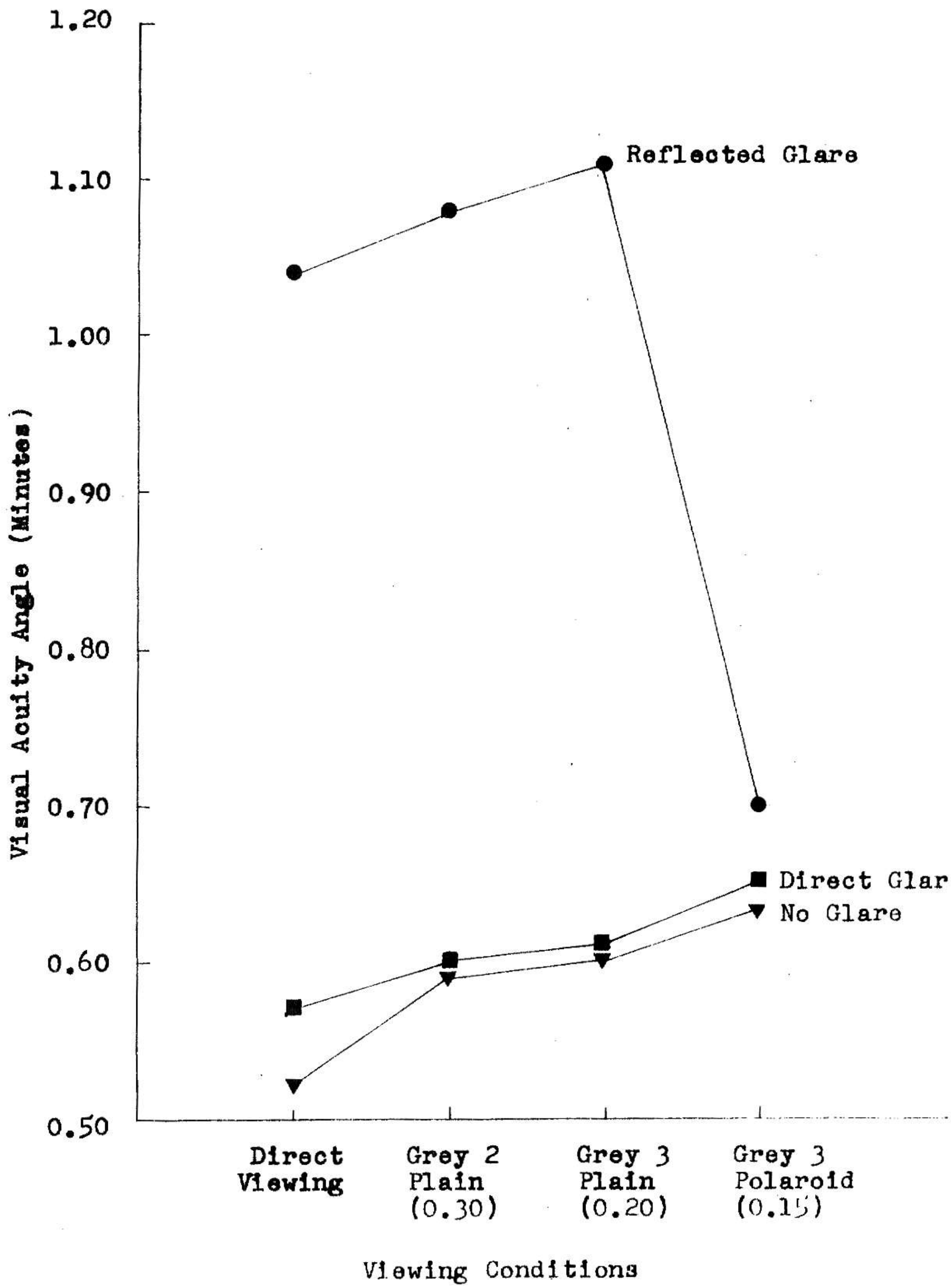


Figure 15. Visual acuity angle for four viewing conditions by three glare conditions.

luminance of 15 footlamberts. Richard (1953), Roper (1953), and Blackwell (1953 and 1954) investigated the effect of glass filters of 0.69 to 0.87 transmission in background luminances of 0.01 to 11 footlamberts (night driving conditions). All found significant losses in the visual acuity. The present study confirms those findings for higher luminance levels. However, the effect of sunglasses at very high levels of luminances encountered in most outdoor activities, still remains to be seen. It is expected that as luminance is increased the difference among viewing conditions would decrease since the absolute values of the transmitted luminances will be quite high.

The effect of sunglasses in direct glare condition was quite similar to that of no glare conditions, that is there was no significant loss in visual acuity until the transmission of sunglasses was reduced to 0.15. This was expected since polaroid sunglasses should not help in direct glare situations.

Thus the hypothesis that any kind of sunglasses can only result in a loss of visual acuity is confirmed for no glare and direct glare.

The primary purpose of this study was to test if the polaroid sunglasses reduced visual disability due to reflected glare. As shown in Figure 15, viewing through Grey 3 polaroid sunglasses produced a drastic improvement in the visual acuity in reflected glare condition. In fact, the use of polaroid sunglasses almost completely eliminated the disability due to reflected glare. The mean visual acuity angle for polaroid sunglasses with reflected glare was not significantly different from polaroid sunglasses with no glare or direct glare situations. This was expected since the angle of reflection (45°) was selected very close to the polarizing angle for the material of the reflecting surface (53^{o}). The usefulness of polaroid sunglasses depends upon the angle of reflection and the orientation of reflection. When reflection on a vertical surface is due to a glare source at the side of the eye, polaroid sunglasses would be of little use. Although statistically insignificant, even in the reflected glare condition, the use of plain sunglasses apparently resulted in some loss in visual acuity. So, the theoretical hypothesis formulated in the introduction section has been confirmed. That is, polaroid sunglasses but no others improves visual acuity in reflected glare conditions.

The subjects' variability was expected because of the natural difference in the visual acuity for the different subjects. There was a significant learning effect, which was also expected. The learning effect was maximum for reflected glare condition. There does not seem to be any logical explanation of this effect. One subject, however, did comment that he found himself more settled in coping with reflected glare condition with each replication.

Subjective Judgments of Visual Performance

The results obtained by analyzing subjective judgment of visual performance were comparable to the those obtained by analyzing actual visual acuity angle measurements. The mean values of percent subjective judgments and actual measurements are given in Table 23. The correlation coefficient between the two indices is 0.88. Thus, when people are presented with varying seeing conditions, they do realize how much they see. However, there was one subject (number 5) who judged that he saw better

TABLE 23
A Comparison for Means of Subjective Judgments of Visual Performance (percent) and Actual Visual Performance (percent), for Three Glare Conditions by Four Viewing Conditions

Viewing Conditions	Glare Conditions					
	No Glare		Direct Glare		Reflected Glare	
	Judgment Means (percent)	Actual Means (percent)	Judgment Means (percent)	Actual Means (percent)	Judgment Means (percent)	Actual Means (percent)
Direct Viewing	100.0	100.0	89.5	93.6	64.7	50.0
Viewing Through Grey 2 Plain Sunglasses (Transmission equals 0.30)	98.2	87.9	91.7	87.0	68.1	48.4
Viewing Through Grey 3 Plain Sunglasses (Transmission equals 0.20)	94.8	86.5	97.8	84.9	60.3	46.9
Viewing Through Grey Polaroid Sunglasses (Transmission equals 0.15)	95.0	82.3	97.7	80.3	88.5	74.2

with all sunglasses in all kinds of glare conditions; a judgment which was contrary to actual findings. Furthermore, comparison of percent judgments and percent acuity results showed a consistant bias to overestimate the seeing capability. Moreover, since in the present study the subjects had a very difficult visual task in a laboratory to base their judgments on, the subjective estimation is not necessarily expected to have the same kind of correlation to the visual acuity in most of the outdoor visual activities. So any generalization based on such a procedure should be made very carefully. This would be exemplified by the erroneous common judgment that "Sunglasses help me see better."

Discomfort Glare

For the magnitude estimation of discomfort glare, the present study was limited to the reflected glare. The finding that polaroid sunglasses resulted in significantly reduced discomfort glare was expected because polaroid sunglasses eliminate discomfort glare due to reflected glare. Another interesting but unexpected effect was the effect of different transmissions of sunglasses on discomfort glare. With direct viewing, the mean luminance for discomfort glare was 1270 footlamberts. With glasses of 30% and 20% transmissions, the discomfort glare values were 1800 footlamberts and 2150 footlamberts. The absolute values for the sunglasses conditions would thus be 540 and 430 footlamberts. None of these values compare with 1270 footlamberts (mean value for direct viewing). This was probably due to a visual constancy effect. The viewer probably tends to compromise in his judgment between the lower luminances seen through the sunglasses and the high luminances he "knows" are "out there."

Practical Implications

Since the present study was conducted for indoor luminance levels (100 foot Lamberts), the practical implications are related to industrial type situations more than to outdoor seeing. In some inspection tasks or even in machining tasks, the presence of reflected glare reduces visual acuity. The polaroid sunglasses have a potential for use in some of these situations. In an ordinary turning task on a lathe, the disability due to the light reflected from the shining part might be reduced by use of properly designed polaroid safety glasses, instead of plain safety glasses. Since even for lower levels of luminance and at low transmission (0.15), polaroid sunglasses were found to have improved visual acuity for reflected glare, their use is strongly recommended in preference to anything else. Polaroid sunglasses with high transmission (0.40 to 0.50) may be ideal for normal outdoor activities. Use of any sunglasses is not recommended for any indoor situation, where there is no glare.

Future Research

For the future research it is recommended to test a wider range of sunglasses for higher luminance levels. At very high levels of luminances encountered in most outdoor activities, it is expected that difference among viewing conditions would decrease since the absolute values of transmitted luminances will be quite high.

Another extension of the present work can be to test polaroid safty glasses for luminance levels found for different industrial tasks.

CONCLUSIONS

The mean absolute value of visual acuity angle for no glare condition with direct viewing was found to be 0.52 minutes. Considering the visual distortion of the gap of the Landold ring due to necessity of viewing at an angle of 45^{o}, this was comparable to the value 0.40 minutes obtained by Moon and Spencer (1944) for the same background luminance (100 footlamberts).

There were significant losses in visual acuity due to reflected glare and plain sunglasses. Polaroid sunglasses resulted in the best visibility. Although statistically insignificant, direct glare apparently did reduce visual acutiy.

There were significant effects for the interaction between glare and viewing conditions. The best acuity angle was in the no glare condition and with direct viewing. There was significant loss in visual acuity for low transmission sunglasses (0.15) for no glare and direct glare conditions. Although statistically insignificant, even sunglasses of transmissions 0.20 & 0.30 apparently did reduce visual acuity in all the conditions. There was a drastic gain in visual acuity with polaroid sunglasses even at the lowest transmission (0.15) in the reflected glare condition.

Subjective judgments of visual performance were comparable to the actual visual acuity measurements. Although the correlation coefficient between two indices is 0.88, the comparison of percent judgments and percent acuity results showed a consistant bias to overestimate the seeing capability. So, any generalizations based on such a procedure should be treated very carefully.

Polaroid sunglasses significantly reduced discomfort glare. This was expected because the study of discomfort glare was limited to only reflected glare. The discomfort glare was not reduced in proportion to the transmissions of the sunglasses. This was probably due to a visual constancy effect.

Since the study was conducted for an indoor luminance level (100 footlamberts), the practical implications are related to the use of polaroid safety glasses in industrial type situations with reflected glare. However, since even at low levels of luminance (100 footlamberts) and at a low transmission (0.15), polaroid sunglasses increased visual acuity and reduced discomfort glare in reflected glare condition, their use is strongly recommended in preference to anything else.

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PLAIN AND POLAROID SUNGLASSES AND VISUAL PERFORMANCE, DISABILITY GLARE, AND DISCOMFORT GLARE

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ABSTRACT

Two experiments were conducted on six subjects. In the first experiment, visual acuity angle and subjective judgment of visual performance were determined in a background luminance of 100 footlamberts for four viewing conditions (direct viewing, viewing through plain sunglasses of 20 percent and 30 percent transmission, and viewing through polaroid sunglasses of 15 percent transmission) and three glare conditions. The three glare conditions were no glare, direct glare (equivalent veiling luminance equals 6.8 footlamberts), and reflected glare (1000 footlamberts). In the second experiment, the subjects estimated the magnitude of discomfort glare with four viewing conditions, but only for reflected glare.

The absolute value of the acuity angle was higher in comparison to previous work (possibly due to distortion of the task at an angle of 45^{o}). Visual acuity was reduced by reflected glare, sunglasses, and direct glare although the reduction due to direct glare was not statistically significant. Polaroid sunglasses increased visual acuity in reflected glare. Polaroid sunglasses were also significantly better in reducing discomfort glare than plain sunglasses for reflected glare. Although the correlation of judgments of visual acuity and measured acuity was .88, there was a consistant bias to estimate visual acuity higher than it actually was.